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Peatland Dynamics Simulation Model: A Literature Review and Modelling Design

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Peatland Dynamics Simulation Model:
A Literature Review and Modelling Design

by

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ABSTRACT

This report briefly reviews the existing conceptual and simulation models for peatlands and provides an outline for developing a model to simulate peatland dynamics in western continental Canada. The model is designed to be generic in structure but can be validated using estimated parameters and observed peat accumulation data for continental boreal peatlands. The available data from peat profiles and field measurements are used to understand the underlying processes that govern peatland development at different temporal scales. These empirical data are also used to estimate parameters for the model inputs. The objectives of the proposed model are (1) to understand the interactions of different biological and environmental factors in boreal peatlands, (2) to realistically simulate peat accumulation and decay over the last several millennia using proxy paleoclimate data as drivers and peat profiles as validations, and (3) to project the future change of peatlands as atmospheric carbon sources or sinks under different climate change scenarios, disturbance regimes and management practices. The basic approach is to build a model based on current understanding of peatland processes and supported by available field data.

INTRODUCTION

The current global carbon (C) budget has a “missing carbon sink” of 1.8 Pg C yr^{-1} (1 Petagram = 10^{15} g), which is believed to be primarily in Northern Hemisphere terrestrial ecosystems. The mechanisms responsible for this terrestrial accumulation of carbon are, however, unclear (Houghton et al., 1998). In the meantime, increasing evidence suggests the temperate latitudes (30-60^{o}N) of the Northern Hemisphere could act as a strong terrestrial C sink (Ciais et al., 1995; Fan et al., 1998). Northern (boreal and subarctic) peatlands have accumulated at an average net rate of 0.096 Pg/year to a total C pool of up to 455 Pg during the Holocene (Gorham, 1991); this C pool is about one-third of the total world soil C pool of 1395 Pg (Post et al., 1982). In contrast, the global vegetation C pool is estimated at 610 Pg (Schimel, 1995), whereas the production and respiration flux of global vegetation and soils is on the order of 60 Pg per year (Schimel, 1995). Although northern peatlands have a relatively low average net accumulation rate during the Holocene, the relatively large size of their C pool raises concerns that northern peatlands may become either significant sources or sinks for atmospheric C under a changing climate. There is also little known about the variability of C sequestration in peat through time, and in response to climate change (Moore et al., 1998).

Change of peatlands to C sources (due to net peat degradation) or sinks (due to net peat accumulation) through time would significantly affect the global C budget. Furthermore, while vegetation and upland soils are larger pools with larger fluxes, they represent shorter-lived C pools, as the carbon in them is exposed to oxidation and thus has a shorter residence time than does C in peatlands or other water-saturated sediments. Conversely, much of the C flux from peatlands to the atmosphere is in the form of highly radiatively active methane (CH_4) rather than CO_2.

Temperature is a dominant control of C dynamics in upland soils, with the decay rate of soil organic matter and consequent C release to the atmosphere increasing with increasing temperature in the tropics (Trumbore et al., 1996), as well as through soil thaw in northern ecosystems (Goulden et al., 1998). In northern peatlands, hydrological changes play an important role in regulating peatland dynamics, both in terms of total flux and in terms of the nature (CO_2 vs. CH_4) of that flux (Moore and Knowles, 1989; Siegel et al., 1995).

Peatland dynamics are a function of the balance of production of living plants in the acrotelm (surface aerobic layer) and decay rates in both acrotelm and catotelm (underlying anaerobic layer); all of these processes relate positively to temperature (Clymo 1984; Clymo et al., 1998). As new peat in the acrotelm is exposed to oxygen and varying water levels, it is subject to a very high decay rate. Once in the catotelm, the decay rate declines sharply and becomes much more constant through time. The rate of peat passage from acrotelm to catotelm therefore determines the net peat accumulation. The acrotelm residence time is in turn regulated by water-table depth (WTD) and the balance of acrotelm production and decay (Clymo, 1984). Thus, peatland dynamics at various temporal scales result from complex and non-linear relations with thermal and moisture conditions.

