14 Modeling Ecosystem Processes and Peat Accumulation in Boreal Peatlands

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14.1 Introduction

Northern peatlands have accumulated up to about 450 Gt of carbon, mostly during the Holocene (the last 12,000 years) after the last glaciation (Gorham 1991; Clymo et al. 1998). Although northern peatlands have a relatively low average net accumulation rate (e.g., 19.4 g C m^{-2} $year^{-1}$ in western interior Canada; Vitt et al. 2000), their extent, high-latitude location, and the large size of their carbon pool raise concerns that northern peatlands may become significant sources for atmospheric carbon under a changing climate. However, significant uncertainties exist in addressing peatland carbon responses to climate change. The credible assessment of carbon sink–source relationships in peatlands must be based on the understanding of processes responsible for carbon-accumulation patterns over short and long terms.

Peatland dynamics are a function of the balance of photosynthetic production of living plants atop the acrotelm (surface and upper oxic layer) and decomposition of litter and peat in both the acrotelm and the catotelm (underlying anoxic layer) (Ingram 1978; Clymo 1984). Owing to the complex interactions involved in peatland dynamics, a model is often used to facilitate understanding of processes and to make projections. Because peatlands are ecosystems bordering between upland and aquatic ecosystems, they have some unique features that cannot be easily accommodated in standard ways as for other ecosystems. The objective of this chapter is to review some existing models that have been used to simulate peatland carbon dynamics.

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14.2 Model Overview

Yu et al. (2001a) reviewed several models by grouping them into two main categories: conceptual models and simulation models. Conceptual models describe relationships of different processes and can be used to examine the consequences of various assumptions (Clymo 1992). A simulation model is used to mimic and reproduce the behavior of the systems in as much detail as possible. However, this division is not always straightforward. Here we further divide simulation models, based on model complexity, into ecosystem models and hybrid models (Table 14.1). Ecosystem models attempt to consider all the essential parameters that would determine the ecosystem processes concerned, based on a modeler's understanding and preference of important parameters. Hybrid models can be considered as models with complexity intermediate between that of the simplest conceptual models and that of detailed ecosystem models, which are often specifically designed for peatlands.

Table 14.1. Summary of three categories of models for analyzing peatland dynamics

Type	Key feature	Usefulness	Example
Conceptual models	Use the most generalized parameters to capture the first-order patterns and trajectories of peatland dynamics	Understanding long-term fundamental dynamics, and interpreting peat-core data	Clymo (1984); Yu et al. (2003a)
Hybrid/intermediate models	Include the unique features of peatlands by using functional groups as an integration approach	Integration of processes at various time scales, and projections of future changes in peatlands	Hilbert et al. (2000); Frolking et al. (2001); Bauer (2004); Belyea and Malmer (2004)
Ecosystem models	Parameterized for detailed ecosystem processes, through either modifying existing ecosystem models or developing models specifically for peatlands	Understanding the importance and interactions of various parameters and processes responsible for peatland dynamics	Frolking et al. (2002); Zhang et al. (2002); Chimnar et al. (2002)

14.3 Long-Term Trajectory of Peat Accumulation

The simplest model of peatland functions can be used to provide insights into the trajectory or the first-order prediction of the overall long-term dynamics. When we examine a peat-core record, we know that the peat has accumulated a certain amount of mass over the time period determined by basal age. However, the peatland may have reached that mass through very different trajectories (Fig. 14.1). Different trajectories imply different underlying fundamental processes. One such model is the peat growth model proposed by Clymo (1978), which treats the accumulating peat as a two-layer system: the acrotelm (thin, oxic, upper layer) and the catotelm (thick, anoxic, underlying layer) (Ingram 1978; Ivanov 1981). The acrotelm represents the freshly deposited organic materials that are still mostly above the water level, whereas the catotelm is the peat permanently under the water table, representing the long-term, millennial-scale peat deposit. The boundary between these two layers is approximately at the mean depth of the lowest summer water table (maximum water-table depth) for bogs (Clymo 1984), but may be determined by variables other than water-table depth in rich fens, such as redox conditions. The model is originally based on the concept of Ingram's (1982) hydrologically oriented two-dimensional representation of raised bogs in an oceanic climate. The major feature of this model is the use of a proportional decay function (e.g., a single-exponential model; Jenny et al. 1949; Olson 1963; Wieder

