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Modeling Short-Term and Long-Term Carbon Accumulation in Northern Peatlands

Steve Frolking
University of New Hampshire - Main Campus, steve.frolking@unh.edu

Nigel T. Roulet
McGill University

Tim Moore
McGill University

Pierre J.H. Richard
McGill University

P M. Lafleur
Trent University

See next page for additional authors

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Authors

Steve Frolking, Nigel T. Roulet, Tim Moore, Pierre J.H. Richard, P M. Lafleur, Jill L. Bubier, and P Crill

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Steve Frolking
Institute for the Study of Earth, Oceans, and Space
University of New Hampshire, Durham, New Hampshire, USA 03824
E-mail: steve.frolking@unh.edu

Nigel Roulet
Department of Geography, McGill University
805 Sherbrooke Street West, Montréal, Quebec, Canada H3A 2K6
E-mail: roulet@felix.geog.mcgill.ca

Tim Moore
Department of Geography, McGill University
805 Sherbrooke Street West, Montréal, Quebec, Canada H3A 2K6
E-mail: moore@geog.mcgill.ca

Pierre J.H. Richard
Département de géographie, Université de Montréal
C.P. 6128 Centre-ville, Montréal, Quebec, Canada H3C 3J7
E-mail: Pierre.Richard@UMontreal.ca

Peter M. Lafleur
Department of Geography, Trent University
Peterborough, Ontario, Canada K9J 7B8
E-mail: plafleur@trentu.ca

Jill Bubier
Department of Earth and Environment, Mount Holyoke College
South Hadley, Massachusetts, USA
E-mail: jbubier@mtholyoke.edu

Patrick Crill
Institute for the Study of Earth, Oceans, and Space
University of New Hampshire, Durham, New Hampshire, USA 03824
E-mail: patrick.crill@unh.ca

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Introduction

Northern peatlands have enormous carbon (C) stocks, are (or have been) persistent C sinks, are a major source of atmospheric methane, cover a substantial area, and are located where they will be subjected to both climatic change and increasing anthropogenic impacts (Gorham 1991; Bartlett and Harriss 1993). Despite these characteristics, northern peatlands, if included at all, are only superficially considered in most global- and regional-scale ecosystem and biogeochemical modeling and analyses. In a review of circumpolar boreal C budgets, Apps et al. (1993) identified the uncertainty in contemporary C budgets of northern peatlands as one of the most significant remaining gaps in assessment ability.

We present results from two peatland ecosystem models. To test the hypothesis that long-term peat accumulation can be related to contemporary C flux dynamics, we have developed a new model of long-term peat accumulation (the Peat Decomposition Model, PDM). Decomposition rates of the deeper peat are directly related to observable decomposition rates of fresh vegetation litter. Plant-root effects (subsurface oxygenation and fresh litter inputs) are included. PDM considers two vegetation types (vascular and nonvascular) with different decomposition rates and aboveground to belowground litter input ratios. We are using PDM to investigate sensitivities of peat accumulation in bogs and fens to productivity, root to shoot ratio, tissue decomposability, rooting and water table depths (WTD), and climate.

We have also developed the Peatland CARbon Simulator (PCARS), a process-oriented model of the contemporary C balance of northern peatlands. Components of the ecosystem model are as follows: vascular and nonvascular plant photosynthesis and respiration, net aboveground and belowground production and litterfall; aerobic and anaerobic decomposition of organic matter in the peat profile; production, oxidation, and net flux of methane; and loss of dissolved organic carbon with drainage water. The model is driven by hourly air and soil temperatures, WTD, and drainage, either from observational data or from a peatland parameterization of the Canadian Land Surface Scheme (CLASS; Verseghy 1991) coupled to a local climate model or driven by surface meteorological observations. Simulations predict a complete peatland C balance for one season or up to several years.

Long-Term Peat Accumulation and Decomposition

The long-term PDM (Frolking et al. 2001) can be used as a stand-alone model of peat accumulation over millennial time scales. PDM has focused on linking peat decomposition and accumulation rates down through the profile to observable surface properties (e.g., litter bag decomposition studies, vegetation net primary production [NPP]), and characteristics of the vegetation and peat profile. The model tracks annual peat layers, which accumulate in a coherent chronological stratigraphy below the root zone. Cohort decomposition is modeled as follows:

$$\frac{dm}{dt} = -k_0 m_0 \left(\frac{m(t)}{m_0}\right)^{\alpha}$$

where m_0 is the initial mass, k_0 is the decomposition or mass loss rate at time (t) 0, and the parameter α is set to 2.0, so that the mass loss rate falls off linearly with mass lost. Additionally, PDM accounts for the effects of WTD, rooting depth and root litter inputs, moss versus vascular plant productivity, and aboveground versus belowground productivity.

PDM generates peat accumulation profiles from the surface (present) to the base (5 000 to 10 000 yr ago). It can be evaluated with both long-term accumulation rates (e.g., with carbon-14 analyses, as in Fig. 1) and more recent accumulation rates (e.g., lead-210 analyses, as in Weider 2001). Peatland site characteristics that are included in PDM (e.g., rooting depth, moss versus vascular plant productivity, and aboveground versus belowground productivity) can differ from one peatland to another, and peat accumulation rates can be very sensitive to the site values for these properties (e.g., Fig. 2; Frolking et al. 2001). All of these characteristics, which vary across space, may also have varied over the developmental history of any single peatland. However, PDM is a static model and cannot account for these dynamics.

Contemporary Peatland C Fluxes

We have also recently completed the initial development of a new model of peatland ecosystem C fluxes, PCARS (Fig. 3; Frolking et al. 2002). The model simulates hourly or daily rates of vegetation photosynthesis and respiration, litter and peat decomposition, and methane production and oxidation to generate component and net C balances. The primary evaluation site is the instrumented Mer Bleue bog in eastern

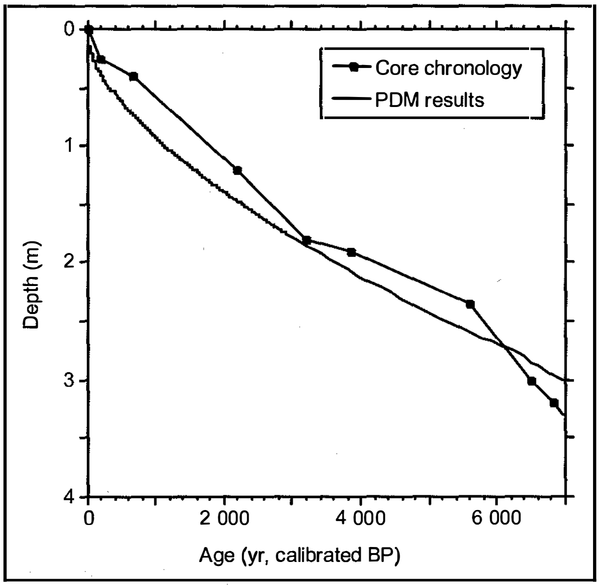

Figure. 1. Observed and simulated (by the Peat Decomposition Model [PDM]) age–depth profile at Mer Bleue bog (Frolking et al. 2001).

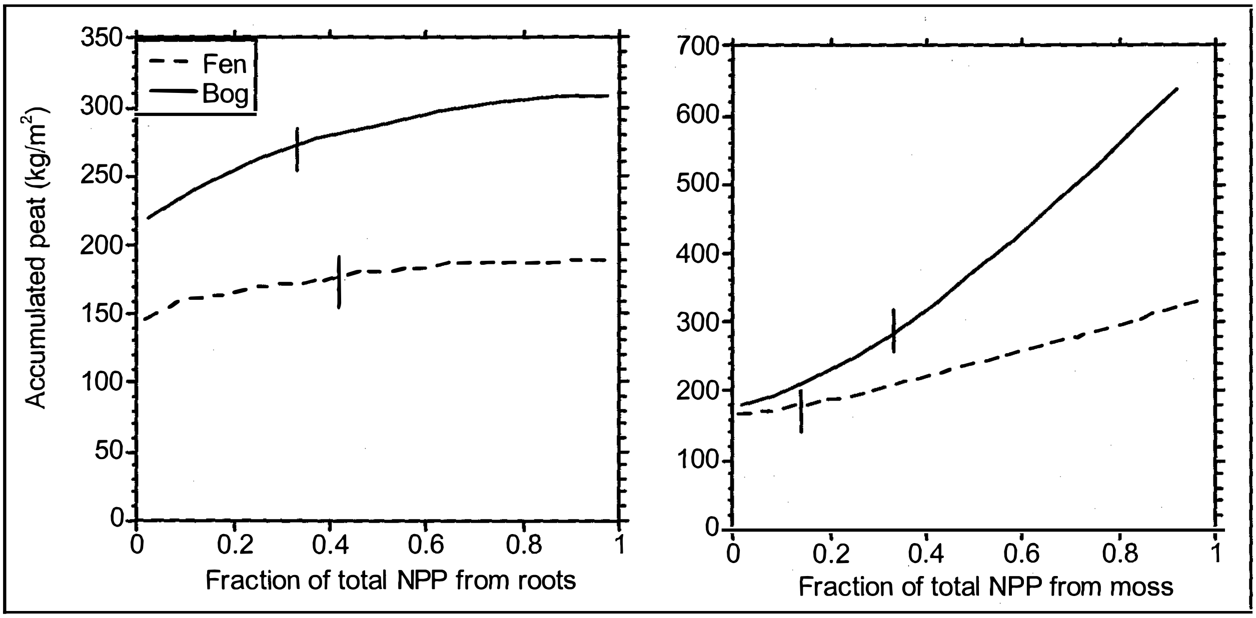

Figure. 2. Sensitivity of total peat accumulation (over 8 000 yr) in the fen and bog scenarios of the Peat Decomposition Model to root and moss fractions of net primary productivity (NPP). Vertical bars mark baseline scenario values.

Ontario (Lafleur et al. 2001). We compared initial model results with the first 2 yr of tower flux data from Mer Bleue (Fig. 4). PCARS captures the magnitudes and seasonality of the fluxes well, although some discrepancies remain to be addressed. PCARS results are also generally consistent with measurements of aboveground vegetation NPP and estimates of belowground vegetation NPP (Moore et al. 2002).

For peatlands with very dry conditions and low water tables, PCARS has simulated significant ecosystem respiration (net ecosystem exchange [NEE] < 0), which is not apparent in the field data. We believe that this result is more related to overestimation of decomposition of partially drained peat associated with low water tables than it is to overestimation of plant respiration or underestimation of plant photosynthesis. We are working to improve the parameterization of peat water content in the saturated zone above the water table and the effect of peat water content on decomposition rates.

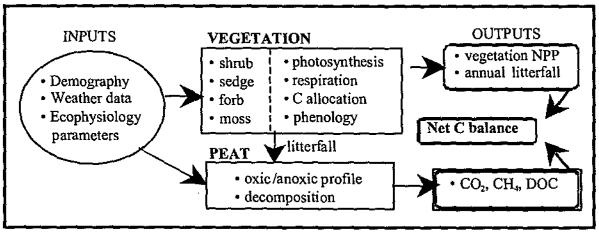

Figure. 3. Basic structure of the Peatland CARbon Simulator ecosystem model. C = carbon, NPP = net primary productivity, CO_2 = carbon dioxide, CH_4 = methane, DOC = dissolved organic carbon.

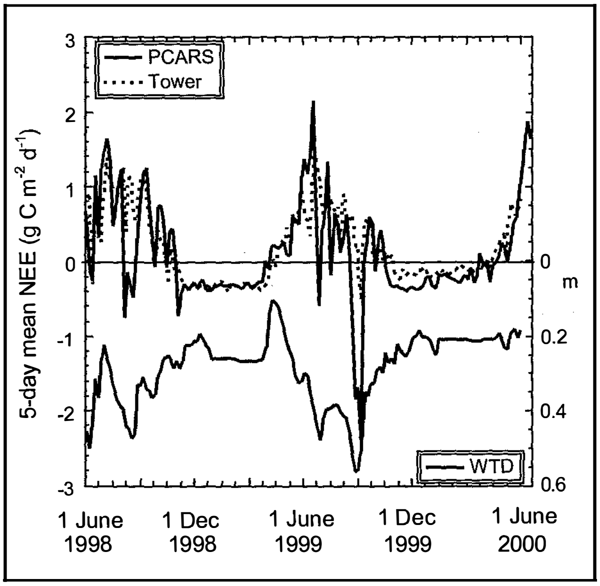

Figure. 4. Weekly average carbon dioxide exchange (as net ecosystem exchange, NEE) and water table depth (WTD) at Mer Bleue. See Lafleur et al. (2001) for site and measurement descriptions. PCARS = Peatland CARbon Simulator.

We are still evaluating the model results. A key question is how well PCARS partitions total respiration between vegetation (autotrophic respiration) and decomposition (heterotrophic respiration). In the current simulations, total annual ecosystem respiration is about 500 g C m^{-2}, with about 55% autotrophic and 45% heterotrophic respiration. These predictions can be compared with field estimates of total photosynthesis and annual vegetation NPP (the difference between these two equals autotrophic respiration), but measuring belowground NPP is very difficult.

Discussion

With a very general parameterization, PDM fen and bog age–depth profiles were similar to data from the most recent 5 000 yr for three bog cores and a fen core from eastern Canada but overestimated accumulation for three other bog cores from that region (Frolking et al. 2001). In addition to the expected sensitivities of peat accumulation to site NPP, PDM results indicate that peat accumulation is sensitive to the ratio of aboveground to belowground NPP and to the ratio of moss to vascular NPP. PDM sensitivity was also evaluated with eight climate scenarios (warmer or cooler [±3°C] and wetter or drier [±25% WTD], to yield warm and wet, warm and dry, cool and wet, and cool and dry scenarios), and four scenarios of ecophysiological sensitivity to temperature (low [$Q_{10} = 2$] and high [$Q_{10} = 3$] for both NPP and decomposition rate). Warmer and wetter conditions were most conducive to peat accumulation. When the sensitivities of NPP and decomposition rate to temperature were the same (both low or both high), NPP effects dominated, and warmer conditions led to enhanced accumulation, whereas cooler conditions led to reduced accumulation. Only when decomposition rate Q_{10} was set to 3 and NPP Q_{10} to 2 did cooler temperatures cause enhanced accumulation and warmer temperatures reduced accumulation. These results all emphasize the importance of being able to estimate at least a rough vegetation successional and productivity history of the peatland. At this stage, PDM does not do this. We plan to link PDM to the dynamic peat accumulation model of Hilbert et al. (2000) to develop a more realistic portrayal of peat accumulation under varying environmental conditions.

Initial results with the PCARS model indicate that it can capture the seasonal dynamics and magnitudes of the major C fluxes of a northern peatland. PCARS has been designed to be forced by output from the peatland parameterization of the CLASS model, which will facilitate simulations exploring the sensitivity of peatland NEE to interannual variability in weather. The model will continue to be evaluated at Mer Bleue which is predominantly *Sphagnum* and ericaceous shrubs and will also be tested at other sites with different vegetation types.

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Table 1. Mean annual temperature and precipitation for the eight study sites

Site	Mean annual temperature (°C)	Mean annual precipitation (mm)
Sylvie's Bog, Alberta	0.2	465
Bleak Lake Bog, Alberta	1.4	493
ELA bogs, Ontario	2.1	623
Marcell S-2 Bog, Minnesota	4.2	670
Nova Scotia Bog, Nova Scotia	6.1	1474
Big Run Bog, West Virginia	7.9	1560
Tamarack Swamp, Pennsylvania	8.3	1181
Cranesville Swamp, Maryland	8.7	1202

Note: ELA = Experimental Lake Area.

Methods

At each site, one or two peat cores (10 cm in diameter, 45 cm deep) were collected and returned to the laboratory, where they were frozen and sectioned into 2-cm depth intervals. Each section was dried, weighed, and ground. From each section, a 3-g subsample was digested with concentrated hydrochloric acid, concentrated nitric acid, and hydrogen peroxide; solubilized polonium (Po) isotopes were then passively plated onto silver disks for activity measurement on an EG&G model 576A alpha spectrometer (Ortec Products). Before digestion, 250 mBq of polonium-209 was added as a chemical yield tracer (cf. Wieder and Yavitt 1994). Organic matter concentration for each section was quantified as loss on ignition (at 450°C). NPP and depth-dependent decay values were estimated for each core by means of the empirical modeling approach detailed in Wieder (2001).

Results

Based on ^{210}Pb dating, net vertical peat accumulation was variable. For example, the top 20 cm of peat represents the remains of 29–124 yr of NPP (data not shown). From peat bulk densities and organic matter concentrations, vertical accumulation was converted to net accumulation of organic matter. Over the past 50 yr, net accumulation of organic matter ranged from 6.9 to 13.1 kg m^{-2} and was not related to either mean annual temperature or mean annual precipitation (Fig. 2A). Estimates of NPP, ranging from 0.237 to 1.057 kg m^{-2} yr^{-1}, were comparable to literature values for temperate and boreal peatlands. Both NPP and decomposition integrated through the top 20 cm of peat increased significantly with both mean annual temperature and mean annual precipitation (Figs. 2B and 2C). An equivalent of 41%–77% of the organic matter added to the peat deposit was lost by decomposition in the top 20 cm of the peat column (Fig. 2D). Organic matter turnover (expressed as decomposition in the top 20 cm/NPP) also increased significantly with both mean annual temperature and mean annual precipitation (Fig. 2D).