Due to the complex interactions involved in peatland dynamics, a simulation model is needed to facilitate understanding of processes and to make projections. The objectives of this report are (1) to review existing conceptual and simulation peat models, (2) to examine the available field data for conceptual understanding of the interactions and for estimating parameters, and (3) to lay out a plan for the development of a new model.

This modeling exercise is part of the Sustainable Forest Management Network of Centres of Excellence - Landscape Carbon Budget (LCB) program. This program is targeted at the development of a Decision Support System for use in projecting the impact of various land use options and disturbances, including climate change, on boreal landscapes in western Canada. The model developed here is eventually to be implemented as part of this Decision Support System, receiving hydrological and chemical inputs from the forest and lake components, and in turn affecting them.

PEATLAND MODELS: AN OVERVIEW

Quantitative peatland models can be roughly grouped into two basic types: conceptual models and simulation models. Conceptual models describe relationships between different processes and can be used to examine the consequences of various assumptions (Clymo, 1992). They can be thought of as the verbal, mathematical or graphical representation of theory. The basic requirement for a conceptual model is that it should be based on understanding of the real world; in the case of peatlands, the biology and hydrology of peatland dynamics. A simulation model is built upon the conceptual model and connects different components, and its purpose is to mimic and reproduce the behaviors of real-world systems, through changing a parameter or a set of parameters over time. Such models are typically implemented as computer-based models and can be useful for exploring the complex responses of a system where individual components are well understood but where their interactions are poorly understood. Such models can be used, in a first generation, for exploring the consequences of hypotheses and theories, and in subsequent generations, for making predictions about system behaviors under changing forcing factors. While a conceptual model may remain essentially a verbal description of directions and rough magnitudes of relationships, a simulation model will require quantitative inputs and yield quantitative outputs. Here we present a brief review of existing peatland models of both types.

Conceptual Models

There are three main conceptual models of peat growth and development (Table 1); all focus on bogs to the exclusion of fens or other wetland types. The first, and in many ways most developed, is Clymo's (1978) model, which has been further developed in Clymo (1984) and Clymo et al. (1998). The second model is Ingram's (1982) model, and the third is Almquist-Jacobsen and Foster's (1995) model.

Clymo's model is based on the assumption that peat is produced in the living surface of the acrotelm and decays exponentially after it is produced. Clymo distinguishes between acrotelm and catotelm decay rates, and the rate of acrotelm production is an asymptotic function of water table depth (the distance between the peat surface and the water table). This simple model allows a peat deposit to thicken at a variable rate, but is not well designed for net peat degradation.

Ingram's (1982) model is more hydrologically oriented and is a two-dimensional representation of raised bogs. The model is formulated to investigate the influence of hydrology on bog cross-sectional shape, with a drier climate resulting in a flatter bog.

Almquist-Jacobson and Foster (1995) integrated peat hydrology, bog growth and differentiation of surface features into a single model. This is the most elaborate of the conceptual models, and like the Ingram model, it represents a two-dimensional raised bog. The major difference is that while the Ingram model mainly represents internal processes, the Almquist-Jacobsen model includes explicit representation of external processes.

Simulation Models

There are five main simulation models for peatlands (Table 2), including a simulation model implementation of Clymo's conceptual model (Clymo, 1984).

Forrester's (1961) model is an integrated whole system model using a system modelling approach. It is conceptually similar to Clymo's model, in that it is not spatially explicit. The model does, however, require several parameters that may be difficult to obtain, and no validation or test of the model is provided.

Wildi's (1978) model, on the other hand, is designed for testing at a specific site. Its major drawback is the large number of site-specific parameters required, including nutrients information. It simulates a two-dimensional cross-section of the peatland, and is designed for investigating controls on bog form. It is partially validated.

Winston's (1994) general, hydrology-oriented model is based on Clymo's and Ingram's models, but includes special consideration of the initial growth phase. Like Wildi's model, it is implemented as a two-dimensional cross-section model, and is designed for investigating controls on bog form and coal formation. It has been validated using real data.

Korhola et al. (1996) developed a topography-driven three-dimensional peat initiation, growth and expansion model. There are no explicit climate or water table drivers in this model, making it unsuitable for investigating effects of climate change.