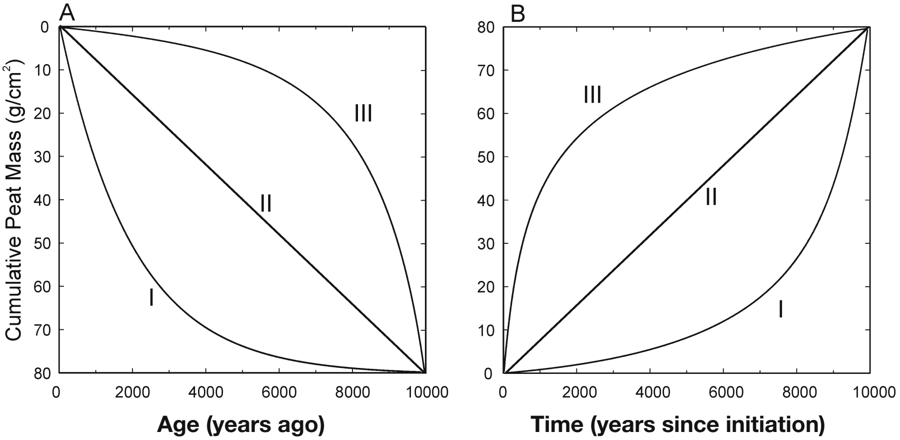

Fig. 14.1. Trajectories of the long-term carbon accumulation in peatlands: **A** derived from peat-core data; **B** simulated over time. There are three first-order scenarios: *I* higher apparent accumulation rates in younger peat and lower rates in older peat (concave pattern); *II* constant apparent accumulation rates; and *III* lower apparent accumulation rates in younger peat and higher rates in older peat (convex pattern)

and Lang 1982) to represent decay processes in both the acrotelm and the catotelm, which assumes that the rate of mass loss is directly proportional to the amount of material remaining.

Carbon accumulation in peatlands is a function of the balance between production of living plants atop the acrotelm and decomposition in both the acrotelm and the catotelm (Clymo 1984). As litter and new peat in the acrotelm are exposed to oxygen and varying water levels, they are subject to a higher decay rate. Once litter and peat are in the catotelm, the decay rate declines sharply and becomes independent of minor climatic fluctuations. The rate of peat transfer from acrotelm to catotelm, or the acrotelm residence time, therefore largely determines net peat accumulation. Water-table depth and the balance of acrotelm production and decay in turn regulate the acrotelm residence time. Clymo (1984) proposed a conceptual model of bog growth, in which constant productivity and exponential decomposition produce a concave cumulative peat mass–age curve, evidenced in most nonboreal oceanic bogs (Fig. 14.2a).

It has been assumed that the processes causing peat to accumulate in continental regions are similar to those in oceanic regions and also that fens are similar to bogs, although with more complicated hydrology (Clymo 1984). There are, however, limited data available to test the valid-