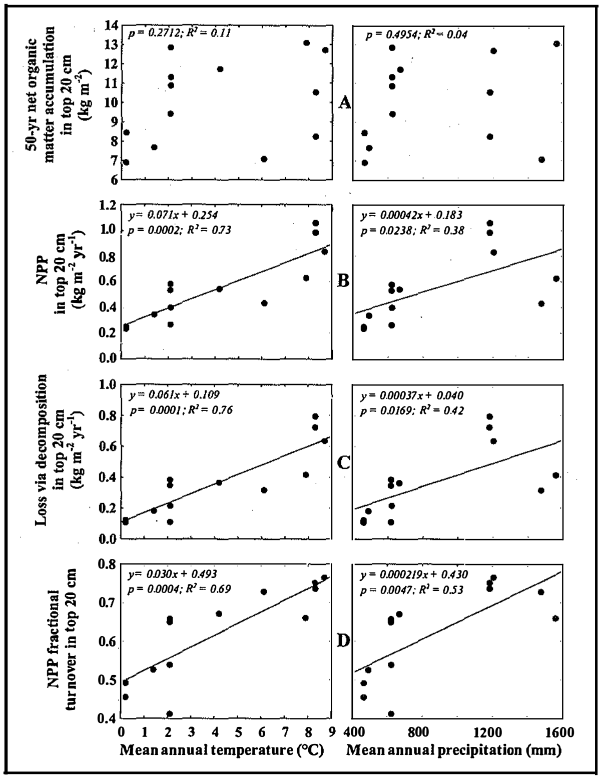

Figure 2. Relationships of net organic matter accumulation over the past 50 yr (A), net primary production (NPP) (B), decomposition (C), and NPP fractional turnover (D) in the top 20 cm of peat to mean annual temperature and mean annual precipitation. Regression lines are shown only for significant relationships.

Discussion

Although net organic matter accumulation over the past 50 yr was not related to either mean annual temperature or mean annual precipitation (Fig. 2A), both NPP (Fig. 2B) and near-surface decomposition (Fig. 2C) were accelerated at higher temperatures and precipitation levels. Hence, in a warmer, wetter climate, a possibility for the northern boreal regions of the world (Raisanen 1997; Moore et al. 1998), peatlands may experience a greater rate of organic matter turnover (shorter residence time) in the top 20 cm of peat (Fig. 2D). Net accumulation of organic matter may remain largely unaltered, although the more rapid turnover of organic matter may result in peat deposits with a greater bulk density in the top 20 cm.

Predictions under scenarios of a warmer, dryer climate are less certain, as the stimulatory effects of warmer temperatures on both NPP and decomposition would be offset by the inhibitory effects of less precipitation. At this time, there is insufficient evidence, either from modeling or from field measurement and experimentation, to conclude which factor, temperature or precipitation, has or will have a greater influence on the processes that influence net accumulation of organic matter in peat.

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Putting the Bog into Context: Modeling Landscape Controls on Peatland Development in Continental Climates

Ilka E. Bauer
Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E9
Email: ibauer@ualberta.ca

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Introduction

Peatland development is controlled by factors operating at a variety of different scales. Regional climate provides a general framework within which more local physiographic factors allow for the development of conditions conducive to peat initiation. Once peatlands are established on a landscape, hydrological changes resulting from peat accumulation not only control autogenic patterns of vegetation succession (Weber 1908) but can also change local drainage patterns and promote further peatland development (e.g., Kulczynski 1949; Ivanov 1981). In continental western Canada, extensive peatlands have developed under the influence of a cold, dry climate. The current southern limit of their distribution is controlled by a combination of climate and physiographic factors (Halsey et al. 1998). Given the smaller atmospheric moisture surplus, continental peatlands are likely to be under stronger physiographic control than those in oceanic regions. This notion is supported by local distributions of different landform types (Kulczynski 1949; Tolonen 1967; Heinselman 1970) and by a strong link between peatland occurrence and certain aspects of surficial geology at the southern limit of their distribution (Halsey et al. 1998).

In Clymo's (1984) peat accumulation model, the maximum depth that a peatland can attain is determined by the ratio between catotelm productivity and decomposition. Peat accumulation is largely controlled by autogenic processes, with climate determining the ultimate shape (not the height) of a peatland (cf. Ingram 1982). This conceptual model, explicitly developed in the context of oceanic raised bogs, is probably inappropriate for describing the long-term dynamics of continental peatlands. Several subsequent studies have combined Clymo's ideas about peat accumulation with more dynamic conceptions of hydrological processes: Winston (1994) examined (among other things) the effects of groundwater influx, and Hilbert et al. (2000) developed a model that uses several feedback processes to couple peat accumulation to water-table dynamics. None of these models, however, attempts to incorporate the successional dynamics of peatland vegetation. Since peatland vegetation is controlled by hydrological factors (water table depth and water chemistry; e.g., Sjörs 1950; Gignac et al. 1991; Gorham and Janssens 1992) and affects peat accumulation through differential decay (Johnson and Damman 1993; Szumigalski and Bayley 1996), it should be included in peat accumulation models. Here I describe a simulation model currently being developed that combines autogenic peat accumulation processes, vegetation dynamics, and hydrological factors in an attempt to provide a more complete picture of peatland evolution.

Model Structure

The model simulates the production and decay of annual cohorts of peat. Vegetation and hydrological parameters are adjusted at each time step to reflect changes in environmental conditions resulting from peat buildup (Fig. 1).

Peat Accumulation

A new peat cohort is created each year, and previous cohorts are decomposed at rates that depend on their botanical composition and stratigraphic position relative to the water table (Fig. 2). The boundary between (fast) acrotelm decay and (slow) catotelm decay is gradual, with decay in the transition zone depending on the proportion of time spent above the water table. For each cohort, the model keeps track of the mass of four different litter types, which can be decayed at different rates. Cohort mass and assumed bulk

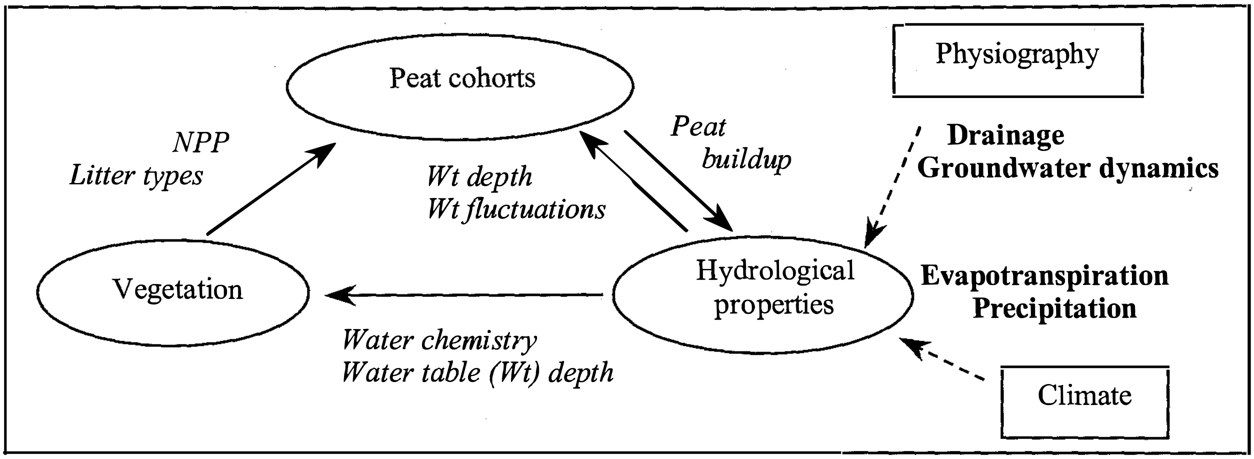

Figure 1. Relationship between the main model components. NPP = net primary production. Interactions (solid arrows) between main model components (circled). Italicized type denotes mechanisms of interaction (e.g., hydrology affects vegetation through water chemistry and water table depth). Climate and physiography define boundary conditions that are set at the beginning of each simulation (broken arrows; bold type).

density profiles are used to rebuild stratigraphy at the end of each time step.

Hydrological Factors

To allow for identification of main peatland types, the model calculates a hydrological budget that recognizes two different types of water (Fig. 3): "mineral-poor" water enters the peatland primarily as precipitation, whereas "mineral-rich" water enters through groundwater discharge or seepage. Both water types can be lost by evapotranspiration, seepage, or recharge to an underlying aquifer. The position of the water table and the mineral-rich water limit relative to the peat surface are recalculated at the end of each time step.

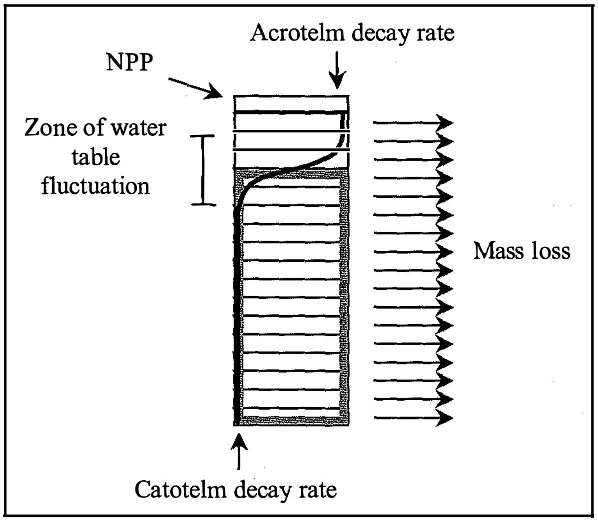

Figure 2. Production and decay of annual peat cohorts. NPP = net primary production.

Vegetation

At present, four peatland types are recognized: three types of rich fen (open, shrubby, and treed) and *Sphagnum*-dominated communities (poor fens and bogs), which are always treed. On the basis of the water budget calculations, the model uses a set of simple decision rules to determine which peatland type will be present at the beginning of the next time step (Fig. 4). Each peatland type is characterized by a different

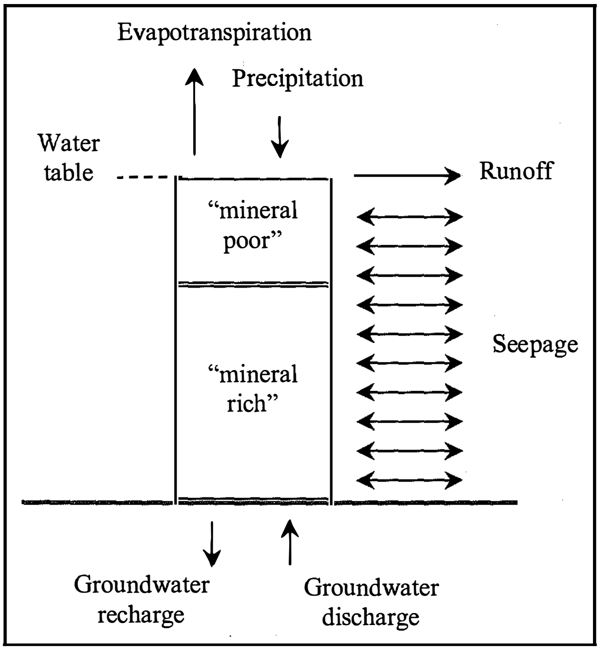

Figure 3. Parameters used in water budget calculations.

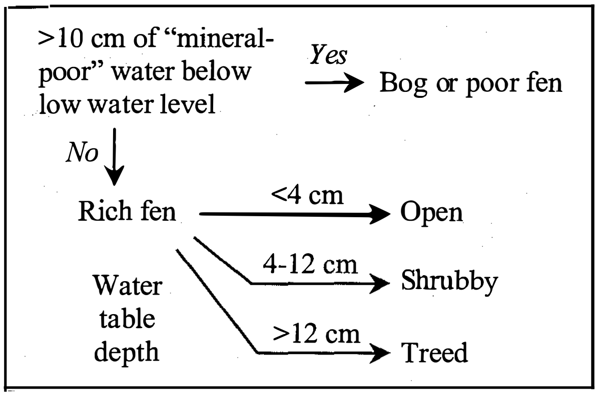

Figure 4. Decision rules used to assign current peatland type. Water table cutoffs for the different rich-fen communities are based on data in Zoltai et al. (2000).

vegetation composition, and net primary production and the relative proportions of different litter types are adjusted accordingly.

Preliminary Results and Further Work

Preliminary results indicate that the model captures basic aspects of peatland dynamics reasonably well. *Sphagnum*-dominated peatlands, for example, have high potential for peat accumulation but can only exist within certain hydrological frameworks. Under limiting atmospheric moisture conditions, peat accumulation depends on groundwater discharge or seepage, with accumulation rates depending on groundwater input and resultant position of the water table (Fig. 5). At present, the results are mainly regarded as qualitative, with both the hydrological and vegetation components needing further development. Recognition of only four peatland types differing markedly in botanical composition means that small shifts in water-table parameters cause abrupt changes in litter composition and potential for peat accumulation. Restriction of vegetation response to transitions between the main peatland types may have a stabilizing effect and prevent succession to *Sphagnum* under some climate scenarios.

The main aim of the present work is to understand within-site variability in peat accumulation and successional development. The model will be parameterized and used to examine the development of several cores from a large peatland complex in the Mid-Boreal of Alberta (113°15'W 55°03'N). According to criteria defined by Halsey et al. (1998) the climate of the region is potentially limiting for peatland development. However, *Sphagnum*-dominated communities are present, and peat has accumulated to depths of over 4 m in some parts of the site. Basal carbon-14 dates and macrofossil analyses reveal marked differences in peat accumulation rates and vegetation development between cores. The model, once completed, will be used to examine whether such differences can be explained by the different physiographic positions of coring locations.

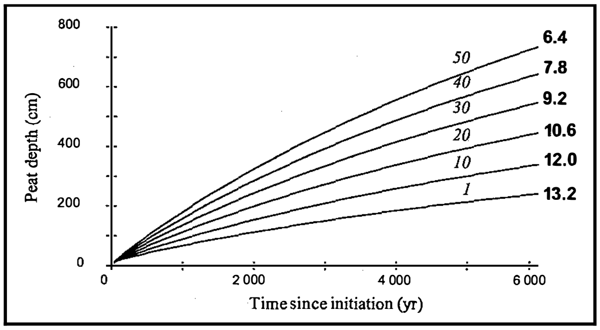

Figure. 5. Peat accumulation over 6000 yr in fens receiving groundwater input (1–50 mm/yr), with precipitation equal to potential evaporation. Numbers on the right represent water-table position (centimeters below peat surface) at the end of each simulation. Fens that receive more groundwater input have equilibrium water tables closer to the peat surface and accumulate peat at a faster rate.

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Differential Response of Peatland Types to Climate: Modeling Peat Accumulation in Continental Western Canada

David Beilman
Department of Biological Sciences
University of Alberta, Edmonton, Alberta, Canada T6G 2E9
Canadian Forest Service, Northern Forestry Centre
5320 – 122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: dbeilman@nrcan.gc.ca

Zicheng Yu
Canadian Forest Service, Northern Forestry Centre
5320 – 122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: zyu@nrcan.gc.ca

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Introduction

Western Canadian continental peatlands (within Alberta, Saskatchewan, and Manitoba) represent a large pool of carbon (C), presently storing 48.0 Pg C (Vitt et al. 2000). Rates of C sequestration by northern peatlands are variable. Although Gorham (1991) estimated the rate for the world's northern peatlands at 28.1 g C m^{-2} yr^{-1}, more recent regional estimates range from 14.1–22.5 g C m^{-2} yr^{-1} in Finland (Mäkilä 1997) to 21 g C m^{-2} yr^{-1} in a peatland-rich landscape in Manitoba (Rapalee et al. 1998) and 19.4 g C m^{-2} yr^{-1} for western Canada (Vitt et al. 2000). Short-term studies of individual peatlands show even greater variability, with rates as high as 68 g C m^{-2} yr^{-1} (Lafleur et al. 2001), and interannual switches from net sinks to net sources of atmospheric C in response to climate has been reported (Shurpali et al. 1995; Lafleur et al. 1997; Joiner et al. 1999). Climate projections based on models driven by greenhouse gases show warmer and variably wet conditions in continental western Canada (Moore et al. 1998; Boer et al. 2000). The potential response to climate change of the large C stores in northern peatlands and their C-accumulating nature is important to global C balances, is highly complex given the diversity of peatland types (Gorham 1991), and remains poorly understood (Moore et al. 1998). Peat accumulation modeling has largely focused on bogs and has only begun to address the range of conditions across different peatland types (e.g., bogs and fens; Frolking et al. 2001). Little effort has been made to assess patterns of peat accumulation and response to climate across the different peatland types of continental western Canada.