Hilbert et al. (in review; N. Roulet, 1998, personal communication) model the interactions between different components of a peatland using a system dynamics approach. This model shows two possible steady-state configurations for a peatland, depending on water relations, to which the authors ascribe the characters of bogs and fens. Of the existing simulation models, this is the most well suited to further development for investigating the impacts of climate change on a peatland and is the only one able to simulate fens as well as bogs. Like Clymo's model, however, it is developed for regions with a moister climate than the continental regions of western Canada. This model can also be seen as an outgrowth of Clymo's conceptual model, but with considerable added explicit functional relationships.

Hereafter we will accordingly focus on the Clymo model, which will be used as a conceptual foundation for developing a peatland dynamics simulation model. We suggest directions for further development similar to those found in the Hilbert model, but more specifically suited to continental peatlands, and taking into consideration the availability of field data from continental regions.

Table 1. Summary of conceptual models for (raised) peat bogs.

Model	Basis	Basic Formulation	Assumption	Consequence	References
Clymo Model	Dynamic balance of p and α determines peat accumulation	$dM/dt = p - \alpha M$	Constant proportional decay rate, $\alpha = \alpha_C$	$M_t = (p/\alpha)*(1-\exp(-\alpha_C*T))$; asymptotic limit to p/α_C	Clymo (1978, 1984), Clymo et al. (1998)
			Linear decreasing decay rate, $\alpha = \alpha_L*(M_t/M_0)$	$M_t = (p/\alpha_L)*\ln(1+\alpha_L*T)$; no limit	
			Non-linear decreasing decay rate, $\alpha = \alpha_Q*(M_t/M_0)^2$	$M_t = (p/\alpha_Q)*((1+2\alpha_Q T)^{1/2}-1)$; no limit	
Groundwater Mound Model	Peat hydrology and hydraulic properties determine bog shape and size	$U/K = H^2/(2Lx - x^2)$	Elliptical cross-section, saturated catotelm, water balance determines the bog dimension	Dry climate results in broader/flatter bog; maximum bog height: $H_m = L*(U/K)^{1/2}$	Ingram (1982)
Integrated Model	Both external and internal processes determine the peat shape, accretion, and expansion	$L = (p/\alpha)(2K/U)^{1/2}$	As above	Lateral expansion is controlled by vertical growth; peat growth and expansion rates decrease over time under stable climate	Almquist-Jacobson and Foster (1995)

Note: M = peat mass; p = peat addition rate; α = proportional decay rate; α_C, α_L, and α_Q = decay constant for constant, linear and quadratic decay models; T = time; U = net recharge percolating down to the water table (index of effective moisture); K = hydraulic conductivity (permeability); H = height of peat bog; L = radius of bog; x = distance from bog edge.

Table 2. Summary of peat bog simulation models.