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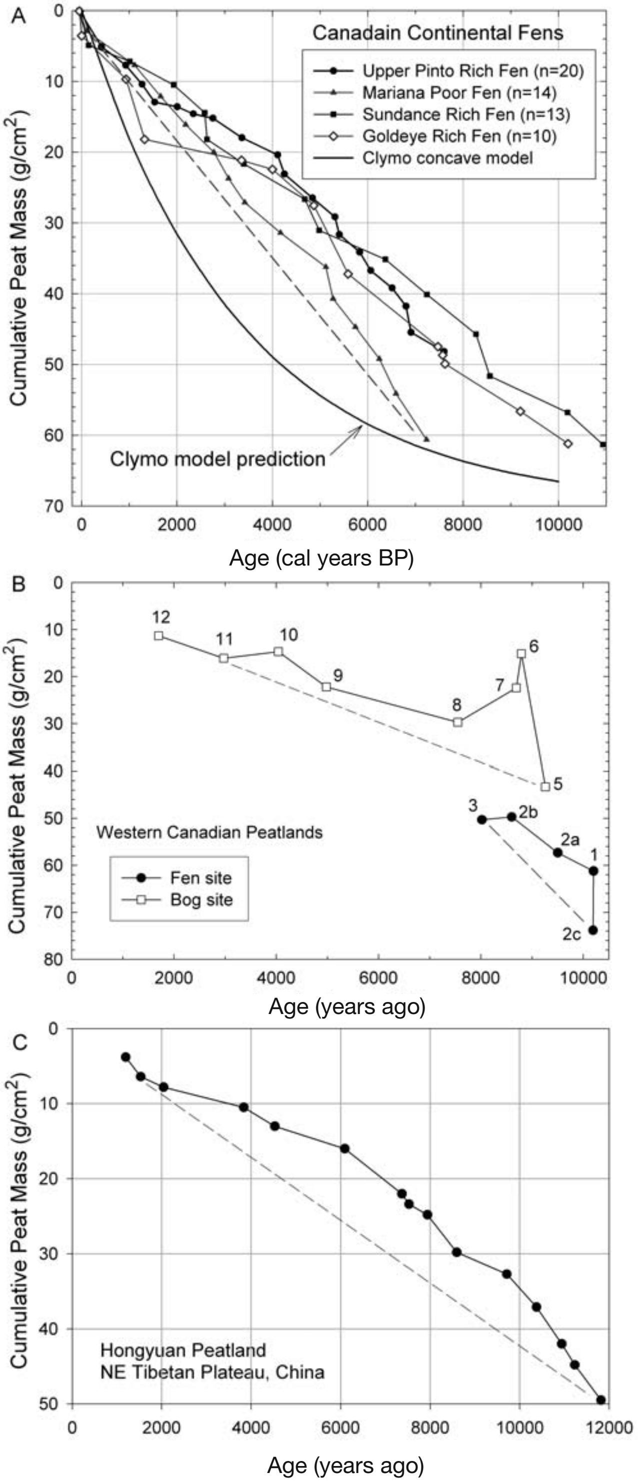
Fig. 14.2. **A** Peat accumulation pattern from four continental peatlands in western Canada, which have more than ten dating points (*n*; ^{14}C dates and tephra markers with known ages) (Yu et al. 2003a; and unpublished data). Upper Pinto Fen (*UPF*; Yu et al. 2003a), Sundance Fen, and Goldeye Fen (unpublished data) are from the Rocky Mountain Foothills region of Alberta, while Mariana Fen (unpublished data) is in boreal plain of north-central Alberta. The concave pattern ("Clymo model prediction") as often documented in oceanic bogs is also shown schematically for comparison (Clymo 1984). **B** Regional synthesis curves of continental fens and bogs in western Canada, with each point representing the basal date and cumulative peat mass from an individual site. Fens tend to be older and accumulate more peat than bogs do; and both fens and bogs seem to show "convex" accumulation trajectories. For some bogs, if they succeeded from fens, then the age for the bog base rather than basal peatland was used. *1* Goldeye Fen, AB (unpublished data), *2* Muskiki Fen, AB (three cores; Kubiew et al. 1989), *3* UPF, AB (Yu et al. 2003a), *5* Slave Lake Bog, AB (Kuhry and Vitt 1996), *6* Legend Lake Bog, AB (Kuhry 1994), *7* Buffalo Narrows Bog, SK (Kuhry 1994), *8* Mariana Lake site 16 Bog, AB (Nicholson and Vitt 1990), *9* Wathaman Bog, SK (Kuhry 1994), *10* La Ronge Bog, SK (Kuhry et al. 1992), *11* Beauval Bog, SK (Kuhry 1997), *12* Gypsumville Bog, MB (Kuhry 1997). **C** Peat accumulation pattern of Hongyuan sedge-dominated peatland on the northeastern Tibetan Plateau, southwest China, based on 15 ^{14}C accelerator mass spectrometry dates (Hong et al. 2003). Bulk density and organic matter content are not available from the site, so we assumed a constant bulk density of 0.1 g cm^{-3}. The core is dominated mostly by yellowish-brown and brownish-black herbal peat, so likely slight variations in bulk density may not change the general accumulation pattern


A
Canadain Continental Fens
Upper Pinto Rich Fen (n=20)
Mariana Poor Fen (n=14)
Sundance Rich Fen (n=13)
Goldeye Rich Fen (n=10)
Clymo concave model
Clymo model prediction
Cumulative Peat Mass (g/cm²)
0 10 20 30 40 50 60 70
0 2000 4000 6000 8000 10000
Age (cal years BP)
B
Western Canadian Peatlands
Fen site
Bog site
12 11 10 9 8 7 6 5 3 2b 2a 1 2c
Cumulative Peat Mass (g/cm²)
0 10 20 30 40 50 60 70 80
0 2000 4000 6000 8000 10000
Age (years ago)
C
Hongyuan Peatland
NE Tibetan Plateau, China
Cumulative Peat Mass (g/cm²)
0 10 20 30 40 50
0 2000 4000 6000 8000 10000 12000
Age (years ago)

ity of the bog model in continental fens as well as bogs (Kubiw et al. 1989; Charman et al. 1994; Kuhry and Vitt 1996). My focus has been on studies of continental peatlands in western Canada, because there are two main aspects in which the peatlands there differ from the raised bogs that form the basic Clymo model: (1) peatlands are dominantly fens and (2) they are under a continental climate (strong seasonality and lower effective moisture). In continental western Canada (the provinces of Alberta, Saskatchewan, and Manitoba), peatlands cover 365,157 km^2 (approximately 20 % of the land area) and store approximately 50 Gt C (Vitt et al. 2000). However, the majority of these peatlands are fens (64 % of the peatland area, including 35 % treed fens and 29 % open fens), and only 36 % are bogs, with permafrost bogs accounting for 28 % of the total peatland area. About half of the fens are rich fens, which thus comprise the dominant peatland type in continental western Canada. The continental climate has a relatively limited water supply, with strong seasonal and interannual variability. While several western Canadian fens have been moderately well studied (Vitt et al. 1994, 2000), more data will be needed to fully establish the functional differences between continental fens/bogs and the more maritime bogs envisaged by Clymo and others. In the following is a summary of recently published and ongoing work on continental fens and a synthesis of previously published data related to peat accumulation patterns.