Model, Peatland Types, and Parameters

In this study, we applied the acrotelm–catotelm conceptual model (Clymo 1984) to four generalized western Canadian peatland types to investigate potential differences in C sequestration behavior. The four peatland types were permafrost-underlain peat plateaus, continental bogs, treed fens, and treeless fens. Areal coverages for these types are known for continental western Canada from extensive interpretation of aerial photographs and mapping (Vitt et al. 2000). We extended the model to incorporate the influence of changes in peatland hydrologic characteristics (water table depth [WTD] below surface) on peat decomposition rates at the interface between the upper (acrotelm) and lower (catotelm) peat layers. To facilitate visualization of changes in WTD, the model calculates peat depth while conserving mass as peat is transferred from acrotelm to catotelm. A drop or rise in the WTD influences peat decomposition in the model by introducing either more aerobic conditions into the catotelm (drop in WTD) or more anaerobic conditions into the acrotelm (rise in WTD). A specific mass of peat is partitioned from either the total acrotelm or the total catotelm mass, which decomposes at an intermediate value (the average of acrotelm and catotelm decomposition rate for each peatland type). For the peat plateau, catotelm decomposition is set to zero and does not change under drier conditions, because the catotelm is frozen. The model has been parameterized with the best available information for each of the four peatland types (Table 1). Here we analyze model performance by comparing modeling results to basal peat ages and depths from paludified peatlands from across western Canada (millennial-scale peat accumulation rates); testing the sensitivity of peat accumulation to linear, gradual changes in model parameters (century-scale rates); and investigating the behavior of each type in response to general climate change scenarios.

Sensitivity to Changes in Model Parameters and Climate Change Scenarios

Modeled peat depths showed reasonable agreement with calibrated basal radiocarbon dates and depths for all peatland types (Fig. 1). Sensitivity analyses showed that peat depths and accumulation rates were strongly affected by gradual linear changes in net primary production (NPP) over 100 years and to changes in acrotelm decomposition rates (±50%) and changes in WTD (±10 cm) (Fig. 2). Linear decreases in NPP and WTD and increases in acrotelm decomposition within these ranges resulted in a leveling-off of peat accumulation and often a decrease in peat depth by the end of the simulation period (Fig. 2). Peat accumulation is most sensitive to changes in NPP and acrotelm decomposition, which have a variable effect on peat accumulation patterns that is strongly affected by the acrotelm depths of the different peatland types.

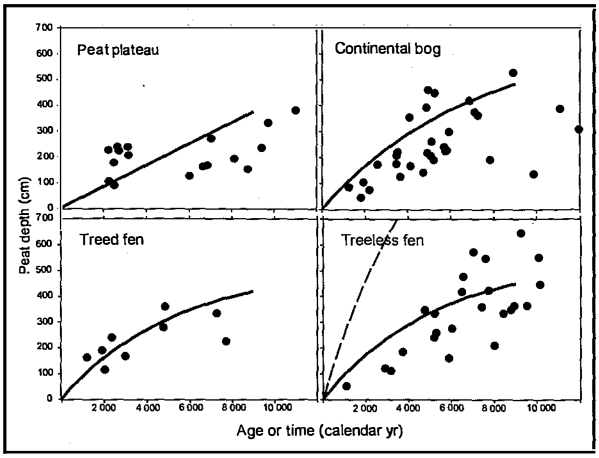

Figure 1. Comparison of modeled long-term peat accumulation (solid lines are peat depths from 9 000-yr model runs) for each peatland type and calibrated basal radiocarbon dates and depths from Halsey et al. (1998). For treeless fen, the dashed-line simulation is based on the acrotelm–catotelm boundary defined by water table depth (Table 1).

When the model was run under a warm scenario the higher temperatures (and equivalent functional response) led to higher rates of C sequestration in all peatland types, despite the effect of increased decomposition (Table 2).

Table 1. Peatland extent, characteristics, and model parameters for four generalized peatland types in continental western Canada

	Peat plateau	Continental bog	Treed fen	Treeless fen
Surface area (km^2)a	94 946	33 469	104 287	116 352
Mean permafrost or water table depth (cm) (*n*)[b]	52 (52)	35 (98)	21 (83)	5 (126)
Acrotelm depth (cm)	52	35	21	15[c]
Mean NPP (g m^{-2} yr^{-1}) (and range)[d]	*372 (182–481)*	497 (237–669)	497 (237–669)	423 (182–757)
Acrotelm				
Mean decomposition (yr^{-1})	*0.006*	*0.016*[e]	*0.024*	*0.024*
Bulk density (kg m^{-3})[b]	105.8	67.6	72.9	82.7
Organic matter density (kg m^{-3})[b]	96.6	62.5	65.2	73.3
Catotelm				
Mean decomposition (yr^{-1})[a]	0	0.000 139	0.000 185	0.000 185
Bulk density (kg m^{-3})[b]	110.1	123.3	128.3	115.3
Organic matter density (kg m^{-3})[b]	99.1	110.0	112.8	102.0

[a] Vitt et al. (2000).

[b] Zoltai et al. (2000).

[c] Based on mean rooting depth (unpublished data).

[d] Campbell et al. (2000).

[c] Yu et al. (2001).

Note: NPP = net primary production. Italicized values are best estimates based on interpretation of relevant literature.

Table 2. Final carbon accumulation rates after 100 yr of model simulation with increasing net primary production (NPP) and acrotelm decomposition (*k*) and changing water table depth (WTD) scenarios[a]

	Accumulation rate (g C m^{-2} yr^{-1})			
Model	Peat plateau	Continental bog	Treed fen	Treeless fen
No change	19.5	37.7	34.4	34.5
Increased NPP, increased *k* (warm)	26.5	57.0	55.1	54.6
Increased NPP, increased *k*, WTD drop (warm and dry)	26.5	12.5	–13.2	–7.1
Increased NPP, increased *k*, WTD rise (warm and wet)	51.5	98.8	121.6	130.6

[a] NPP and acrotelm decomposition increases are based on $Q_{10} = 2$ and a 3.54°C mean annual temperature increase for the peatland area of continental western Canada taken from a regional climate model (3 × CO_2 scenario) (Laprise et al. 1998).

Although analyses showed that peat accumulation is more sensitive to NPP and acrotelm decomposition change than to WTD change, inclusion of conservative WTD changes (± 10 cm) in the scenarios resulted in either a further increase or a decrease in C accumulation relative to baseline values (Table 2). Fens (treed and treeless) showed a greater range in rates between wet and dry scenarios than peat plateaus and bogs. Total fen coverage in continental western Canada is nearly twice that of peat plateaus and bogs (Table 1), which compounds the importance of this variability at the regional level (Fig. 3).

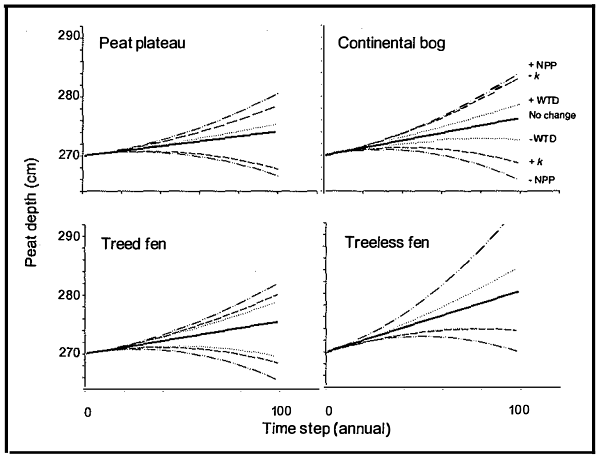

Figure 2. Sensitivity of peat accumulation in each peatland type to changes in model parameters. Maximum and minimum net primary production (NPP) values were taken from the range of values given in Campbell et al. (2000) for treed peatlands (bogs and treed fens together) and open fens and peat plateaus (Table 1). Decomposition rates were changed ± 50% for each peatland type, and water table depth (WTD) was changed ± 10 cm. Initial peat depth (268 cm) is the average peat depth across all types (Zoltai et al. 2000). K = acrotelm decomposition, plus sign = increase, minus sign = decrease.

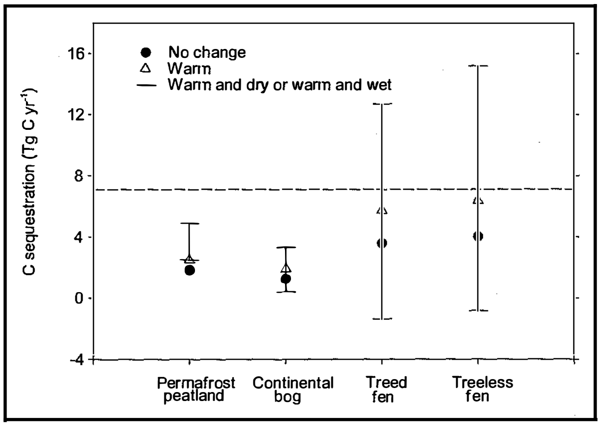

Figure 3. Variability in modeled carbon (C) sequestration rates for peatland types in continental western Canada. Values are based on scenarios from Table 2 and peatland surface areas are taken from Table 1. The broken line shows the estimated mean C sequestration rate for all peatlands. in continental western Canada over the last 1 000 years (7.1 Tg yr^{-1}; Vitt et al. 2000).

Conclusions

The conceptual model reasonably simulates long-term peat accumulation for each peatland type and is sensitive enough to capture short-term variability in peat accumulation rates. Potential changes in peatland WTD caused by changes in precipitation and temperature regimes, and the associated influence on peat decomposition, represent an important component of peatland C balances in western Canada. Fens are intrinsically variable in western Canada, with extended water chemistry and nutrient gradients and more variable plant communities than peat plateaus and bogs. If the two-layer peat accumulation model as parameterized here accurately simulates the relative behavior of continental peatland types, geogenous peatlands (fens) may be where much of the variability in C sequestration occurs on the landscape. The similar behavior of treed and treeless fens reported here is an artifact of limitations in available data for model parameterization; thus, our future conceptual modeling efforts will consider continental fens collectively. We are currently applying the model to assess regional spatial patterns in C sequestration variability and uncertainty, using gridded data for peatland type and cover, peat depth, basin topography, and climate.

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Does the Convex Pattern of Peat Accumulation Matter in Understanding Peat Carbon Dynamics?

Zicheng Yu
Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: zyu@nrcan.gc.ca

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Introduction

Peat accumulation is a function of the balance between production of living plants atop the acrotelm (the surface aerobic layer) and decomposition in both the acrotelm and the catotelm (the underlying anaerobic layer) (Ingram 1978; Clymo 1984). Because litter and new peat in the acrotelm are exposed to aerobic conditions and to varying water levels, they are subject to a high decay rate. Once plant materials are in the catotelm, the decay rate declines sharply and becomes much more independent of minor climatic fluctuations and therefore tends to be constant through time. The rate of peat transfer from acrotelm to catotelm therefore largely determines net peat accumulation. The Clymo (1984) bog growth model assumes constant production and decomposition rates, which produce a concave cumulative mass – age curve for the peat, as seen in most oceanic raised bogs.

High-resolution Holocene data collected recently from a rich fen in central Alberta (the Upper Pinto fen [UPF]) indicate a convex peat-accumulation pattern. This pattern has also been suggested by published data for other continental sites (Kubiw et al. 1989; Kuhry and Vitt 1996). During the *Scorpidium*-dominated period, from about 7 000 to 1 300 calendar yr BP at the UPF, the peat-accumulation pattern, as derived from 15 calibrated carbon-14 dates and 260 bulk density measurements, was convex (Fig. 1). This convexity could be explained by a unidirectional decrease in the rate of peat addition over time.

Here, I fit the UPF data to an extended model and describe a sensitivity analysis to investigate the carbon (C) dynamic implications of this convex accumulation pattern. The results suggest that continental peatlands could reach their growth limit sooner and their declines in C sequestration capacity faster than would be suggested by the Clymo model, even in the absence of any climatic change.

A Model with Changing Peat-Addition Rates

In the conceptual bog model (Clymo 1984), two variables determine long-term peat accumulation in the catotelm: the rate of peat addition (p) and the decay rate (α). In the single exponential model—$dM/dt = p - \alpha * M$, with a solution of $M = [p/\alpha] * [1 - \exp(-\alpha * t)]$—the peat-addition rate (p) determines the general slope of the cumulative peat mass versus age curve, and the decay constant (α) determines the curvature of the curve. Both variables can change over time, but the peat-addition rate is likely to be more

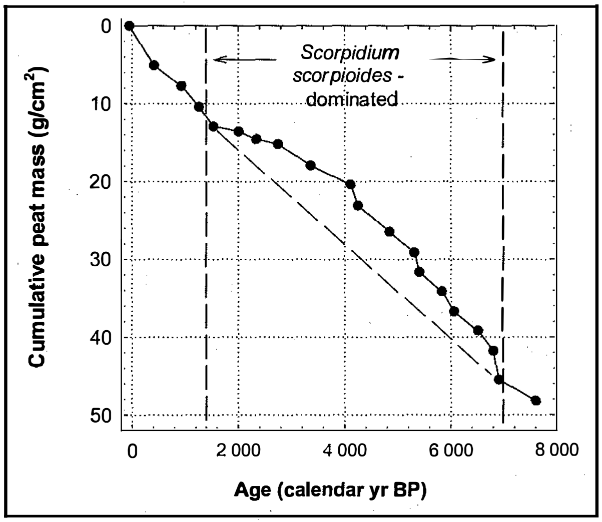

Figure 1. The cumulative peat mass – age profile from the Upper Pinto fen core, based on 20 AMS carbon-14 dates and 398 bulk density measurements. Excluding the basal and top woody peat, the *Scorpidium*-dominated nonwoody peat shows a convex age–depth curve.

sensitive to vegetation type and environmental parameters and thus more variable than the catotelm decay rate.

Following the suggestion of Clymo (2000), a modifier for peat-addition rates, which is in exponential form has been added. The extended conceptual model is then given as follows:

$$\frac{dM}{dt} = p^{*}e^{-b^{*}t} - \alpha^{*}M$$

where M = cumulative peat mass, p = eventual peat-addition rate, α = catotelm decomposition rate, and b = peat-addition rate coefficient. This equation has an analytical solution:

$$M = \left(\frac{p}{\alpha - b}\right)^{*}\left(e^{-b^{*}t} - e^{-\alpha^{*}t}\right)$$

This extended model was used to fit the data from the UPF and to carry out the sensitivity analysis. Figure 2 shows the fitting results, with comparison to results from Clymo-type model, using different peat-addition rates.

Sensitivity Analysis and Causal Factors

As for the concave pattern (Yu and Campbell 1998), the changing decomposition rate has relatively limited influence, especially on younger peat (Fig. 3A). In contrast, changing the peat-addition rate has a noticeable influence on the amount of peat accumulated (Fig. 3B). The peat-addition rate coefficient (b) mostly determines the curvature of the convex curves, with smaller values approaching a straight line (Fig. 3C).

Why would the rate of peat addition to the catotelm show a unidirectional decrease over time in continental peatlands? This decline is likely related to the moisture-limited continental climate and to the hydrologic characteristics of fens and some continental bogs that have groundwater influences (e.g., Glaser et al. 1997). In a moisture-limited continental climate, peat-addition rates likely change in response to changes in peatland height, local hydrologic conditions and nutrient availability, as well as regional climate. Continuous upward peatland growth would potentially increase the distance of the peatland surface from the regional water table and reduce nutrient inputs derived from groundwater to living plants, thus limiting their growth, especially for moisture-sensitive *Scorpidium scorpioides*. This change, relating to peatland height growth, is independent of regional climate change.

Is there any evidence to support the actual values the peat-addition rate suggested by these modeling analyses? Assuming that catotelm decomposition is relatively constant over this 5 400-yr period (decomposition rate has limited influence on overall peat accumulation anyway, as shown in Fig. 3A), the model suggests that the peat-addition rate was 191.83 g m^{-2} yr^{-1} initially, at 5 400 calendar yr BP, and it then decreased exponentially at a rate of 0.000 37 yr^{-1} to 26.01 g m^{-2} yr^{-1} at present (Figs. 3C and 3D). It is possible that

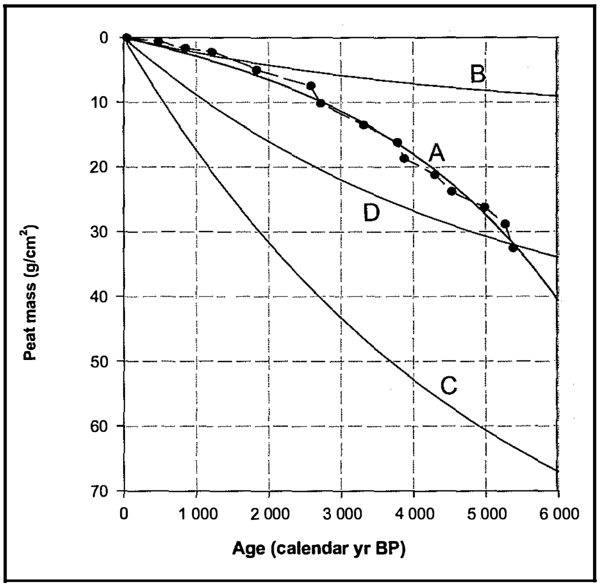

Figure 2. The 15 data points of the Upper Pinto fen (UPF) core dominated by *Scorpidium* (dots and dashed line). Curve A is a fit of the above equation, with a constant decay rate (0.000 2 yr^{-1}, an average value for the catotelm in continental Canada), which yields eventual peat-addition rate of 26.01 g m^{-2} yr^{-1} and b = 0.000 37 yr^{-1}). Curve B results from a Clymo-type model, with constant decay rate of 0.000 2 yr^{-1} and constant peat-addition rate of 26.01 g m^{-2} yr^{-1} (eventual peat-addition rate). Curve C is as B, but with a peat-addition rate of 191.83 g m^{-2} yr^{-1} (initial peat-addition rate at 5 400 yr BP). Curve D is a match of the Clymo (1984) results to the convex model at 5 400 yr BP, which suggests a peat-addition rate of 97.20 g m^{-2} yr^{-1}.