Model	Assumption	State Variable	Number of Parameter	Driver Factor	References	Comments
Forrester's systems model design	All components of peatland system are connected to determine peatland dynamics	Plant biomass (length), water, energy (derived temperature), CO_2 and CH_4 in four vertical layers from living plant to deep peat (n = 22)	Numerous, depending on how much details in actual simulation	Climate (energy inputs, moistures)	Forrester (1961); Clymo (1992)	Complex design; potentially including all the aspects of peatland system; numerous unknown or hard-to-known functional relations and parameters; no spatial components; no validation/test provided
Peatland ecosystems 2-D model	Vegetation and peat spatial distribution and succession caused by interactions of water, peat, nutrients and vegetation	Peat, water, nutrients (solutes), bog plant biomass, and fen plant biomass (n = 5); each of them in 9 submodels along a pre-defined slope	20	No explicit drivers; objective is to distribute modeled variables spatially over time	Wildi (1978)	Site-specific (because of slope specification); over-parameterized; nutrients as explicit state variable; simulating equilibrium distribution of five state variables along a slope (9 submodels) over time; qualitative validation
Hydrology-driven 2-D model	Rate of rise in the water table controls the peat accumulation rate; initial peat increment occurring at a constant rate; thickness of acrotelm decreases over time	Thickness of initial peat layer; catotelm peat thickness (hydrology – peat relations)	Hydrology-related parameters; production and decay rates	Moisture conditions, water table; assumption-consequence modelling	Winston (1994)	Developed from Ingram's (1982) and Clymo's (1984) models, with some modified assumptions; strictly speaking, not a realistic simulation model but sensitivity-testing model; validated with field data (peat profiles; 1-D and 2-D cross-section) using prescribed parameters; model intended for interpreting coal bed formation
Topography-driven 3-D model	Terrain slope determines the rate of lateral expansion; vertical peat growth follows Clymo's assumptions	Not a process-based model; use estimated parameters to reconstruct 3-D distribution of peat and carbon	Bulk density, CH_4 efflux, production and decay rates for each of three different peat forms; lateral expansion rate	No drivers; empirical model	Korhola et al. (1996)	A 3-D peatland initiation, growth and expansion model, but not a process-based, so no climate and hydrology drivers; objective is to use estimated parameters to reconstruct an observed peat bog
Nonlinear dynamic model	Net water input determines the bog height and water-table depth; plant growth rate is a quadratic (unimodal) function of WTD	Catotelm peat depth, water-table depth	Hydrology-related rates (drainage, evaporation, max and min WTD, peat water content); production rate, decay rate, maximum growth rate	Climate moisture condition (precipitation); assumption – consequence testing	Hilbert et al. (submitted); N. Roulet (1998, personal comm.)	Not a realistic simulation model, but exploring the possible multiple equilibrium states caused by nonlinear dynamics; the hypothetical growth function is key assumption; no interaction between acrotelm and catotelm (constant bulk density); no examples given and no validation from field data

THE CLYMO MODEL

Clymo's peat bog growth model (Clymo, 1978, 1984; Clymo et al., 1998) has proven to be robust and is the basis of most existing peat models; it provides a solid foundation for model development. As indicated by Clymo (1984), many processes that cause peat to accumulate in fens are similar to those in bogs, though fens are probably hydrologically more complex. There are two main ways in which the peatlands of western Canada differ from those that inform the basic Clymo model: they are dominantly fens, and they are in a continental climate. The continental climate causes a relatively limited water supply, with strong seasonal and inter-annual variability. While several western Canadian fens have been moderately well studied, more data will be needed to fully establish the functional differences between continental fens/bogs and the more maritime bogs envisaged by Clymo. In the meantime, Clymo's model will serve as a theoretical underpinning.

The Clymo model treats the accumulating peat as a two-layer system: the acrotelm (thin, aerobic, surface layer; "active layer" in Ivanov, 1981) and the catotelm (thick, anaerobic, underlying layer) (terms sensu Ingram, 1978). The boundary between these two layers is approximately at the mean depth of the summer minimum water table. The major feature of this model is the use of a proportional decay model (e.g., single exponential model, Jenny et al., 1949; Olson, 1963) 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. This is essentially a half-life model, and implicitly assumes the peat to be a homogenous material, with different half-lives in the acrotelm and catotelm due to the different conditions (aerobic vs. anaerobic) that obtain in the two layers. This treatment is supported by limited field data of moss decay measurements in the acrotelm (e.g., Baker, 1972), and by a number of peat profiles in the catotelm (see summary in Clymo, 1984). It is also theoretically realistic in terms of mathematical and biological behaviors (Wieder and Lang, 1982). This model can be expressed as a series of equations:

For the acrotelm:

(1) $dM_a/dt = p_a - \alpha_a M_a$

where p_a = net primary productivity (NPP; g m^{-2} yr^{-1}), M_a = peat mass per unit area (g m^{-2}), and α_a = exponential decay constant (yr^{-1}).

The general solution is:

(2) $M_a = (p_a/\alpha_a)\,[1 – \exp(-\alpha_a t)]$

which implies that peat starts accumulating from zero (t = 0) and increases exponentially to the upper limit of p_a/α_a ($t = \infty$).