Several detailed studies on fens have been published (Kubiw et al. 1989; Yu et al. 2003a) that indicate fens behave differently from bogs in terms of peat accumulation pattern, implying different processes and mechanisms. A detailed record of 20 accelerator mass spectrometry (AMS) dates and centimeter-resolution bulk density and macrofossil analysis from a rich fen (Yu et al. 2003a) and other high-resolution fen records from our ongoing work in Alberta show convex patterns of the age–depth curves (Fig. 14.2a), significantly different from well-documented patterns in oceanic raised bogs (Clymo 1984). From a regional perspective, I have reviewed published sites from western Canada that have multiple radiocarbon dates and bulk density measurements to evaluate the regional patterns of peat accumulation in both bogs and fens. I found that at regional and multiple-site scale these continental peatlands tend to show a convex cumulative mass–age curve (Fig. 14.2b). Similarly other studies on continental bogs also show a convex age–depth pattern (e.g., in Alberta, Kuhry and Vitt 1996; in Siberia, Turunen et al. 2001). A continental peatland dominated by sedges (e.g., *Carex mulieensis*) in southwestern China also showed an unequivocal convex pattern (Hong et al. 2003; Fig. 14.2 c). The peatland is located on the northeastern Tibetan Plateau at an elevation of 3,466 m above sea level, under a continental monsoonal climate with a mean annual precipitation of 700 mm. The 495-cm core of sedge peat was dated by 15 AMS dates, covering the entire Holocene.

Fens tend to be older than bogs, at least in the Rocky Mountain Foothills, and fens of the same ages contain more carbon than bogs. By comparing sites from oceanic regions, Draved Mose accumulated 25 g cm^{-2} dry mass during its 7,000-year history (Aaby and Tauber 1975; Clymo 1984), while a bog at Psaansuo in Finland accumulated 36 g cm^{-2} dry mass over 8,000 years (Ikonen 1993), mostly because of a low bulk density of approximately 0.06 g cm^{-3}. In western Canada, fens accumulated more than 50 g cm^{-2} peat mass over the 8,000-year period.

Greater amounts of peat accumulated at individual sites, together with larger fen areas (Vitt et al. 2000), indicating that fens are much more important in carbon dynamics of northern peatlands, at least in western North America. Also, the fact that fens tend to be more sensitive to climate and hydrological changes (Hilbert et al. 2000; Beilman et al. 2001) implies that fens could play an important role in determining the carbon budget of boreal forests in projected future climate change.

14.4 Causes of Convex Accumulation Patterns

What could have caused the convex age–depth shape of the peat accumulation curves as documented for continental boreal peatlands? Peat addition rates (PARs) and decomposition rates determine long-term peat accumulation in the catotelm. Both variables can change over time, but the PAR is likely to be more sensitive to vegetation type and environmental parameters and thus more variable than the catotelm decomposition rate. The PAR is determined by production and aerobic decomposition above the acrotelm–catotelm interface that usually lies 50 cm or less below the peat surface, where environmental conditions (e.g., temperature, moisture, and chemistry) vary greatly. In contrast, the catotelm decomposition is determined by conditions within the catotelm, and deeper peat is less susceptible to environmental influences acting from the surface.

Here the core data from the Upper Pinto Fen (UPF) core in Alberta are used as an example to explore the underlying processes that might explain the observed pattern (Fig. 14.3a). The peat core was dominated by *Scorpidium scorpioides* between 6,700 and 1,300 calibrated years before the present, and the 15 dating points during that period were analyzed using an extended model with variable PARs (Yu et al. 2003a; Fig. 14.3b). Assuming the catotelm decomposition rate is relatively constant over the 5,400-year period, the extended model suggests that the PAR was initially 191.8 g m^{-2} $year^{-1}$, decreasing exponentially at a rate of 0.00037 $year^{-1}$ to 26.0 g m^{-2} $year^{-1}$ at the end of the period. It is likely that a newly initiated fen on a mineral-rich landscape would have much higher plant production, or lower acrotelm decomposition. A sensitivity analysis reveals the