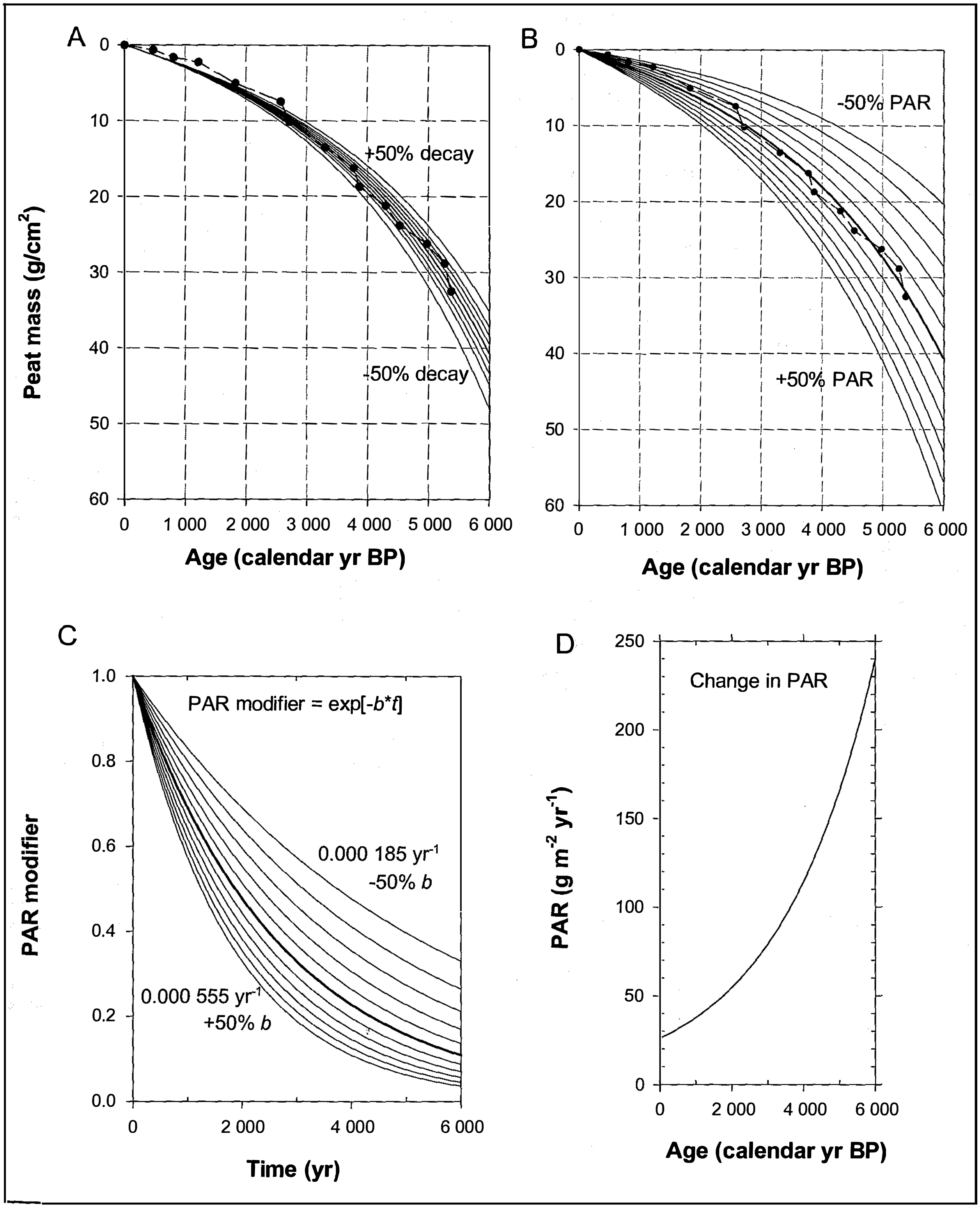

Figure 3. Sensitivity analysis of the convex model. (A) The influence of changing decomposition rate when the base value is 0.000 2 yr^{-1} (thick red line), showing changes from 50% less (0.000 1) to 50% more (0.000 3 yr^{-1}). (B) The influence of changing peat-addition rate (PAR), with eventual PAR of 26.01 g m^{-2} yr^{-1} as the base case (50% increase to 39.02 and 50% decrease to 13.01 g m^{-2} yr^{-1}). (C) Change in PAR modifier over time as a function of *b*, which determines the curvature of the curves. (D) Change in PAR with age in the base case, showing decrease from initial PAR of 191.83 at 5 400 cal yr BP to 26.01 g m^{-2} yr^{-1} at present.

a newly initiated fen on a mineral-rich landscape would have much higher production or lower acrotelm decomposition. The measured net primary production and litter decay data tend to show large variations (Campbell et al. 2000). Could these variations relate to history of peatlands or to the depth or age of the peat deposits? A large increase in peat-accumulation rates in internal lawns after melting of permafrost (Turetsky et al. 2000) would be an analog to the initial condition for a peatland.

Implications

The convex pattern of peat accumulation has important implications for building simulation models and for projecting future peat C dynamics (Frolking et al. 2001). The model suggests that the continued decrease in peatland productivity caused by vertical growth in continental peatlands would eliminate C sequestration capacity over time, even in the absence of climate change. The peatlands could reach their growth limit faster than the previous model (Clymo 1984) suggested, because of decreasing production over time as well as continued decomposition of all catotelm peat. Without the dramatic compositional change that occurred at about 1 300 calendar yr BP (Fig. 1), the *Scorpidium*-dominated fen would have reached its limit then, as suggested by the last four dated points.

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Modeling Carbon Accumulation in Rocky Mountain Fens Using the CENTURY Ecosystem Model

Rodney A. Chimner
Institute of Pacific Islands Forestry, USDA Forest Service
1151 Punchbowl Street, Room 323, Honolulu, Hawaii, USA 96813
Graduate Degree Program in Ecology and Department of Earth Resources
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: rchimner@fs.fed.us

David J. Cooper
Graduate Degree Program in Ecology and Department of Earth Resources
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: davidc@picea.nar.colostate.edu

William J. Parton
Natural Resources Ecology Laboratory
Colorado State University, Fort Collins, Colorado, USA 80523
E-mail: billp@nrel.colostate.edu

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Despite the global importance of peatlands as a major sink or potential source of carbon (C), they have been neglected in ecosystem C modeling (Maltby and Procter 1996). To simulate C cycling in peatlands, either new models must be developed or current models from other ecosystems must be modified for peatlands. The objectives of this study were to test whether the CENTURY ecosystem model could simulate long-term C accumulation and short-term changes in C storage in response to hydrologic changes in three fens in the Southern Rocky Mountains of Colorado. Although CENTURY was originally developed as a grassland ecosystem model and has never been used to simulate wetlands, its ability to successfully simulate long-term soil C dynamics (Kelly et al. 1997; Smith et al. 1997) and its adaptability to many ecosystem types make CENTURY a logical choice for attempting to simulate soil C accumulation in sedge-dominated fens.

The CENTURY ecosystem model simulates soil organic matter (SOM) dynamics according to a monthly time step with the following major input variables: monthly precipitation, monthly average maximum and minimum air temperatures, soil texture, atmospheric and soil nitrogen (N), and lignin and N content of plant material (Metherell et al. 1993; Parton et al. 1993). CENTURY uses a plant submodel to simulate plant production, which is in turn incorporated into the SOM submodel that simulates C and N cycling in the soil (phosphorus and sulfur cycling modules are also available). Plant production and C cycling are modified by soil temperature and soil moisture, which are simulated in the hydrology and soil temperature submodels.

Soil organic matter decomposition is simulated by three pools: active, slow, and passive organic C pools (Fig. 1). The active pool consists of microbes and microbial by-products associated with SOM decomposition and has a turnover time of less than 1 yr. The slow pool includes plant and microbial products that are biologically resistant to decomposition and has a turnover time of tens of years. The passive pool is very resistant to decomposition and includes stabilized biological products that are chemically recalcitrant or physically protected; it has a turnover time of hundreds to thousands of years. The modeled turnover time of these pools is a function of the abiotic decomposition factor, which is controlled by soil temperature, nutrient and water availability, and anoxic conditions.

The Caribou and Zapf's fens in Colorado's Front Range were used for the parameterization phase of the modeling. Caribou fen is located on the west side of the continental divide at 3 400 m elevation. The peat is 190 cm thick and has a basal

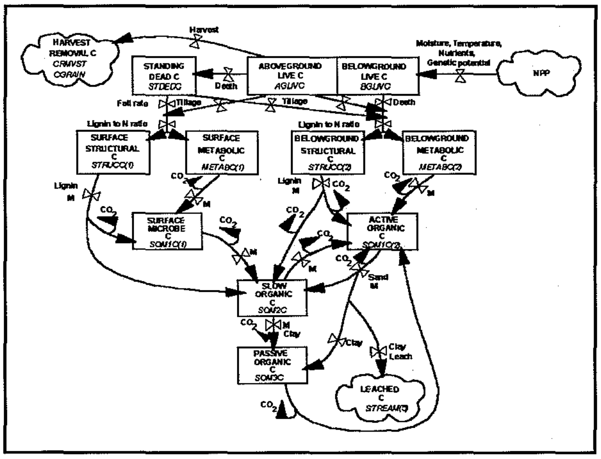

Figure 1. Carbon (C) pools and flows in the CENTURY ecosystem model (Metherell et al. 1993). NPP = net primary production, N = nitrogen, CO_2 = carbon dioxide. M = multiplier for effects of moisture, temperature, cultivation, LEACH = H_2O leached below 30 cm, SOMTC = SOM1C(2)+SOM2C+SOM3C+STRUCC(2)+METABC(2), SOMSC = SOM1C(2)+SOM2C+SOM3C.

date of 10 525 yr BP. The vegetation is dominated by *Carex aquatilis, Carex nigricans,* and *Eleocharis quinqueflora.* Zapf's fen is at 2 725 m on the east side of the continental divide, has a peat body 130 cm thick, and a basal date of 5 000 yr BP. Its vegetation is dominated by *Carex utriculata.* Little moss cover occurs at either site.

After CENTURY was parameterized with data from Caribou and Zapf's fens, a fen located in the West Elk Mountains, near Crested Butte, in western Colorado was used to test whether CENTURY could predict peat accumulation in an unparameterized fen. Keystone fen was chosen because data, including radiocarbon dates, were available from a previous analysis of fossil pollen (Fall 1997a, 1997b). Keystone fen is located at 2 920 m elevation, intermediate in elevation between Zapf's fen and Caribou fen. The dominant plant species at Keystone fen are *C. aquatilis, C. utriculata,* and *Eriophorum angustifolium* and, in contrast to the other sites, *Sphagnum* mosses are abundant. Keystone fen has 1 m of sedge peat over 1 m of woody and highly humified peat, and a basal date of approximately 9 000 yr BP.

Long-term C accumulation rates were parameterized in CENTURY by altering the three anaerobic variables and comparing the predicted long-term C accumulation rates to measured values (Fig. 2). The final parameterization of CENTURY underpredicted C accumulation rates in Caribou fen for the period 3 000 and 8 000 yr BP but accurately predicted rates for the first 1000 years, as well as the final total C value. CENTURY overpredicted C accumulation rates in Zapf's fen for the period 3 000 and 4 500 yr BP, but better predicted the first 1 500 yr and the final value. Long-term peat accumulation rates were simulated on the basis of current mean weather, which does not allow for climate variability over time. Incorporating paleoclimatic conditions might create a more realistic model of long-term C accumulation.

We tested the parameterized CENTURY for predicting C storage in Keystone fen. Measurements of soil C showed that Keystone fen

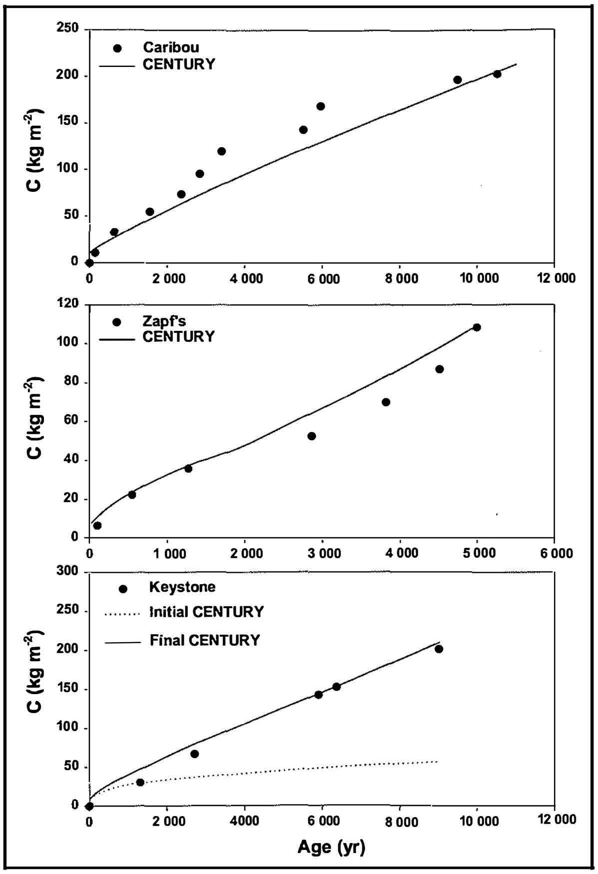

Figure 2. Modeled versus measured total soil carbon (C) for Caribou, Zapf's, and Keystone fens. The figure for Keystone fen shows the initial simulation, which used parameterizations developed from both Caribou and Zafp's fens (dotted line), and the final simulation, which used parameterizations from only Keystone fen (solid line).

accumulated approximately 200 kg C m^{-2} over 9 000 yr. CENTURY predicted that only 56 kg C m^{-2} would accumulate, and it overpredicted plant production. This result suggests that the anaerobic variables calibrated with data from Caribou and Zapf's fens did not produce a successful model for Keystone fen, most likely because CENTURY predicted longer periods of aerobic soils than actually occurred; however, CENTURY could be parameterized for Keystone fen by altering the two anaerobic variables that determine when the site becomes anaerobic.

Two simulations were run with the final parameterizations for each fen to investigate the physical composition of fen peat and the effect of altering precipitation on C accumulation rates. For all three sites, CENTURY predicted that the belowground structural pool accounted for about 55% of soil organic C. The second largest C pool was the slow pool, and the third largest was the passive SOM pool. The sum of the remaining C pools (aboveground structural, aboveground metabolic, surface microbial, belowground metabolic, and active organic C) made up on average less than 2% of the C stored.

To further explore the usefulness of an ecosystem model for C accumulation in peatlands, we altered precipitation levels in CENTURY for Zapf's fen to determine if CENTURY could predict changes in C accumulation rates. This scenario was run for 5 000 yr with the mean weather mode. Then, for an additional 100 yr, the weather mode was changed to stochastic, which allowed random dry years to occur. According to this simulation, Zapf's fen accumulated 109 kg C m^{-2} over the first 5 000 yr, at an average rate of 19.5 g C m^{-2} yr^{-1}, but then lost 7 kg C m^{-2} over the next 100 yr (Fig. 3).

In conclusion, our results indicate that an ecosystem model such as CENTURY can be used to simulate C dynamics in peatlands. However, to better model peatlands at multiple sites, CENTURY should be modified to allow anaerobic conditions to be created by high water tables, instead of the current configuration, which is based on the ratio of rain to potential evapotranspiration.

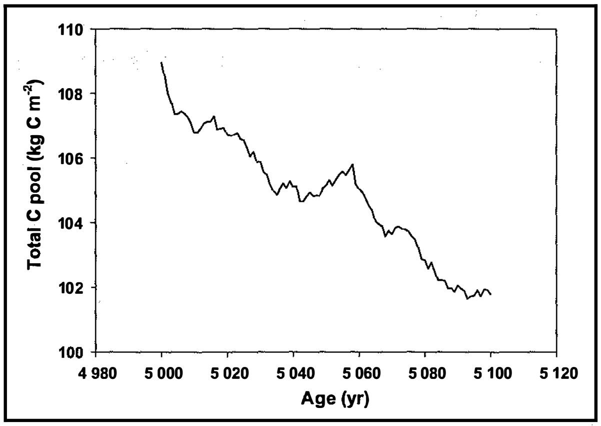

Figure 3. Total soil carbon (C) decline over 100 yr of simulated drier conditions in Zapf's fen, after a period of 5 000 yr during which C accumulated.