Similarly, for the catotelm:

(3) $dM_c/dt = p_c - \alpha_c M_c$

with general solution:

(4) $M_c = (p_c/\alpha_c)\,[1 - \exp(-\alpha_c t)]$

where p_c = catotelm "productivity" (rate of peat addition to catotelm; g m^{-2} yr^{-1}), M_c = peat mass (g m^{-2}), and α_c = decay constant (yr^{-1}).

When considering both the acrotelm and catotelm, eq. (1) becomes:

(5) $dM_a/dt = p_a - \alpha_a M_a - p_c$

The connection is through the following equation (rearrangement of above equation) at the steady state, i.e. when $dM_a/dt = 0$ (no further increase of peat mass/depth in the acrotelm):

(6) $p_c = p_a * \exp(-\alpha_a t_A)$

where t_A is the time that plant matter spends passing through the acrotelm, calculated as:

(7) $t_A = -\ln(1 - \alpha_a M_a / p_a)/\alpha_a$

(Note: there is an error in Clymo (1984) eq. (10) on page 618)

The parameters of p_a and α_a are based on field and experimental data. The range as summarized in Clymo (1984) is 240 – 900 g m^{-2} yr^{-1} for p_a, and 0.01 – 0.8 yr^{-1} for decay constant α_a. The parameters p_c and α_c can be and usually are estimated from dated peat profiles, with an average of 50 g m^{-2} yr^{-1} for p_c and 0.0001 yr^{-1} for α_c.

Clymo et al. (1998) further develop and extend the conceptual model, considering three different decay models as the proportional decay rate, α: (1) constant model (constant α), (2) linear model (α decreases linearly as a function of proportion of original dry mass remaining), and (3) quadratic model (α decreases non-linearly with proportion remaining) (see Table 1 above for a summary of mathematical formulation and biological consequences). The constant model implicitly assumes the mass to be chemically homogenous, which is certainly not the case. There are different components in peat, each with a different inherent "carbon quality" (ease of biological use and therefore decay). The constant decay model is the simplest, and appears to fit the field data well, but the linear model is a better compromise between biological realism and mathematical complexity. From available data, there is no apparent justification for using a quadratic or other non-linear model.

DYNAMIC THREE-DIMENSIONAL PEATLAND INITIATION, EXPANSION, AND DECAY MODEL: CONCEPTUAL DESIGN

Design of an Ideal Simulation Model

An ideal model is not one with the greatest realism, but rather one with the most efficient balance of realism, computational efficiency, ease of parameterisation, ease of validation, and ease of interpretation. The ideal model must therefore include explicit representation of those processes under investigation and those processes thought to be most important to peatland development, but should not attempt to represent less important processes. At the same time, it should balance accuracy of representation of process with simplicity.

Because of the three-dimensional nature of peatlands, an ideal model would consider peatland initiation from mineral soils, lateral expansion of peatlands and vertical growth as shown schematically in Figure 1. Obviously, soil and peatland hydrology plays important roles in the initiation of fens, transformation of fens to bogs, and lateral expansion of both fens and bogs. A preliminary design of a grid-based, spatially explicit peatland dynamic model is summarized in Figure 2.