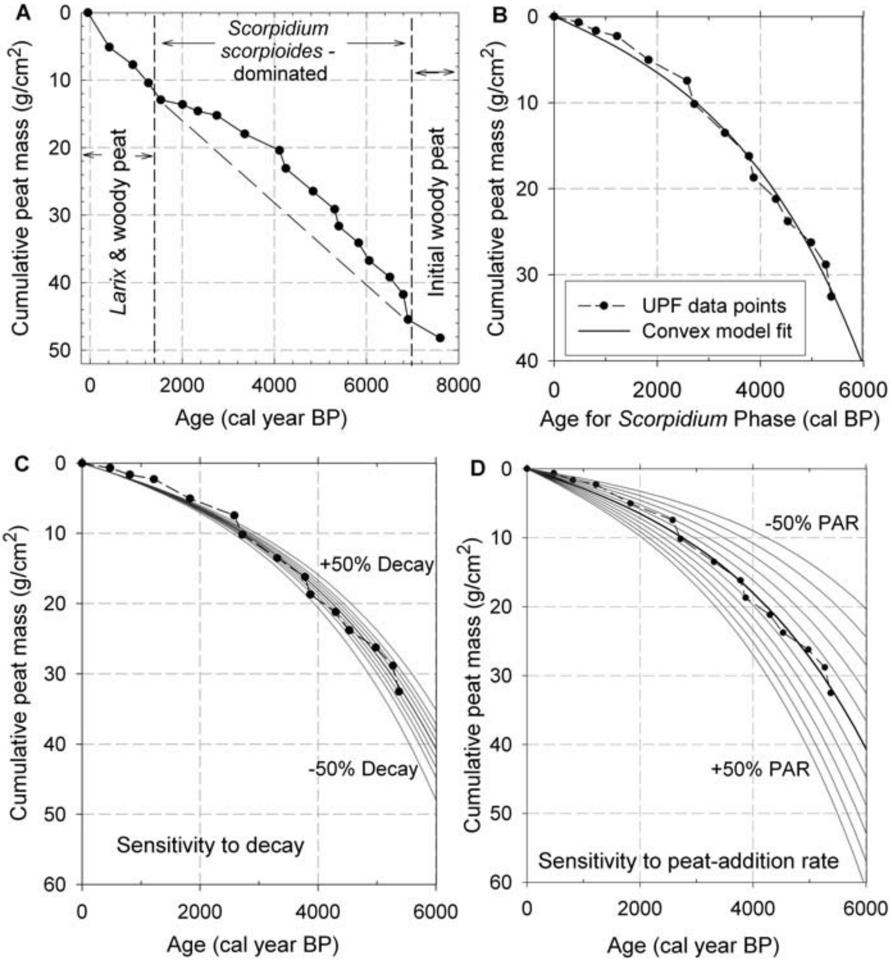


Fig. 14.3. Modeling and sensitivity analysis of the UPF core from Alberta (Yu et al. 2003a). **A** Cumulative peat mass from the UPF core, based on 20 AMS ^{14}C dates and 398 bulk-density measurements. **B** Cumulative peat mass during the period dominated by *Scorpidium* between 6,700 and 1,300 calibrated years before the present for the UPF core (n=15 data points; *dots* and *dashed line*) and modeled fit curve using an extended model with variable peat-addition rates (*PARs*). The model used a fixed decomposition (decay) rate of 0.0002 year^{-1}, which yields an eventual PAR of 26.0 g m^{-2} year^{-1} and an initial PAR value of 191.8 g m^{-2} year^{-1} for that 5,400-year convex period. **C** Sensitivity analyses of changing decomposition rate using the base value of 0.0002 year^{-1} (*thick line*), showing changes from 50 % less (0.0001 year^{-1}) to 50 % more (0.0003 year^{-1}). **D** Sensitivity analysis of changing PAR with an eventual PAR of 26.0 g m^{-2} year^{-1} as the base case (50 % increase to 39.0 g m^{-2} year^{-1}, and 50 % decrease to 13.0 g m^{-2} year^{-1})

effects of changing model parameters on the overall pattern of peat accumulation. As with the case for the concave accumulation pattern (Yu et al. 2001b), changing the decomposition rate has only a relatively limited influence, especially on recently formed peat (Fig. 14.3 c). In contrast, changing the PAR has a noticeable effect on the amount of peat accumulated, including the amount of younger peat as well as older peat in the final profile (Fig. 14.3d).