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Modification of a Forest Hydrology Model to Simulate Temporal and Spatial Variations in Moisture and Temperature in Forested Peatlands

Fan-Rui Meng
Faculty of Forestry and Environmental Management, University of New Brunswick
Fredericton, New Brunswick, Canada E3B 6C2
E-mail: fmeng@unb.ca

Jag S. Bhatti
Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: jbhatti@nrcan.gc.ca

Paul A. Arp
Faculty of Forestry and Environmental Management, University of New Brunswick
Fredericton, New Brunswick, Canada E3B 6C2
E-mail: Arp2@UNB.Ca

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Introduction

Large amounts of carbon (C) are stored in peatlands. Global climate change and various land-use activities may mobilize these C pools by increasing the rate of decomposition and subsequent release of carbon dioxide (CO_2) to the atmosphere. Such mobilization is largely determined by microclimate and hydrological conditions within the peatlands. The objective of the research described here is to quantify some of the temporal and spatial variation in moisture and temperature conditions within peatlands with seasons and weather, on the basis of hydrological modeling and interpretation of digital satellite images.

A three-part submodule procedure is described (Fig. 1): (1) a nonspatial forest hydrology model, used to calculate average daily peatland moisture and temperature according to weather and peat depth for different peatland types; (2) a digital terrain model, applied to ascertain drainage patterns and watershed boundaries; and (3) a combination of the results of the first two parts to develop spatiotemporal variations in water table depth, moisture, and temperature conditions within the watershed. These hydrological parameters can be combined with nonspatial C emission and peatland dynamic models to calculate peatland C budget across different spatial scales.

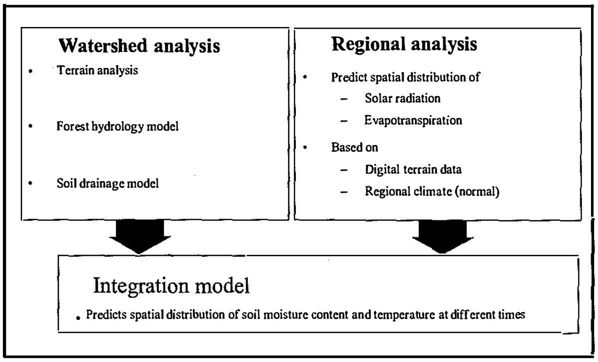

Figure 1. Modular approach to quantifying spatial and temporal variations in soil temperature and moisture.

Calculations for the nonspatial hydrology model are based on interpretation of regional potential evapotranspiration in relation to average daily net radiation, wind speed, and air temperature (Penman's model). Daily net radiation across peatlands can be estimated from a landscape energy-balance radiation model. Modeled surface temperatures and moisture conditions can be verified in part with satellite images (especially infrared images).

Modifications of the Forest Hydrology Model

The forest hydrology model (ForHyM2) is an aspatial watershed simulation model that can be used to simulate water and heat fluxes through all major stand compartments (canopy, snowpack if present, forest floor, rooted portion of the mineral soil, and subsoil). As such, the model can be used to calculate canopy interception, water equivalents in the snowpack, soil moisture, soil temperature, and extent of frost in the ground. The ForHyM2 model, its performance for various essentially humid locations in North America and Europe, and its ForHyM and ForSTeM precursors have been described in detail by Arp and Yin (1992), Yin and Arp (1993), Meng et al. (1995), Bhatti et al. (2000), and Yanni et al. (2000). Forest hydrological conditions have been successfully modeled in the relatively humid regions of Atlantic Canada, Quebec, Ontario, and the eastern United States, where annual precipitation ranges from 900 to 1 500 mm. In this paper, we explore the potential applications of ForHyM2 to forest conditions and watersheds within the relatively dry forest region of Saskatchewan, where upland forest and peatland occur together in a complex landscape mosaic, and within the Prince Albert Model Forest in particular; annual precipitation here ranges from 300 to 600 mm. We have applied the model to uplands (jack pine and mixed wood forests) and bog peatland (black spruce forest). In this region, evapotranspiration and interception of rain and snow constitute a large proportion of the local water budget.

We now describe the modifications that allowed us to increase the model's applicability to northern forest regions with low precipitation rates.

(1) Potential evapotranspiration from the forest floor ($\mathrm{PEP_{ff}}$) and the mineral soil ($\mathrm{PEP_{soil}}$) was adjusted as follows:

$$\mathrm{PEP_{ff}} = \mathrm{K_{ff}}\,[0.65 + 0.35\,\mathrm{LAI}/(k_{\mathrm{LAI}} + \mathrm{LAI})]\,\mathrm{PanET}$$

$$\mathrm{PEP_{soil}} = (1 - \mathrm{K_{ff}})\,[0.65 + 0.35\,\mathrm{LAI}/(k_{\mathrm{LAI}} + \mathrm{LAI})]\,\mathrm{PanET}$$

where $\mathrm{K_{ff}}$ is a partitioning factor accounting for rooting depth (Arp and Yin 1992), 0.65 and 0.35 are calibration parameters (Jewett et al. 1995), LAI is the leaf area index ($\mathrm{m^2/m^2}$), k_{LAI} is a leaf area calibration parameter, and PanET is potential evaporation from open water surfaces.

(2) Actual evapotranspiration from the forest floor ($\mathrm{AET_{ff}}$) was calculated as follows:

$$\mathrm{AET_{ff}} = \mathrm{PEP_{ff}}\,[\exp(k_w \mathrm{EWC_{ff}}) - 1]\,/\,[\mathrm{PEP_{ff}} + \exp(k_w \mathrm{EWC_{ff}})]$$

For solving this equation, the effective water content of the forest floor ($\mathrm{EWC_{ff}}$) was determined as follows:

$$\mathrm{EWC_{ff}} = \max[0, (W_{\mathrm{ff}} - \mathrm{PWP_{ff}})/\mathrm{FC_{ff}}]$$

where k_w is a calibrated parameter, W_{ff} is the water content of the forest floor, $\mathrm{PWP_{ff}}$ is the water content at the permanent wilting point, and $\mathrm{FC_{ff}}$ is the water content at field capacity. Actual evapotranspiration from mineral soil was calculated with the same formulation.

(3) Wetlands constitute a large proportion of the northern Saskatchewan landscape. At the watershed level, the proportion of wetland area to upland area should therefore influence water flow and water budget, by lack of interception (open water surfaces) and unimpeded evapotranspiration rates. Hence,

$$\mathrm{AET_{wet}} = \mathrm{PanET\ Wetland\_area}\,/\,\mathrm{Watershed\_area}$$

where $\mathrm{AET_{wet}}$ is the actual evapotranspiration of the wetlands.

(4) Extensive wetland formations along lakes and water channels tend to retard stream flow. This retardation is addressed as follows:

$$\mathrm{dWetland\_water}\,/\,\mathrm{d}t = K_{\mathrm{wetland}}\mathrm{Wetland\_water}$$

where Wetland_water is the amount of water that is subject to flow and K_{wetland} is a watershed-specific calibration parameter. In the model, Wetland_water is calculated as a downstream water reservoir that receives all upland flows, and this reservoir discharges water according to the equation above.

(5) Snow interception and snow throughfall were calculated as follows:

$$\mathrm{Snow\_interception} = \mathrm{Snowfall}\,K_s\mathrm{LAI^2}\,/\,[(\mathrm{Snowfall} + K_s)(k_L + \mathrm{LAI^2})]$$

$$\mathrm{Snow\_throughfall} = \mathrm{Snowfall^2}/(1 + \mathrm{LAI^2}/k_L)\,/\,(\mathrm{Snowfall} + K_s)$$

where K_s and k_L are calibration parameters.

(6) Interception of snow and rain is affected by the intensity of precipitation during each such event. For example, light summer rains may not reach the ground of a dense forest stand. Similarly, interception would be very small during a heavy rainstorm. The model is calibrated to use daily data. However, if the precipitation were averaged over a longer period, the interception parameter would need to be adjusted. The interception scale factor for ForHyM2 is given by the following equation:

$$\text{Interception\_scale\_adjustment} = 1/\min(30, \text{Input\_time\_scale})$$

where Input_time_scale is the time resolution for input precipitation data (in days).

(7) Snow remains in the canopy as long as the canopy's carrying capacity for snow is not exceeded. Also, snow sublimation from the canopy can be considerable (Pomeroy et al. 1998). In the model, snow sublimation is calculated as formulated originally (Arp and Yin 1992).

(8) In general, soil to subsoil flow is limited by the amount of precipitation that is not intercepted or evapotranspired. For saturated soil conditions, water flow is partitioned into surface runoff and interflow through the forest floor and through the mineral soil when subsoils, soils, and the forest floor become saturated. For such situations, it is assumed that lateral permeability exceeds vertical permeability because of the generally increasing soil bulk density with increasing soil depth (or decreasing macro- and micro-pore space with increasing soil depth). For unsaturated water flow, potential differences between the soil and the subsoil lead to water transfers from soil to subsoil at the following rate:

$$dW_{\text{soil}}/dt = K_p\,(\text{WP}_{\text{soil}} - \text{WP}_{\text{sub}})$$

$$\text{where } \text{WP}_{\text{soil}} = \frac{-15\ln[(1 + K_{\text{WP}})\text{FC}_{\text{soil}}/\text{MC}_{\text{soil}} - K_{\text{WP}}]}{\ln[(1 + K_{\text{WP}})\text{FC}_{\text{soil}}/\text{PWP}_{\text{soil}} - K_{\text{WP}}]},$$

K_{WP} is a calibration parameter, FC_{soil} is the moisture content at field capacity, MC_{soil} is the soil moisture content, and PWP_{soil} is the moisture content at permanent wilting point. It is assumed that water potential is −0.1 and −15 bars (-0.1×10^5 Pa and -15×10^5 Pa) at field capacity and permanent wilting point, respectively.

Preliminary Results

Presented in detail are some of the pertinent hydrological calculations that deal with snow accumulations, snowmelt, infiltration, soil percolation, soil moisture, and stream discharge based on long-term records of daily and monthly rain, snow, air temperature, and rudimentary site descriptors for northern Saskatchewan, for several watersheds (specifically the Montreal and Spruce rivers) and different forest cover types. Special considerations are given to the calculations of evapotranspiration, canopy interception, unsaturated flow from soil to subsoil, wetland-to-upland ratio effects, and the effects of wetland water flow on watershed stream discharge. Also included are calculations for heat fluxes into and through the peatland substrate, as well as temperatures and extent of frost as functions of substrate depth, obtained by accounting for the energy balance at the ground–atmosphere interface under conditions of variable forest cover and leaf area index. Model performance was checked with field-monitored data for snow interception, snow accumulation, and stream discharge. Actual data for stream discharge rate for both river basins were obtained from the *Historical Stream Summary* (Environment Canada 1991). Climate data used in the simulation were those published by Environment Canada (1994).

The modeling results were generally consistent with the field observations. As indicated in Figure 2, frost (soil temperatures < 0°C) should penetrate to the subsoil at each location. This analysis shows that on-the-ground accumulations of snow were insufficient to protect the soil and subsoil from freezing, which is not the case in many areas such as northern Ontario, northern Quebec, and northern Atlantic Canada. Moisture in the forest floor and the mineral soil fluctuated considerably. Simulated soil moisture contents (percent by volume) of forest floor, mineral soil, and subsoil for different forest cover types are plotted in Figure 3. Percent soil moisture levels were calculated to decrease from the forest floor to the subsoil on the two upland sites (jack pine and mixed wood). For the black spruce site (a forested peatland site), subsoil moisture contents were calculated to be close to saturation year-round. Subsoil water content for the black spruce stands will be used to generate available water table depth information for the peatland C dynamic model.

Modeling C Dynamics for Forested Peatlands

Spatial climate data are readily available for regions across Canada through the climate records

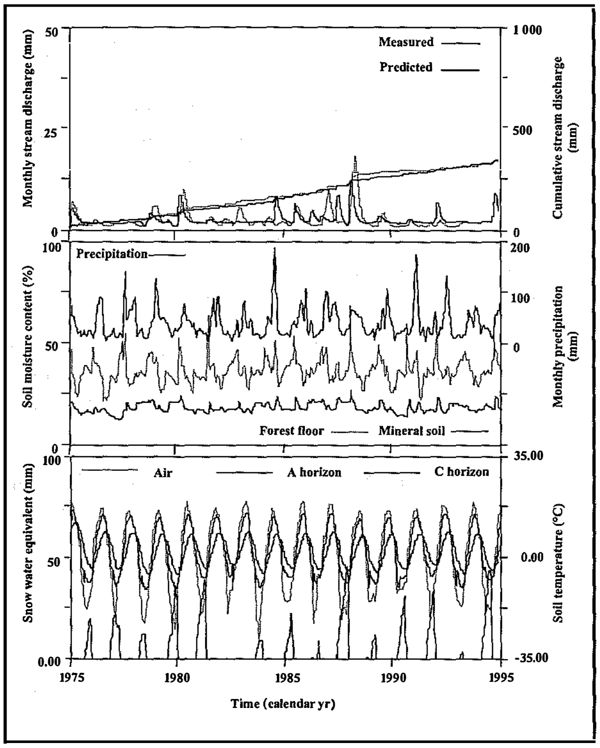

Figure 2. Measured and predicted stream discharge and cumulative stream discharge of the Spruce River (top), predicted soil moisture content (middle), and snow water equivalents and soil temperature (bottom) within the Prince Albert Model Forest, from 1975 to 1995.

published regularly by Environment Canada. Predictions of climate conditions in different climate change scenarios are also available through Environment Canada. Models to calculate potential solar radiation and surface temperature, on the basis of geographic information systems (GIS), are available (Meng et al. 1996; Bourque et al. 2000). A GIS-based potential evapotranspiration model (required to link ForHyM2 and the spatial model) is under development (see Meng et al. 1996). The spatial evapotranspiration model can be calibrated with estimates based on Landsat-TM images, a method used and reviewed by a number of researchers (Hatfield et al. 1983; Hall et al. 1992; Carlson et al. 1995). To obtain estimates of the contribution of peatlands to the global C budget, the proposed spatial hydrology model can be integrated with an aspatial peatland C dynamics model. There is a strong need to initiate research activity toward this goal.

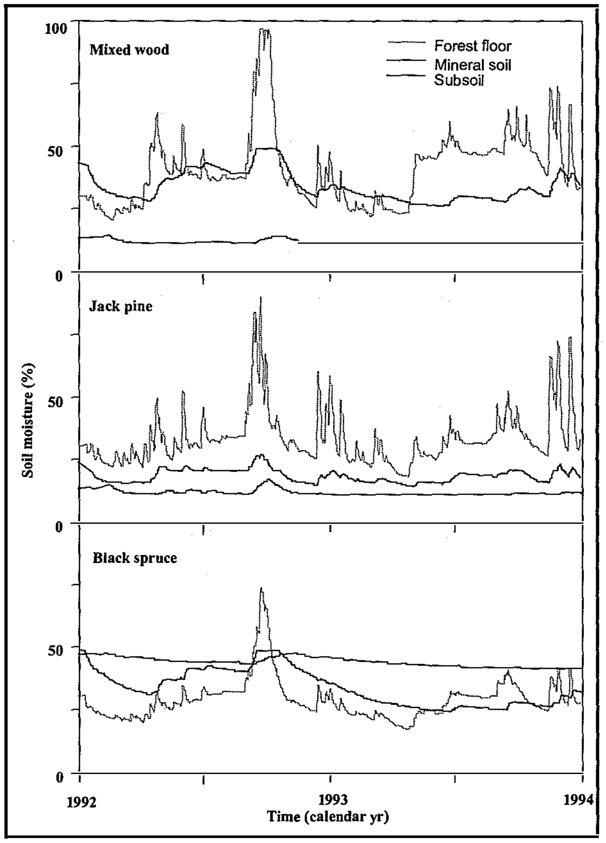

Figure 3. Modeled temporal soil moisture variations under different forest types in the Prince Albert Model Forest.

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Simulating Peatland Fire Regimes and Impacts on Carbon Dynamics

William J. de Groot
Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
bdegroot@nrcan.gc.ca

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Introduction

Peatlands cover about 1.14 × 10^6 km^2 of the boreal and subarctic regions of North America, storing an estimated 397–455 Tg of carbon (C) (Gorham 1991; Zoltai and Martikainen 1996; Zoltai et al. 1998). This northern biome also experiences a great deal of fire activity, which can significantly influence peatland C storage. During the period 1959–1999, an average of 1.9 × 10^6 ha were burned annually in the Canadian boreal and taiga ecozones (Amiro et al. 2001), which represents 29% of the total area burned in Canada during that 41-year period. Although most of the area burned was represented by upland sites, all northern fires have the potential to burn into peatlands whenever fuel moisture conditions reach a lower limit.