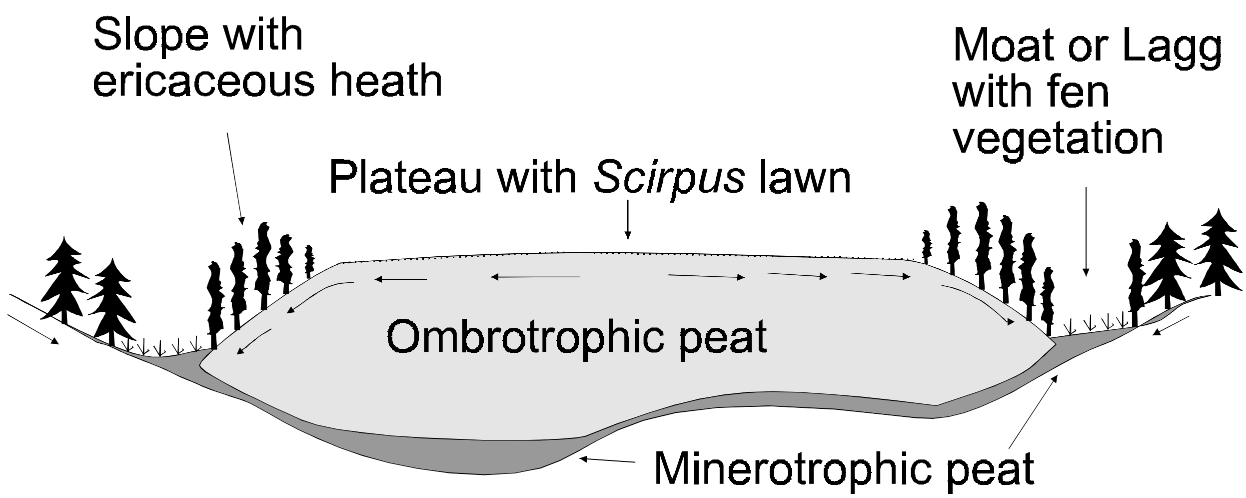


Figure 1. Schematic diagram showing the basic 3-D structure of a peatland (modified from Dammon, 1986).