Why would the rate of peat addition to the catotelm show a unidirectional decrease over time in continental fens? Such a decline may be related to the moisture-limited continental climate and to the particular hydrology of fens and some continental bogs having groundwater (geogeneous water) influences (Glaser et al. 1997). Both autogenic and allogenic processes control the hydrology of peatlands and peatland development (Damman 1986). Local moisture conditions on a peatland surface are determined by a combination of three factors at different temporal and spatial scales: (1) long-term growth of the peatland and associated progressive isolation from the surrounding regional water table (autogenic); (2) regional climatic trends and fluctuations (allogenic; documented in Yu et al. 2003b); and (3) noise from local site disturbances and short-term hydrologic events. The first factor is more important in determining surface moisture conditions in groundwater-dependent continental fens than in the classic raised and blanket bogs of oceanic regions, and a long-term drying trend caused solely by vertical growth of continental rich fens is hypothesized. This reduces the production of moisture-sensitive mosses or increases the acrotelm decomposition, or both, causing a decrease in the PAR. Although this phenomenon might also occur in ombrotrophic bogs because continuous bog growth will accelerate drainage and limit *Sphagnum* production (Damman 1986) or increase acrotelm decomposition (Aaby 1976), it will be more pronounced in continental fens or groundwater-fed bogs owing to greater dependence of these peatlands on local hydrology.

14.5 Modeling Ecosystem Processes in Peatlands

There are several well-established ecosystem models that were originally designed and mostly used to simulate ecological processes in upland ecosystems; for example, TEM (McGuire et al. 2001), CENTURY (Parton et al. 1993), and LINKAGES (Pastor and Post 1986). However, peatland ecosystems have some unique features that need to be considered before any existing upland ecosystem models can be applied to peatlands. These features include waterlogged hydrology, organic soils, a large anaerobic zone, and nonvascular plant dominance. Because of these features, there are strong, coupled interactions and feedbacks among different components of the system, inducing self-regulation to the system dynamics (Beleya and Clymo 2001). Some models for peatlands are based on modification of an existing upland ecosystem model, while others are developed specifically for peatland ecosystems. Some peatland models are generic and can be used for different peatlands, while others are heavily prescribed using site-specific parameters. In any case, peatland ecosystem models consider many more parameters that are responsible for controlling the dynamics than the simple conceptual models do. Many models consider the influence of common environmental conditions (light, temperature, moisture conditions, and chemistry) on net primary production, decomposition, and gas flux rates.

The peatland carbon simulator (PCARS) developed by Frolking et al. (2002) includes components of photosynthesis and respiration of vascular and nonvascular plants, net aboveground and belowground production, and litterfall, aerobic, and anaerobic decomposition of peat. In addition, the model considers production, oxidation, and emission of methane, and dissolved organic carbon loss (Fig. 14.4). The PCARS has been designed in a generalized form that can be applied to all northern peatlands, although it has been more extensively tested against field measurements at one bog in southern Ontario. A unique feature of this model is its ability to link to a model that simulates long-term peat accumulation (Frolking et al. 2001), as a proper peat profile is essential to simulate anaerobic decomposition, a part of the carbon balance term. Also, the model could be coupled to CLASS, the land surface component of the Canadian climate model (Verseghy 2000).

Other attempts have been made to simulate peatland ecosystem processes. Potter et al (2001) applied a NASA-CASA ecosystem model to simulate peatland dynamics over short time scales in western Canada, with major modifications of hydrology (adding run-on) and moss layer for peatlands. Chimnar et al. (2002) modified the CENTURY model, an upland (grassland) soil dynamics model (Parton et al. 1993), in simulating long-term peat accumulation at montane fens in Colorado. In order to mimic conditions in peatlands, they added parameters calculated from effective moisture balance for inducing anaerobic conditions and made adjustments to drainage variables to maintain the water table. Zhang et al. (2002) modified the upland ecosystem model, PnET-N-DNDC, and developed a wetland version of the model, wetland-DNDC. Wildi's (1978) model was designed for testing a specific site, which requires a large number of site-specific parameters, including nutrient information. It simulates a two-dimensional cross section of the peatland and is designed for investigating controls on bog form. Nungesser (2003) designed a model that simulates bog microtopography (hummocks and hollows) in boreal peatlands, which includes submodels of hydrology,