Disturbance is an important factor in boreal C dynamics, and Kurz and Apps (1999) have suggested that the Canadian boreal forest as a whole has recently become a C source because of increased impacts of fire and insects during the 1970s and 1980s. Even though the average annual burn rate for peatlands is lower than that of the remaining boreal forest, the potential for large C losses exists during drought years. This study examined fire regimes and fire effects in northern peatland regions and our current ability to model the impacts of fire on peatlands. Current and future fire regimes (under conditions of climate change) are used to illustrate the modeling of fire effects in peatlands.

Northern Fire Regimes

Fire regimes are defined primarily by the characteristics of fire frequency, fire intensity, fire severity (or depth of burn), type of fire (crown, surface, or ground), season of burn, and fire size (Whelan 1995). In North American peatlands, the effects of fire on C dynamics are mostly influenced by fire frequency and fire severity, although fire intensity, type of fire, season of burn, and fire size may indirectly affect C through changes in peatland communities. In terms of fire frequency, the long-term average fire return intervals in the Canadian boreal and taiga ecozones are 130–400 yr, and the average annual area burned ranges from 1 101 to 5 360 km^2 (Amiro et al. 2001). Peatlands in these ecozones are estimated to have experienced fire return intervals of 75–200 yr in forested boreal swamps and up to 1000 yr in boreal bogs (Zoltai et al. 1998). Estimates of fire severity range from 5 to 20 cm depth of burn in bogs and conifer swamps (Zoltai et al. 1998). Fires in this region are generally very large, given that about 97% of the total area burned in Canada is the result of fires greater than 200 ha (average of 6 754 ha and median of 960 ha; Amiro et al. 2001). Depending on the amount of aboveground standing biomass, most peatland fires are surface fires ranging in intensity from low to high, although high-intensity crowning fires are also common in forested peatlands because of extensive ladder fuels in trees. It is important to note that fire regimes vary widely from year to year and are dynamic over the long term. Therefore, fire frequency for any peatland location can change over time, and there can be great differences in the depth of burn of individual fires.

Fire Effects on Vegetation in Peatlands

All of the fire regime characteristics listed above can affect vegetation composition through the fire ecology traits of individual species. These traits can influence the extent and rate of ingress of shrubs and trees into peatlands, which in turn affects the amount of aboveground standing biomass. Treed bogs can contain as much as 5 000 kg/ha of shrub biomass, whereas tree biomass in forested bogs and conifer swamps may reach 100 to 160 000 kg/ha (Zoltai et al. 1998), so local extinction of woody plant species can have a significant impact on C storage. Many plant species are adapted to regenerating after fire, including black spruce, which releases seed from semiserotinous cones, and numerous shrub species, which resprout from protected basal buds. However, deep burning or high-intensity fires can prevent further C sequestration by woody plants until new propagules arrive on site. Depending on the size and burn pattern of the fire, it could take a long time for peatland areas to reestablish woody C pools. Some species, such as bog birch, are also affected by the season of burn, as root carbohydrate storage and phytohormone levels at the time of a fire can affect subsequent survival and growth rates (de Groot 1998).

Modeling Fire and Peatland Dynamics

Two of the most important effects of fire in peatlands are the impact on community composition and the impact on biomass. Simulation of fire and peatland dynamics can be accomplished by using a basic fire-effects model that calibrates vegetation, biomass, fire regime, and fuel moisture parameters to peatland conditions. BORFIRE is a dynamic boreal fire-effects model designed to simulate the physical and ecological impacts of the fire regime on boreal ecosystems. The model was originally developed for upland shrub-dominated communities in the boreal region (de Groot 1998), and it has since been adapted to simulate boreal forest stands (de Groot et al. n.d.). It could also be similarly adapted to simulate fire effects in peatlands.

In brief, the BORFIRE model simulates changes in plant species composition and associated biomass at the stand level. With regard to peatlands, it does not simulate moss or peat dynamics. Species composition is quantified as either numbers per hectare or percent cover, and biomass levels (as kilograms per hectare) are recorded separately for live and dead material and for belowground and aboveground locations. Changes in the state variables of species composition and biomass are the result of processes of plant mortality, recruitment, growth, decomposition, and biomass (or fuel) consumption during fire. In turn, these processes are driven by climate and fire variables.

Fire is obviously integral to the dynamics of a fire-effects model. Fire causes the death of individual plants and it initiates the recruitment of juvenile plants as individuals compete for the newly available growing space. Between fire events, natural thinning occurs through interspecific and intraspecific competition. The success of any species in a community depends on its ability to survive fire, to regenerate after fire, and to compete with other species. These characteristics are quantified in the model in terms of fire intensity, fire severity, fire frequency (by age to propagule production), season of burn, and shade tolerance relataive to that of other species. Fire also causes a loss of biomass through combustion during the fire event, and the rate of this loss is determined by fuel load and fuel moisture variables. In this way, there is biomass (or fuel load) feedback to the fire, whereby fire intensity increases with increasing biomass.

Biomass loss during fire and post-fire vegetation response are determined in the model through the interaction of physical fire characteristics with plant ecology and biomass (or fuel) properties. Fire intensity (kilowatts per meter) is calculated as the product of fuel consumption (kilograms per square meter), rate of fire spread (meters per second) and heat of combustion (18 000 kJ/kg) of fuel (Byram 1959). Fuel consumption and rate of fire spread are estimated from index components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada 1992). Fuel consumption incorporates depth of burn in organic soil, consumption of undecomposed dead surface material (leaves, grasses, and forbs) and woody debris (if present), and aerial fuels of standing live or dead trees and shrubs (if present). Fire intensity and depth of burn are used to calculate plant mortality, and fuel consumption is used to calculate biomass loss and the transfer of biomass from live to dead pools.

Simulation of Fire Regimes and Their Effects in Peatlands

As an example of modeling fire effects in peatlands, the BORFIRE model was used to simulate the impacts of climate change on fire regime and the resulting effects on biomass and tree density in a black spruce swamp. To do this, temperature, relative humidity, precipitation, and wind speed data from the Canadian Global Coupled Model (Flato et al. 2000) were used to estimate FWI System parameters for the Wood Buffalo National Park region during 1975–1990 and 2080–2100. Mean (and standard deviation) monthly values of the FWI System parameters were used to quantify fire regime as seasonally adjusted normal distributions. Area burned during 1975–1990 was used to calculate fire frequency during that period. Fire frequency during 2080–2100 was estimated from FWI System values for 2080–2100 and the correlation of area burned to FWI System values during 1975–1990. Fires occurred stochastically in the model, and burning conditions at the time of fire were randomly selected from the fire regime (the monthly distributions of FWI System parameters). Fuel consumption, rate of spread, and fire intensity were determined from FWI System parameters and the FBP System. Biomass accumulation in trees followed the black spruce growth rate in the lowest site class of the Alberta phase 3 forest inventory (AFS 1985). Decomposition of dead woody material, surface litter, and lower organic layers were based on rates estimated in the Canadian Forest Service Carbon Budget Model (Kurz et al. 1992).

The model was run for 400 years according to the fire regimes for 1975–1990 and 2080–2100, with average fire return intervals of 78 and 56 years, respectively. The simulations were repeated 25 times and averaged. The average tree density was lower under the 2080–2100 fire regime (Fig. 1) because of greater fire frequency, which caused greater tree mortality. Biomass storage (Fig. 2) under the 2080–2100 regime was much lower because of the lower stem density of living trees, the lower detrital input to the forest floor from trees, and the greater depth of burn due to drier future burning conditions.

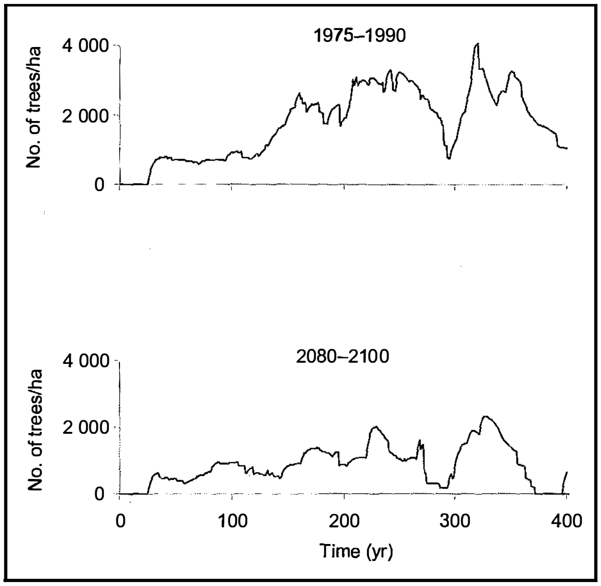

Figure 1. Examples of average stem density for 25 black spruce stands under 1975–1990 and 2080–2100 fire regimes over a 400-yr simulation period.

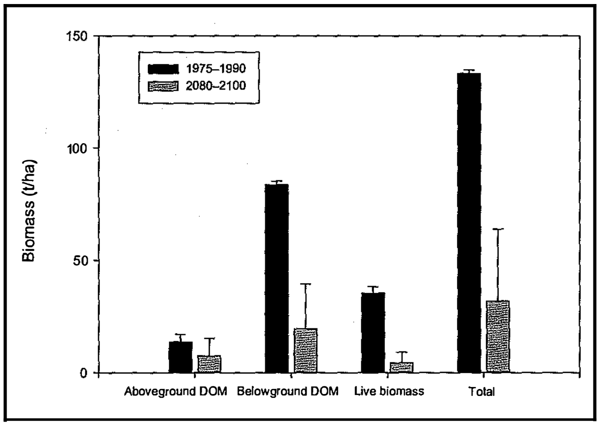

Figure 2. Black spruce biomass storage under 1975–1990 and 2080–2100 fire regimes, averaged over the final 50 yr of the 400-yr simulations. DOM = dead organic matter.

Future Data Needs

Our current ability to simulate the impacts of fire in peatlands is limited by the difficulty of parameterizing models. Although the example presented here illustrates the physical and ecological dynamics that can be simulated, more accurate quantification of peatland processes over a wide range of environmental conditions is required. This would encompass a better understanding of moisture profile dynamics in peatlands; depth of burn in relation to peat moisture content, bulk density, and depth; peat accumulation and decomposition rates; and improved estimates of peatland fire frequencies. Regarding the first two points, some limited work has been done relating the organic soil moisture profile to the FWI System (Lawson and Dalrymple 1996; Lawson et al. 1997) and combustion of organic soils (Hartford 1989; Frandsen 1997), but generally very little work on fire effects has been done for peatlands.

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Modeling Soil Carbon Dynamics in the Boreal Forest at the Regional Scale

Gloria Rapalee
Department of Earth System Science, University of California, Irvine, California, USA
National Aeronautical and Space Administration, Goddard Space Flight Center, Code 923,
Greenbelt, Maryland, USA 20771
RD 1, Box 203, North Duxbury, Vermont, USA 05676 (current address)
E-mail: grapalee@pop900.gsfc.nasa.gov

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Boreal forests and wetlands are currently thought to be significant carbon (C) sinks in global C budgets, and they could become net C sources as the Earth warms (Tans et al. 1990; Ciais et al. 1995; Goulden et al. 1998). Most of the C in these boreal forest ecosystems is stored in the soil and moss (Apps et al. 1993; Peng et al. 1998).

Because of the importance of C in boreal forest soils, as part of the BOReal Ecosystem–Atmosphere Study (BOREAS) of the National Aeronautics and Space Administration, I developed a model that estimates C stocks and fluxes from soil profile data ranging from plot-scale observations to landscape-level patterns. The model was designed to analyze a 733-km² study site in the boreal forest of Manitoba (Fig. 1) but could be adapted for any geographic area. The model is simple enough to be assembled as a series of linked files in a spreadsheet program on a personal computer, yet detailed enough to describe this complex landscape (see Rapalee 2001 for further detail).

The model generates area-weighted, spatially referenced estimates of soil C stocks and fluxes using as a spatial base a gridded soil polygon map and accompanying soil polygon attribute list (Veldhuis and Knapp 2000), along with field data from a 1994 soil survey of the study site (Trumbore et al. 2000; Veldhuis 2000). Spatial variation within the soil polygons is accounted for by fractional components that have similar attributes within each polygon. The model estimates soil C stock and flux per unit area at four scales: (1) the soil pit; (2) the fractional component of each polygon, obtained from the percentage of the total polygon area the component occupies; (3) the soil polygon, obtained by summing respective stocks and fluxes from the fractional components; and (4) the entire 733-km² study site, obtained by summing stocks and fluxes from the soil polygon. The second and third of these scales yield area-weighted averages of each soil map fraction and polygon, respectively, and account for spatial variation within the landscape.

The model incorporates area, depth, and time in estimating soil C fluxes. The three inputs are

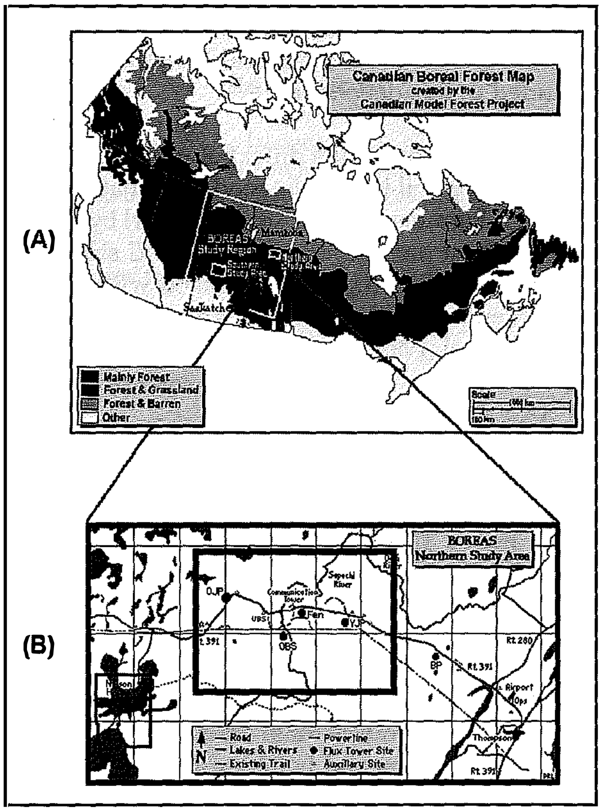

Figure 1. (A) Map of Canadian boreal forests showing the BOReal Environment–Atmosphere Study (BOREAS) study region and the northern and southern sites. (B) Map of BOREAS northern study area. The 733-km² study site is outlined in black. Modified from maps publicly available from BOREAS (http://www-eosdis.ornl.gov/BOREAS/boreas_home_page.html).

soil drainage class, forest stand age (or time in years since the most recent disturbance, most often fire), and soil C stocks. Influence of drainage and incidence of fire are the two factors thought to be most important in controlling annual accumulation rates for soil C in the boreal forest (Gorham 1991; Bonan 1993; Kasischke et al. 1995; Kurz and Apps 1995).

The first steps are to stratify the study site by drainage class and vegetation type, determine forest stand age, and separate the soil profile into two broad layers — surface and deep — which have distinctly different C accumulation rates. The surface layer, a C sink and more influenced by fire, includes moss and soil that is recognizable as organic material. The deep layer, a C source and more influenced by soil drainage, consists of more highly decomposed organic matter (humic material), charred material, and the mineral A horizon, where minor amounts of organic matter are incorporated. The mineral B horizon is also included in this deep layer.

Because C dynamics differ between the surface and the deep soil layers, the model estimates soil C stocks (kilograms of C per square meter) by means of a different method for each layer. C stocks for the surface layers ($C_{t,D}$) are estimated with a time-dependent model of moss growth after fire (Harden et al. 1992; Harden et al. 1997):

$$(I_{\mathrm{surface},D} \ / \ k_{\mathrm{surface},D}) \times (1 - e^{-kt}) \qquad \text{Eq. (1)}$$

where I is input rate, D is the drainage class, k is a decomposition constant, and t is time (in years) after fire. (Input rates and decomposition constants are taken from Trumbore and Harden's [1997] simple model of C turnover derived from radiocarbon field studies.) C stocks for the deep layers (C_{SS}) are estimated from common soil series (SS) on the basis of field observations from the soil survey and laboratory data from individual soil profiles (Davidson and Lefebvre 1993):

$$\sum BD_h \times \%C_h \times T_h \qquad \text{Eq. (2)}$$

where BD is bulk density, h is the soil horizon, %C is percent organic C, and T is soil horizon thickness. C stock for the total soil profile is calculated by summing surface and deep stocks.

Carbon fluxes (grams of C per square meter per year) are calculated separately for surface and deep soil layers, then summed for the total profile. Surface C flux ($dC_{t,D}/dt$), representing net annual storage into upland soils, is calculated with the following equation (Rapalee, Trumbore et al. 1998; Rapalee 2000):

$$I_{\mathrm{surface},D} - (k_{\mathrm{surface},D} \times C_{t,D}) \qquad \text{Eq. (3)}$$

Deep C flux, representing net annual losses from upland soils and net annual storage in wetlands, is estimated with the following equation (Rapalee, Trumbore et al. 1998; Rapalee 2000):

$$I_{\mathrm{deep},D} - (k_{\mathrm{deep},D} \times C_{SS}) \qquad \text{Eq. (4)}$$

The results, as reported by Rapalee, Trumbore et al. (1998) and Rapalee (2000), show that soil C stocks vary with forest stand age and drainage, the largest stocks occurring in very poorly drained, slowly decomposing, and rarely burned fens and bogs and the poorly drained upland peat sites (palsas). The fens, which occupy about 18% of the total area, store about 47% of the total C stocks, mostly in the deep soil layers.

The results indicate that the entire system is a small C sink (21.8 g C m^{-2} yr^{-1}). The surface layers are storing C (30.9 g C m^{-2} yr^{-1}), while the deep layers are releasing C to the atmosphere (–9.1 g C m^{-2} yr^{-1}), for a net loss of deep C. Time since fire is an important factor in the fluxes of the surface layers (Fig. 2A), with the greatest annual rates of increase in the more recently burned sites and a progressive decrease over time. In the deep layers (Fig. 2B), however, drainage is the main factor, with the greatest releases in the moderately well and imperfectly drained sites. The wetlands (fens and collapse scar bogs) are at steady state in the surface layers but are storing C at a slow, steady rate in the deep layers, gaining an estimated 29 and 12 g C m^{-2} yr^{-1}, respectively, in those layers. Each drainage type contributes to the total C flux (Fig. 3), with the more poorly drained sites contributing the most.

The modeled results are within the ranges of those of other field studies in the northern latitudes: total C stock (42 kg C m^{-2}) is within the range (40–70 kg C m^{-2}) reported by Lacelle et al. (1998); annual C flux in the fens (28.8 g C m^{-2} yr^{-1}) is close to Gorham's (1991) estimate of 29 g C m^{-2} yr^{-1} for boreal and arctic peatlands; surface soil flux (25 g C m^{-2} yr^{-1}; Fig. 2A) at imperfectly drained sites over more than 90 yrs is within the range of Harden et al.'s (1997) findings of 25–40 g

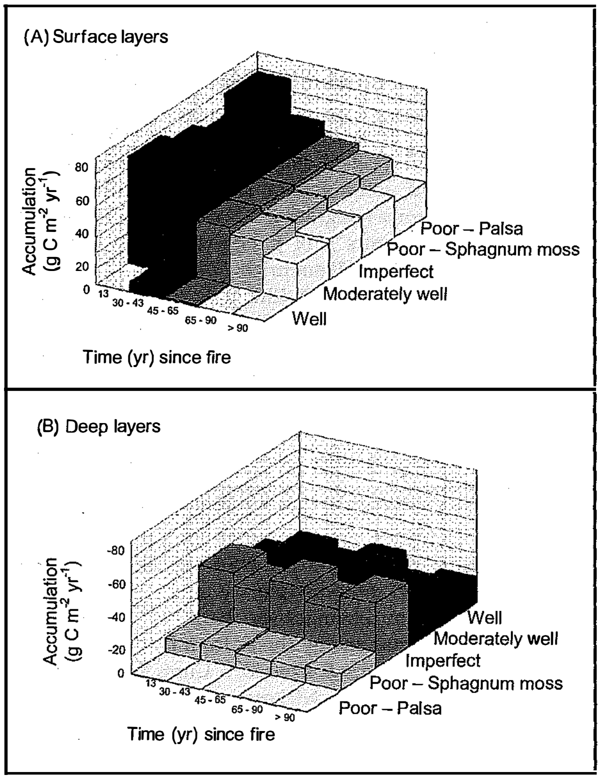

Figure 2. (A) Rates of carbon (C) accumulation (positive values) in surface layers (including moss) for drainage class (*z* axis) and by time since fire (stand age). Values were derived by applying equation 3 over the entire 733-km^2 study site. (B) Rates of C loss (negative values) from deep organic layers (below moss) and mineral soil as a function of soil drainage (*z* axis) and time since fire. Values were derived by applying equation 4 over the entire study site. Reproduced from Rapalee, Trumbore et al. (1998) with permission from the American Geophysical Union.

C m^{-2} yr^{-1}; deep soil flux in older black spruce stands (40 g C m^{-2} yr^{-1}; Fig. 2A) is within the range of Goulden et al.'s (1998) reported 3-year average of 80 ± 50 g C m^{-2} yr^{-1} at a 120-yr-old forest stand within the 733-km^2 study site.

In summary, this simple and portable model generates area-weighted, spatially referenced estimates of soil C stocks and fluxes. The results account for spatial variation within the soil polygons at finer scales than have been previously practical. The modeled values are within ranges of those reported in other published field studies. Finally, this methodology can be applied to other geographic areas.

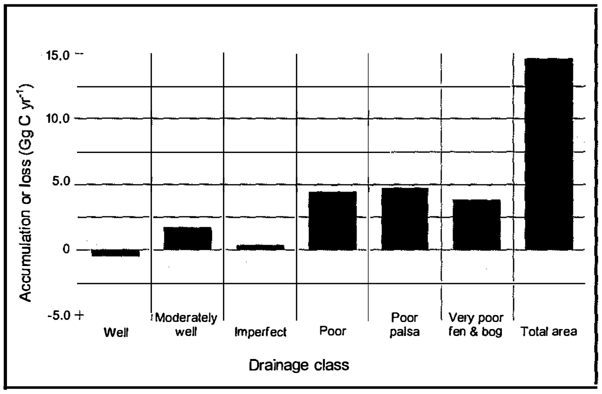

Figure 3. Total annual carbon (C) accumulation (positive values) or loss (negative values) by drainage class for the entire 733-km^2 study site. Values were derived by applying the sum of equations 3 and 4 for each soil drainage class and multiplying by the area covered by each class. Reproduced from Rapalee, Trumbore (1998) with permission from the American Geophysical Union.

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Sinks or Sources? Western Peatlands in a Disturbed Boreal Forest

Merritt Turetsky
Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E9
E-mail: turetsky@ualberta.ca

Linda Halsey
Department of Biological Sciences, University of Alberta
Edmonton, Alberta, Canada T6G 2E9
E-mail: lhalsey@ualberta.ca

R. Kelman Wieder
Department of Biology, Villanova University
Villanova, Pennsylvania, USA 19085
E-mail: Kelman.Wieder@villanova.edu

Dale H. Vitt
Department of Plant Biology, Southern Illinois University
Carbondale, Illinois, USA 62901
E-mail: dvitt@plant.siu.edu

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Boreal and subarctic peatlands are believed to function today as net sinks for atmospheric carbon dioxide (CO_2) and as net sources of atmospheric methane (CH_4). Recently, however, detailed carbon (C) balance studies have concluded that individual peatlands may shift from net C sinks to C sources on an annual basis (Carroll and Crill 1997; Lafleur et al. 1997; Rivers et al. 1998; Alm et al. 1999; Waddington and Roulet 2000). Much research has focused on determining the controls on uptake and release of C in peatlands, particularly under changing climatic conditions. Less effort, however, has been devoted to understanding the cumulative effects of disturbances on peatland C stores. Despite recent evidence pointing toward increasing anthropogenic pressures on Canada's boreal forest (Schindler 2001), most peatland C budgets are constructed over small spatial scales with little emphasis on broad disturbances. It seems evident that natural and anthropogenic disturbances occurring in boreal regions today will alter the C balance in peatlands. Our objective here is to assess the impacts of fire, permafrost melt, peat harvesting, oil sands mining, and hydroelectric reservoirs on the C balance of western boreal peatlands.

Certain disturbances in the boreal forest lead to greater C losses from peatland surfaces. Fire activity in peatlands releases C by direct combustion, as well as through enhanced decomposition rates. Estimates of net C loss due to fires in peatlands range from 2.1 to 4.9 kg C m^{-2} per fire event (de Groot and Alexander 1986; Kasischke et al. 1995; Zoltai et al. 1998; Pitkänen et al. 1999; Turetsky and Wieder 2001). Estimates based on C budget simulations suggest that post-fire C emissions due to decomposition may far outweigh direct losses (Auclair and Thomas 1993; Dixon and Krankina 1993), but field measurements of C flux after fires are needed to complement these modeling approaches. Peat harvesting and oil sands mining remove large amounts of organic matter from the landscape, and the material removed is probably oxidized quickly. Peat harvesting also increases C emissions through high rates of decomposition until vegetation is allowed to colonize the disturbed surface to reinitiate peat accumulation. In western Canada reservoirs are created mainly for hydroelectric generation and are major sources of greenhouse gases, particularly those involving flooding of peatlands (St. Louis et al. 2000).

Disturbance may also have a stimulatory effect on C accumulation, either by increasing net primary production or decreasing decomposition rates. The large amounts of nitrogen deposited as a result of the oil sands operations in northern Alberta may have a fertilization effect on nearby peatlands and may thus affect rates of peat accumulation. The melting of permafrost, occurring today across the localized permafrost zone, has been shown to increase C accumulation in peatlands, most likely through enhanced net primary production accompanied by greater availability of water.

Estimates of the total extent of various disturbances are needed before we can attempt to model the cumulative effects of natural and anthropogenic disturbances on regional C storage in peatlands. Changes in both net primary production and decomposition must be considered in light of changing water tables, thermal regimes, nutrient availability, and species assemblages after a disturbance. Particularly in cases where direct field evidence is lacking, modeling may fill gaps in our understanding of boreal processes.

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The Policy of Peat: How Does Peat Fit in the Kyoto Protocol?

Ian Campbell
Science Branch, Canadian Forest Service, Natural Resources Canada
12th Floor, 580 Booth Street, Ottawa, Ontario, Canada K1A 0E4
E-mail: icampbel@nrcan.gc.ca

◆

During the Kyoto convention on climate change, the participating countries had various views of carbon (C) sinks. The compromise reached was the inclusion of a limited number of forest-related activities (afforestation, reforestation, and deforestation [ARD] since 1990) under Article 3.3 of the Kyoto Protocol, as well as the possibility of adding additional activities under Article 3.4 after further negotiation. The net change in C stock related to these activities in the first commitment period (2008–2012) will be added or subtracted from Canada's assigned amount (reduction of 6% of 1990 levels).

The major issue yet to be decided is which additional activities will be included under Article 3.4 and how they will be included. Major activities being considered for inclusion are revegetation and management of forest, cropland, and grazing land. In addition, Canada has proposed inclusion of shelterbelt planting.

Canada is dissatisfied with the limited range of activities currently listed in the Kyoto Protocol (i.e., ARD) and believes that a broader treatment of sinks and sources is more in keeping with the aims of the *United Nations Framework Convention on Climate Change* for enhancing and protecting sinks and reservoirs.

Canada believes that Articles 3.3 and 3.4 of the Kyoto Protocol are inextricably linked. Article 3.3 by itself produces an unbalanced situation, with perverse incentives. Including the managed forest under Article 3.4 would better reflect what the atmosphere "sees," thus redressing this imbalance. The managed forest is the land area that is subject to forest management and conservation. Areas of forest that are not accessible, and where direct human influence is thus negligible, would not be included.

Canada's position regarding the inclusion of forests and forestry in the Kyoto Protocol is as follows:

(1) parties should be debited for C lost through deforestation;

(2) parties should be credited for C sequestered through afforestation; and

(3) parties should take responsibility for all changes in C stocks — positive or negative — in their managed forest lands.

Although peat is not explicitly mentioned in Canada's position, if Canada's position on the managed forest is accepted by the international community and if the Protocol is ratified, forested peatlands in the managed forest may have to be accounted for. Peat research in the managed forest is in its infancy. If Canada has to account for peat in the managed forest, then research requirements may include the following:

- ascertaining the areal extent and depth of peat in the managed forest;
- determining peat dynamics under various direct anthropogenic disturbances (e.g., harvesting), indirect anthropogenic disturbances (e.g., pollution and climate change), and natural disturbance regimes (e.g., fire, insect, and diseases); and
- developing a greenhouse gas budget for peat dynamics in the managed forest under various management and climate scenarios.

Summary of Breakout Sessions: Carbon Dynamics in Forested Peatlands[a]

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On the final day of the conference, participants were divided into three breakout groups to discuss the following topics:

1. The importance of Canada's peatlands to the global carbon (C) budget (and that of other greenhouse gases) both at present and in the next 100–150 yr.
2. Critical processes driving peatland dynamics.
3. Accounting for change in C stocks in the "managed forests" of the Kyoto Protocol.
4. Knowledge gaps and recommended priorities for peatland research.

The following is a summary of the main points resulting from those discussions.

The Importance of Canada's Peatlands to the Global Carbon Budget (and That of Other Greenhouse Gases) Both at Present and in the Next 100–150 yr

It was the general consensus that peatlands play a significant role in Canada's C budget and that they are important to the global C cycle as well. In terms of methane (CH_4), Canada's peatlands were viewed as important at both the national and the global scales. It was emphasized, however, that because of the paucity of data for both C stocks and C fluxes, quantifying the role of the peatlands remains imprecise. Estimating C stocks in peatlands is problematic because of lack of information on depth and spatial extent of peatlands in some parts of Canada (e.g., Atlantic Canada and Ontario). Current C fluxes in peatlands are similarly poorly known. It has often been assumed that peatlands represent a small C sink (0.02–0.03 Gt/yr), but this assumption is based on average, long-term historical accumulation and not on direct observations of current flux. There are very few such direct observational data, and these vary from year to year, from region to region, and from one peatland type to another.

In the next 100–150 yr, the importance of peatlands to the C budget could escalate significantly because of anthropogenic perturbations to the climate system. These perturbations will likely include significant changes in climatic conditions and in natural disturbance regimes. The following are some factors that are expected to influence future peatland C dynamics:

- fire and permafrost degradation;
- changes in the population and activity of beavers;
- anthropogenic activities such as peat harvesting, forest harvesting, and road construction;
- flooding due to construction of reservoirs for hydroelectric power;
- fire and harvesting of upland forests in a landscape that is a mosaic of peatlands and uplands; and
- other global change factors, such as carbon dioxide (CO_2) fertilization, deposition of nitrogen, and tropospheric ozone pollution.

The impacts of disturbance are poorly quantified at present, and it is difficult to predict the direction and duration of the peatland response (e.g., C sequestration or loss, increased or decreased CH_4 emissions). Particularly for C, however, there is likely to be an asymmetry of risk, with C losses potentially much larger than C gains.

Critical Processes Driving Peatland Dynamics

In terms of long-term development, the critical processes driving peatland dynamics are the feedbacks between production and decomposition on the one hand and biophysical conditions (including temperature, moisture, nutrient availability, and oxygen) on the other, which in turn can be influenced by processes taking place

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[a] Jag S. Bhatti, Zicheng Yu, Michael J. Apps, with Steve Frolking, William J. de Groot, and Rick Bourbonniere (rapporteurs).

within the peatland itself as well as by changes in landscape configurations.

In terms of processes that will influence contemporary C fluxes in peatlands, however, disturbance and perturbation dynamics were thought to be the most critical. Of all the disturbances listed in the previous section, roads and other linear disturbances and fire will probably have the most significant impact on peatlands over the next few decades. Roads and other linear disturbances will affect hydrological characteristics and can be expected to cause both enhanced flooding above (upstream of) and diminished flooding below (downstream of) the disturbance. Culverts do not appear to be adequate to prevent such disturbances. Upland disturbances (particularly fire and forest harvest) will also influence peatland hydrological features, but there is little quantitative data on these disturbances at present.

Accounting for Changes in Carbon Stocks in the "Managed Forests" of the Kyoto Protocol

Accounting for changes in C stocks in the "managed forests" of the Kyoto Protocol will likely prove to be a complicated undertaking, and the presence of forested peatlands multiplies the difficulties significantly. First, it may be important to delineate and quantify those anthropogenic disturbances that cause transitions between forest and nonforest in peatlands, as these will enter the afforestation, reforestation, and deforestation (ARD) realm of the Protocol. For peatlands subjected to multiple disturbances (e.g., climate change and intentional drainage), it may also be necessary to disaggregate the impacts into those that can be attributed to direct anthropogenic effects and those that cannot. Additional complications may result because of the different types of peatlands (each of which has different process rates), the significant interannual variability in C fluxes in these systems, and the expected increase in fire activity as the climate changes.

Knowledge Gaps and Recommended Priorities for Peatland Research

Knowledge gaps

Accurate estimates of C stocks are needed, as well as many more data on current C fluxes from different peatland types. Data are required from all peatland regions to accommodate the significant east–west differences in production and decomposition that are expected because of differences in moisture and nutrient conditions, disturbance patterns, and other factors.

There are also many gaps in our understanding of ecological and landscape-level processes in peatlands:

- response of mosses to changes in temperature and precipitation;
- quantification of belowground net primary production;
- permafrost dynamics (Is it degrading everywhere? Is there a disturbance trigger?);
- paludification and related disturbance effects;
- microbial dynamics and decomposition, particularly in the catotelm;
- expression of regional hydrology in fens and its sensitivity to climatic variability and disturbance or land use in upland regions; and
- dissolved organic carbon (DOC) and its fate.