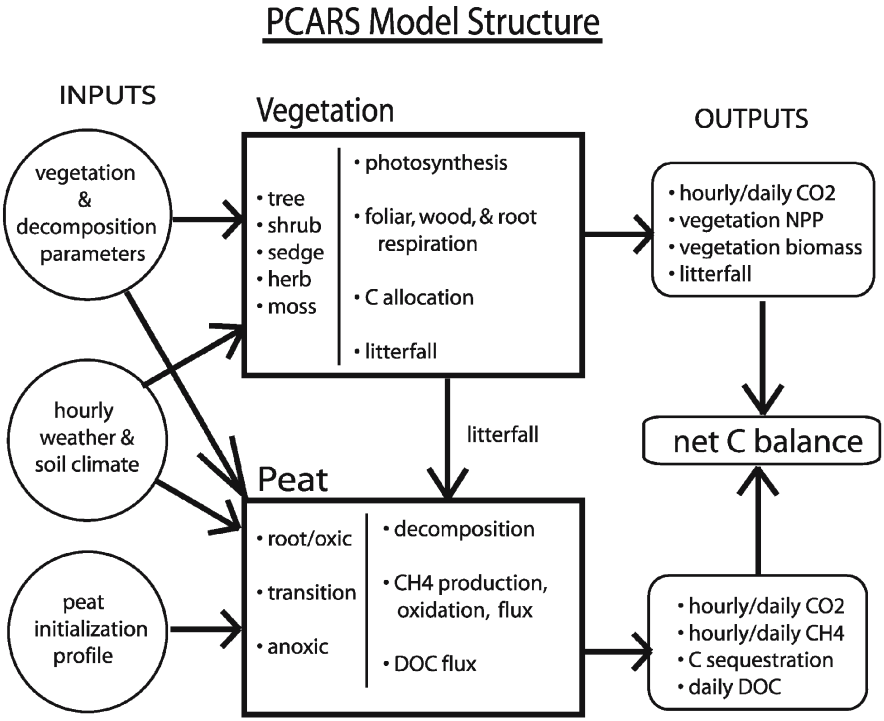


Fig. 14.4. Model structure of peatland carbon simulator (*PCARS*), with an overview of model components (from Frolking et al. 2002)

vegetation, and peat column, and found that microtopography results from the interactions between moss species properties and surrounding physical environment.

14.6 Intermediate Models and Projecting Peatland Dynamics

Some models are specifically designed for studying peatland dynamics, through integrating short-term ecosystem processes with long-term accumulation patterns. A popular approach used for such an integration is cohort treatment of litter inputs and peat column. These models tend to be intermediate in their complexity and details that take into consideration of the unique features of peatlands, especially hydrology and the layered structure, and also use functional types and groups to represent plants and organic fractions. These models have been used to investigate the interactions and feedbacks of biological and physical (hydrological) processes and to provide projections of future changes in carbon sequestration potentials.

Hilbert et al. (2000) modeled the interaction between hydrology (water-table depth) and organic matter (peat production) in peatlands using a system dynamics approach. The model consisting of two coupled nonlinear differential equations shows two possible steady-state configurations for a peatland, depending on water relations, to which the authors ascribe the characters of bogs and fens. There are no interactions between the acrotelm and the catotelm. This model can be seen as an outgrowth of Clymo's conceptual model, but with significant improvement by adding further explicit functional relationships between hydrology and production. Pastor et al. (2002) developed a model of six coupled differential equations that define the interactions between plant species and nutrient

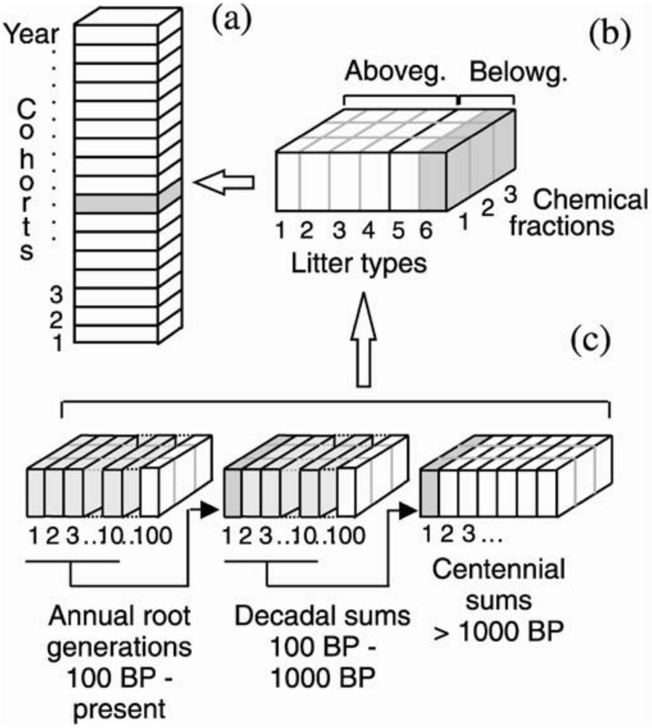


Fig. 14.5. A cohort approach to partitioning organic matter within the peat column as in the model by Bauer (2004). *a* The model follows the fate of a series of annual peat cohorts. *b* Each cohort contains six litter types (aboveground remains from herbaceous, woody, bryophyte and *Sphagnum*, and belowground remains from herbaceous and woody taxa), and mass for each litter type is subdivided into three chemical fractions (soluble, holocellulose, and lignin). *c* Integration of cohorts over time, summarized into 10- or 100-year mass bins

availability, which also result in multiple stable equilibria that represent different types of peatlands.