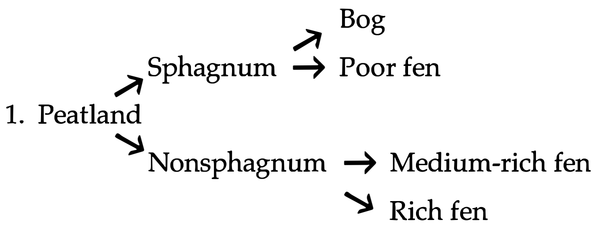
Understanding disturbance dynamics as well as the "critical points" of the other ecological and landscape-level processes (e.g., height of peat relative to the water table) may be especially important, as these phenomena can lead to rapid and dramatic changes.

Recommended research priorities

One research priority is completing the compilation of a map of peatland extent by class. Such a map exists for western Canada but not for eastern Canada. Good data are believed to exist for Quebec, but it seems likely that additional data are needed for Ontario and the Atlantic provinces. Ideally, the peatland map should be directly linked to forest cover maps, so that those interpreting aerial photos will have to designate all such land as either forest or peatland. Doing so will minimize both double-counting and noncounting of portions of the landscape. Participants thought that the differentiation of peatlands from other ecosystems according to the common

"40 cm organic layer" definition for peatlands was inadequate. In assessing, for example, C fluxes, it is more important to adequately assess the influences of the processes inherent to peatlands, which do not recognize an arbitrary depth-measurement boundary.

The following alternative definition was proposed: "a peatland has a well-established lichen–bryophyte layer and a catotelm." This definition may capture areas that have peatland processes but are currently excluded because the organic layer is less than 40 cm (such as parts of the continental Arctic). The following three-level classification scheme for peatlands was also suggested:



2. Permafrost or no permafrost

3. Treed or non-treed

Another priority is compilation of existing peatland data sets. Some C stock and flux data (e.g., for CO_2, CH_4, and DOC) have been collected by various agencies. An obvious opportunity exists to compile these data into a single database. However, doing so may be difficult because of the different classification systems used by each agency. In particular, data for forested peatlands may be difficult to separate from those for lowland forests. If the data can be compiled and stratified by class, however, the flux results could be compared to a summary of peatland extent similarly organized by class. Such a comparison would allow future measurements to focus on the most significant gaps.

A third priority is determining contemporary C exchange by peatland type. There are several possible approaches to this problem. One avenue is the analyses of peat cores dated with lead-210 (^{210}Pb) and data sets for the west (Merritt Turetsky and Kelman Wieder) and for the east (Nigel Roulet) that are currently under development. The compilation of these average fluxes should eventually include an assessment of spatial and temporal variability and should ideally cover all peatland classes. Another approach is to collect flux tower measurements for each peatland class. Since several methods for measuring contemporary C flux are currently in use, intercomparisons are needed so that an aggregate data set (composed of data collected with a variety of methods) can be used in a single assessment with confidence. (The alternative is to use a standardized method for measuring contemporary C flux). A pressing research issue is the reconciliation of contemporary C fluxes with long-term (historical) estimates of C accumulation.

A fourth priority is quantifying disturbance effects on fluxes. At present, there is very little information on disturbance effects (although some may emerge from the analyses of the ^{210}Pb-dated cores and other ongoing studies). In particular, much more research is needed on the total impact of fire on peatlands. Stephen Zoltai made estimates of the area burned (or the fraction of the peat surface that burns when a peatland fire occurs), but little is known about the quantity of peat that is combusted in fires of varying intensity. Other dynamic processes following fire that are poorly understood include the dynamics of post-fire peat mineralization, the time scale for recolonization by bryophytes and vascular plants, and the recovery of net primary production in regrowing peatland vegetation.

The last priority identified was linking the maps and flux measurements (and ancillary data) to spatially explicit and temporally dynamic models. There are two opportunities here: one is to develop peatland ecosystem models (with better parameterization for different peatland types) and the other is to include relevant processes (in particular bryophytes, a near-surface water table and the relevant hydrological features, and anaerobic decomposition processes) into existing forest ecosystem models such as the CBM-CFS2 model (Carbon Budget Model of Canadian Forest Sectors). Both should be pursued.

A recurrent theme among all of the breakout discussions was the need to coordinate research efforts and compile existing information so that research initiatives can focus on the most significant knowledge gaps and duplication of effort avoided. It was suggested that a single agency to oversee peatland studies might be useful in this regard.

APPENDIX 1

Carbon Dynamics of Northern Peatlands: Knowledge Gaps, Uncertainty, and Modeling Approaches

The Northern Forested Peatland Dynamics Working Group[1]

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Peatlands are known to be one of the largest terrestrial carbon reservoirs, presently containing ~400-500 GtC. They are believed to presently sequester 0.036 GtC per year, but this estimate is inferred from long-term historical trends and is highly uncertain. Limited data and understanding of the influence of changing environmental conditions and disturbance (e.g., fires, permafrost melting) on the C budget of peatlands over short and medium time scales (10-100 years) hinder predictions of the changes in the C sink-source relationships under a changing climate. The paucity of data and investigative studies for continental fens and peatlands in the continental arctic, despite their large areal extent and C stocks, is especially limiting for forward predictions of climate change impacts. These were the focal topics of an International Peatland Workshop in Edmonton last March. At the workshop, advances in state of knowledge and uncertainty in the understanding of peatland processes, new modelling approaches to assessing climatic sensitivity and incorporating disturbance effects into regional C budget assessments were reviewed. This presentation reviews the results of that workshop.

Both experimental and modelling approaches have developed rapidly in the last decades and the review suggests useful avenues for future effort. For example, the reconciliation of estimates of C-sequestration rates from contemporary tower C flux and down-core accumulation measurements with ^{14}C and ^{210}Pb dating must be addressed by developing new methodology for intercomparisons of data and models. Several models that are explicitly designed for peatlands or can be applied to peatland ecosystems have been recently developed. These cover a broad spectrum from conceptual models of long-term peatland development and cohort-based and surface vegetation-driven decomposition models, to general ecosystem models and peatland ecosystem models that couple to climate models. The influence of internal peatland dynamics on local hydrological factors presents significant challenges for modelling attempts to assess climate sensitivity at regional and continental scales. Nevertheless, it appears possible to produce a general peatland development model that could mimic both concave and convex peat-accumulation patterns that are observed in oceanic/continental fens and bogs. Such a general model is needed to investigate possible non-linear and dramatic responses of peatland systems to gradual or minor changes in environmental conditions, including transitions between non-forested and forested peatlands or from fens to bogs (i.e., climatic thresholds). The model could also address issues associated with asymmetry of risk (e.g., C losses more likely than C gains over the short-term), and "peatlands at risk" by identifying ones near a critical point (ecological threshold) in their development stage.

Significant progress has been made in the last few years in compiling peatland maps and datasets that distinguish peatland class/type in central Canada but national-scale peatland inventories remain incomplete. Overlaps between forest and peatland inventories, in part because of

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[1] The NFPD Working Group was initiated by participants at an International Workshop on the same title on 23-24 March 2001 in Edmonton, Alberta, Canada. In alphabetical order, they are Mike Apps*, Ed Banfield, Ilka Bauer, Suzanne Bayley, David Beilman, Jag Bhatti, Rick Bourbonniere, Ian Campbell, Rod Chimner, Bill de Groot, Steve Frolking, Linda Halsey, Ted Hogg, Hong Jiang, Werner Kurz, Peter Lafleur, Lana Laird, Bryan Lee, Zhong Li, Fan-Rui Meng, Caroline Preston, David Price, Gloria Rapalee, Pierre Richard, Steve Robinson, Nigel Roulet, Cindy Shaw, Markus Thormann, Merritt Turetsky, Thierry Varem-Sanders, Dale Vitt, Kel Wieder, and Zicheng Yu*. *The poster will be presented by Zicheng Yu and M.J. Apps of the Canadian Forest Service, Canada.

arbitrary definitions rather than functional characteristics, continue to present problems for landscape-scale assessments. To minimize both double-counting and non-counting portions on the peatland landscape, as well as on the forest landscape, units that have functional characteristics somewhere between true forest uplands and peatlands must be identified.

APPENDIX 2
The S.C. Zoltai Slide Collection

Martin Siltanen
Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: msiltane@nrcan.gc.ca

David Price
Canadian Forest Service, Northern Forestry Centre
5320-122 Street, Edmonton, Alberta, Canada T6H 3S5
E-mail: dprice@nrcan.gc.ca

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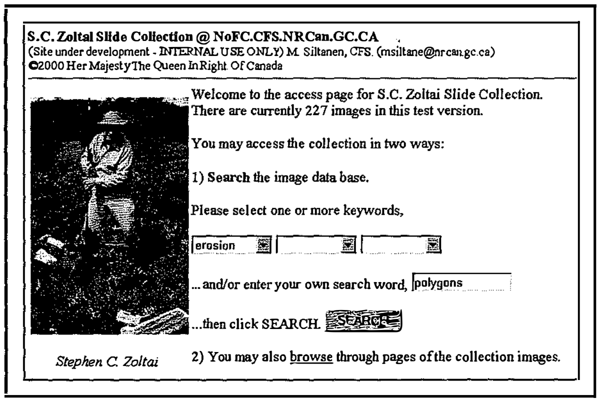
Stephen C. Zoltai took thousands of slides during his career with the Canadian Forest Service, covering a variety of topics from peatlands and pingos to archeology and architecture. Here we present a progress report on a project to generate a digital archive of these slides and to make the images available over the Internet. Documentation will be provided with the archive, taken directly from Mr. Zoltai's own extensive indexing system, which he created and maintained until his death in December 1997.

At present, more than half of the slides have been scanned and the images adjusted for optimal color balance. Associated information includes the date of the photograph, the location (country, province, latitude, and longitude), some key words, and a short description of the item of interest in the slide.

A Web interface has been developed to allow users to search the data base with key words or a free-text search (Fig. 1) and to provide them with thumbnail images of all slides for each matching record, together with the information that Mr. Zoltai recorded for it (Fig. 2). Mouse-clicking on a thumbnail allows the user to see a larger image (Fig. 3). This image can then be saved from the browser for personal use.



S.C. Zoltai Slide Collection @ NoFC.CFS.NRCan.GC.CA
(Site under development - INTERNAL USE ONLY) M. Siltanen, CFS. (msiltane@nrcan.gc.ca)
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Welcome to the access page for S.C. Zoltai Slide Collection.
There are currently 227 images in this test version.

You may access the collection in two ways:

1) **Search** the image data base.

Please select one or more keywords,

erosion

...and/or enter your own search word, polygons

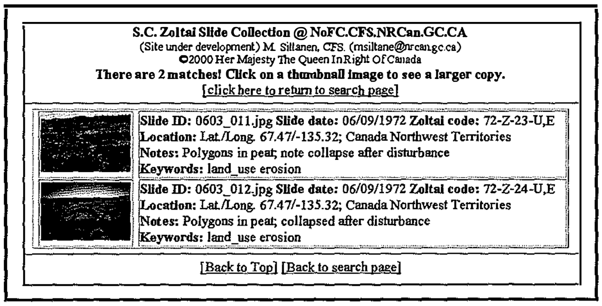
...then click SEARCH.

Stephen C. Zoltai

2) You may also browse through pages of the collection images.

Figure 1. Opening page for slide collection, where user can search by keywords or free text.

All scanned pictures are in 24-bit color, and each measures approximately 800 × 600 pixels. When saved as a low-compression JPEG file, each image is approximately 140 kbytes in size. These



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(Site under development) M. Siltanen, CFS. (msiltane@nrcan.gc.ca)
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There are 2 matches! Click on a thumbnail image to see a larger copy.
[click here to return to search page]

Slide ID: 0603_011.jpg **Slide date:** 06/09/1972 **Zoltai code:** 72-Z-23-U,E
Location: Lat./Long. 67.47/-135.32; Canada Northwest Territories
Notes: Polygons in peat; note collapse after disturbance
Keywords: land_use erosion

Slide ID: 0603_012.jpg **Slide date:** 06/09/1972 **Zoltai code:** 72-Z-24-U,E
Location: Lat./Long. 67.47/-135.32; Canada Northwest Territories
Notes: Polygons in peat; collapsed after disturbance
Keywords: land_use erosion

[Back to Top] [Back to search page]

Figure 2. Sample of a search result, including thumbnail images.

Figure 3. Larger version of image.

image and file dimensions were felt to provide a size and resolution suitable for most presentation purposes. If better resolution is required, the actual slide could be accessed by referencing the slide number to the collection at the Northern Forestry Centre, Edmonton, Alberta. It is anticipated that requests to borrow these slides will be entertained in special circumstances.

The Canadian Forest Service retains all copyright in the images, and, once completed, the collection will be made available on the World Wide Web. However, the extent of public access has yet to be determined. The level of access may depend upon technologies available for watermarking the images and the interest shown in the resource by the scientific community and other groups.

This work is being carried out to acknowledge Mr. Zoltai's many contributions to science and is dedicated to his memory.

APPENDIX 3

Peatland Workshop
March 23–24, 2001 Participant List

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Michael J. Apps
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: mapps@nrcan.gc.ca

Ed Banfield
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: edbanfie@nrcan.gc.ca

Ilka E. Bauer
Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: ibauer@ualberta.ca

Suzanne E. Bayley
Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: sbayley@ualberta.ca

David Beilman
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: dbeilman@nrcan.gc.ca

Jagtar S. Bhatti
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: jbhatti@nrcan.gc.ca

Rick Bourbonniere
Environment Canada
National Water Research Institute
Aquatic Ecosystems Impacts Research Branch
867 Lakeshore Road, P.O. Box 5050
Burlington ON L7R 4A6
CANADA
E-mail: rbourbon@netcom.ca

Ian Campbell
Science Branch
Canadian Forest Service
Natural Resources Canada
12th floor, 580 Booth Street
Ottawa ON K1A 0E4
CANADA
E-mail: icampbel@nrcan.gc.ca

Rodney A. Chimner
USDA Forest Service
Institute of Pacific Islands Forestry
1151 Punchbowl Street, Room 323
Honolulu HI 96813
USA
E-mail: rchimner@fs.fed.us

William J. de Groot
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: bdegroot@nrcan.gc.ca

Caren Dymond
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: cdymond@nrcan.gc.ca

Steve Frolking
Institute for the Study of Earth, Oceans, and Space
University of New Hampshire
Durham NH 03824
USA
E-mail: steve.frolking@unh.edu

Linda Halsey
Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: lhalsey@ualberta.ca

Ted Hogg
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: thogg@nrcan.gc.ca

Hong Jiang
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: hjiangyu@nrcan.gc.ca

Werner Kurz
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: wkurz@nrcan.gc.ca

Peter M. Lafleur
Department of Geography
Trent University
Peterborough ON K9J 7B8
CANADA
E-mail: plafleur@trentu.ca

Lana Laird
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: lalaird@nrcan.gc.ca

Bryan Lee
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: blee@nrcan.gc.ca

Zhong Li
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: zli@nrcan.gc.ca

Fan-Rui Meng
Faculty of Forestry and Environmental Management
University of New Brunswick
Fredericton NB E3B 6C2
CANADA
E-mail: fmeng@unb.ca

Caroline M. Preston
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5
CANADA
E-mail: cpreston@nrcan.gc.ca

David Price
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: dprice@nrcan.gc.ca

Gloria Rapalee
RD 1, Box 203
North Duxbury VT 05676
USA
E-mail: grapalee@pop900.gsfc.nasa.gov

Pierre J.H. Richard
Département de géographie
Université de Montréal
C.P. 6128 Centre-ville
Montréal QC H3C 3J7
CANADA
E-mail: Pierre.Richard@UMontreal.ca

Stephen Robinson
Department of Geography
St. Lawrence University
Canton NY 13617
USA
E-mail: srobinson@stlawu.edu

Nigel Roulet
Department of Geography & Centre for
Climate and Global Change Research
McGill University
805 Sherbrooke Street West
Montréal QC H3A 2K6
CANADA
E-mail: roulet@felix.geog.mcgill.ca

Cindy Shaw
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: cshaw@nrcan.gc.ca

Markus N. Thormann
Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: mthorman@ualberta.ca

Merritt Turetsky
Department of Biological Sciences
University of Alberta
Edmonton AB T6G 2E9
CANADA
E-mail: turetsky@ualberta.ca

Thierry Varem-Sanders
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: tvarem@nrcan.gc.ca

Dale H. Vitt
Department of Plant Biology
Southern Illinois University
Carbondale IL 62901
USA
E-mail: dvitt@plant.siu.edu

R. Kelman Wieder
Department of Biology
Villanova University
Villanova PA 19085
USA
E-mail: Kelman.Wieder@Villanova.edu

Zicheng Yu
Canadian Forest Service
Northern Forestry Centre
5320 – 122 Street
Edmonton AB T6H 3S5
CANADA
E-mail: zyu@nrcan.gc.ca