Frolking et al. (2001) developed a cohort-based peat decomposition model (PDM), in which long-term peat accumulation is directly related to decomposition rates of fresh vegetation litter. The model considers two vegetation types (vascular plant and moss) and root input from vascular plants to deep peat for bogs and fens. The PDM is a static model, assuming constant vegetation production and constant initial litter decomposition. The acrotelm and catotelm are integrated by use of prescribed anoxic factors and bulk density profiles. Bauer (2004) constructed a model to investigate potential effects of environment and vegetation properties on peat accumulation. The model simulates the production and decomposition of annual peat cohorts, which are subsequently integrated over millennial time scales (Fig. 14.5). She found that the factors controlling short-term decomposition are often different from the ones determining long-term decomposition. This highlights the difficulty and challenge of integrating processes over vastly different time scales.

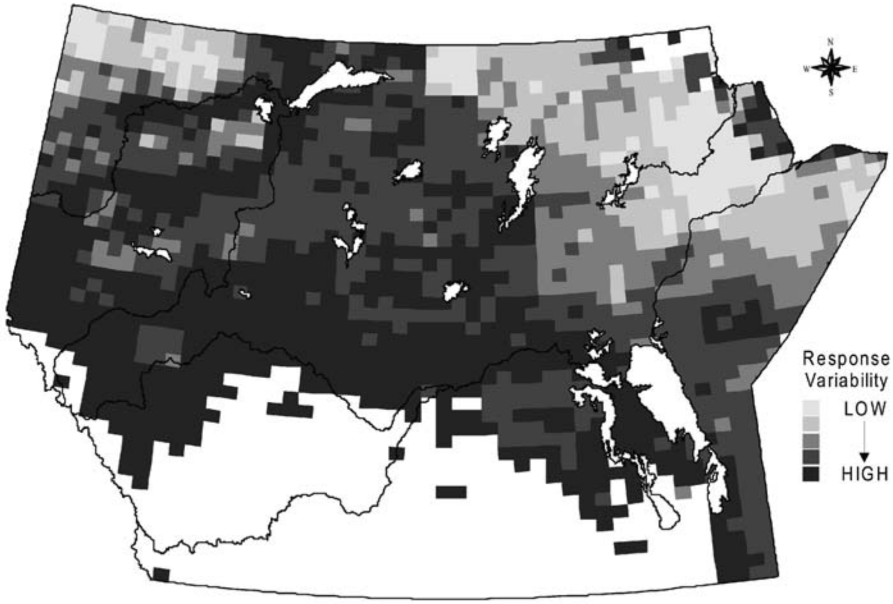


Fig. 14.6. Variability in carbon sequestration between warm/wet and warm/dry climate change scenarios. Calculated as the difference of mean carbon accumulation rate per grid cell between the two scenarios results. Variability in carbon sequestration between warm/wet and warm/dry climate change scenarios calculated as the difference of mean carbon accumulation rate per grid cell. Values range from low (less than 30 g C m^{-2} $year^{-1}$) to high (more than 60 g C m^{-2} $year^{-1}$). (From Beilman et al. 2001)

Belyea and Malmer (2004) linked a model of peat accumulation as described in Yu et al. (2003a) to a model of peatland hydrology and then applied the integrated model to investigate the response of carbon sequestration to climate change in a peatland in Sweden. Some empirical models that are driven by observed data have also been developed and used to make sensitivity analysis and projections. Wieder (2001) presented an empirical model based on ^{210}Pb-dated peat cores, which used depth-dependent decay rates of near-surface (acrotelm) peat to evaluate peatland carbon balance during the last 100–200 years and assessed the sensitivity of peatlands to future climate change. Beilman et al. (2001) took advantage of the extensive peatland survey and database available from western Canada (Zoltai et al. 2000; Vitt et al. 2000) to investigate regional variability and sensitivity of three main types of peatlands (permafrost peatlands, continental bogs, and continental fens). They found that fens located in southern portions of the region appear to show higher variability (Fig. 14.6), implying a large source of uncertainty in response to change in temperature and moisture regimes.

14.7 Conclusions

Various models have been used to investigate processes and dynamics of peatlands. These models range from the simplest conceptual models that intend to understand the first-order trajectory of long-term peat accumulation (carbon sequestration) to the most elaborate ecosystem models that incorporate detailed processes responsible for production, decomposition, and gas fluxes in peatland ecosystems. Some models are modified from existing ecosystem models, while others are deliberately developed to study peatlands by considering their unique characteristics. The peat profiles are an integrated part of peatland ecosystems and make important contributions to heterotrophic respiration of the entire ecosystem, so their inclusion in any model is essential. On the other hand, some key ecosystem parameters, including species composition, production, nutrients, and decomposition, are important for making comparisons with the results from other types of ecosystems. Therefore, it appears that the challenge is to integrate processes that operate over very different time scales, which would be able to offer useful insight to understanding the ecosystem dynamics and to provide robust projections for possible future change.

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