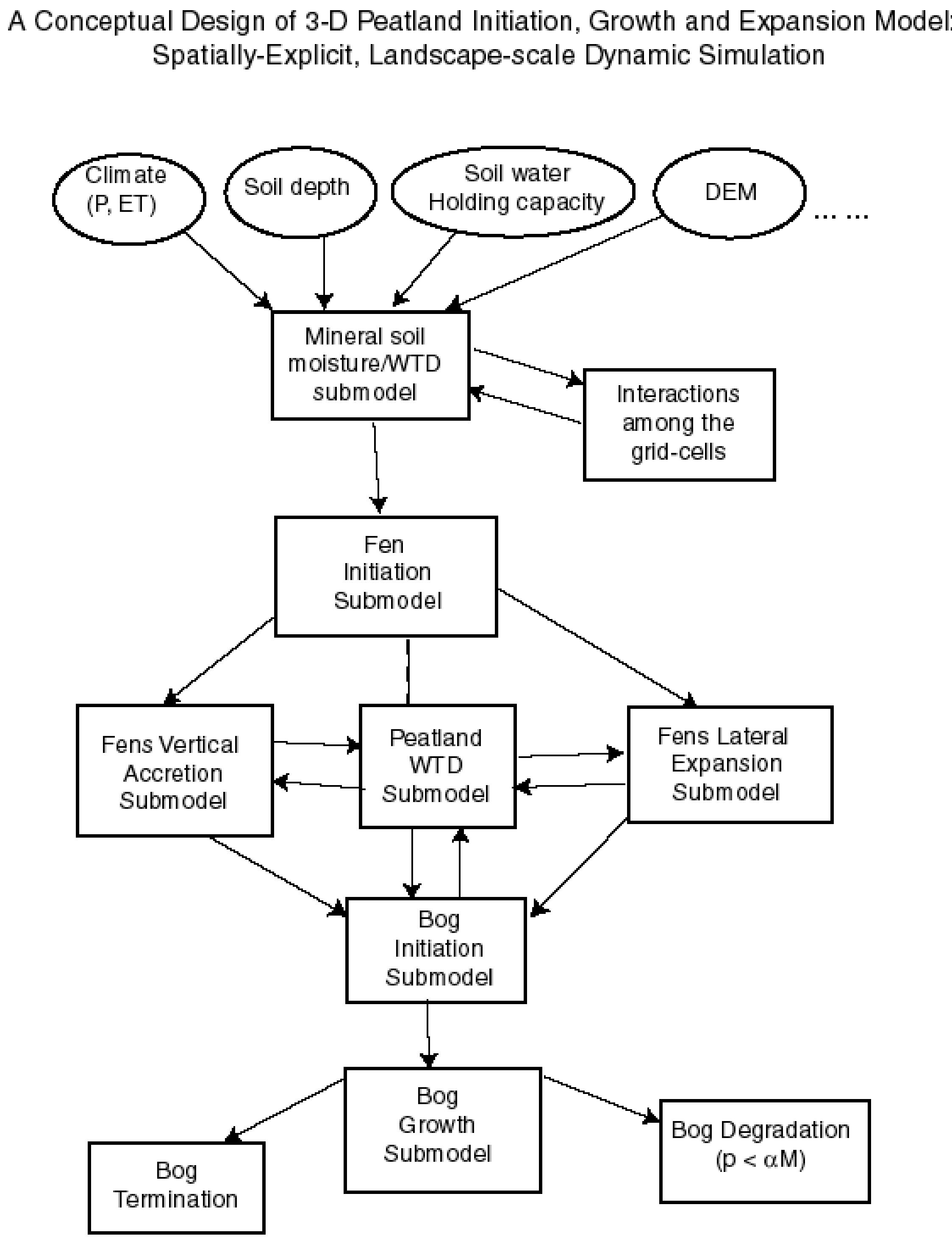


Figure 2. Conceptual design of a 3-D peatland simulation model, which considers peatland initiation, vertical growth and lateral expansion. The model can be dynamically driven by climate variables (e.g., effective moisture).

At any time, there are three basic types of land cover (grid-cells): non-peat mineral soils, fen peat, and bog peat. The simulation starts from a non-peat mineral soil landscape, and soil moisture dynamics are simulated. The mineral soil moisture model will determine when and where on the landscape one or more cells initiate as fen peat, based on predefined criteria for fen peat initiation. The initial fen peat is planted as a thin layer, which will then accrete vertically and expand horizontally, as determined by coupling of the peatland moisture/WTD submodel and peat growth submodels. Bogs initiate when certain predefined conditions are met. Bogs can only initiate from fens, and after initiation bogs grow only vertically. There is no lateral expansion for bogs; apparent bog lateral expansion is in fact conversion of adjacent fen cells to bog. Disturbances and climate changes would be part of the peatland dynamic model, which should be capable of degrading and even terminating a simulated peatland.

All calculations are performed on individual cells. For the mineral soil moisture submodel the time steps are monthly and the outputs are summarized and averaged at the end of each year or decade, for input to peatland submodels as WTD values. The simulation of each cell needs to account for water inflow and outflow between adjacent cells. The peatland model uses a yearly time-step, because of the slow nature of peatland growth.

The Model Structure

1. *Soil Moisture (WTD) Submodel*

The water-table depth (WTD) is a function of precipitation (P), evapotranspiration (ET), soil depth (H) above the impermeable layer, soil moisture holding capacity (C), and inflows and outflows. Spatially, the model can be implemented using a digital elevation model (DEM), coupled with one of several existing distributed watershed hydrology models (see Appendix for a summary of available soil moisture and hydrology models). The submodel can have three soil layers, as in Potter (1997), each with its own soil moisture holding capacity:

S_0: surface ponded water layer (water depth; occurs only when WTD < 0)

S_1: peat layer (acrotelm, catotelm): for mineral soils, $S_1 = 0$

S_2: organic-rich mineral layer

S_3: “parent” mineral layer (clay, silt, sand, etc)

The validation and calibration of the submodel need, at a minimum, complete water budget data for several years from one or more sites. For our purposes, the precipitation and evaporation will be climate drivers for the model. We need to test the behaviors of the model, to see if the model can reproduce the WTD dynamics with known changes in climate conditions. The eventual simulation could start with initial conditions representing newly deglaciated terrain; the WTD submodel therefore needs to be validated over a range of site types including non-peat sites.

2. Fen Initiation Submodel

The critical conditions for fens to initiate from mineral soils are (1) high water table to maintain a wetland (WTD ≈ 0), and (2) stable water table to cause peat accumulation [Δ(WDT)/Δt ≈ 0 and d(WDT)/dt ≈ 0 for a certain period of time]. For an individual cell, if both conditions (1) and (2) above are false, no wetland may initiate in this cell. If condition (1) is true but (2) is false, then a non-peat forming wetland is formed in this cell (e.g., marsh). If both conditions (1) and (2) are true, then the model plants fen vegetation/peat in this cell with a low initial thickness. Obviously, there should be special treatments for permafrost regions; these will not be discussed in this report.

Two very different scenarios could produce conditions suitable for initiating fen peat: regional climate changes and change of local hydraulic conditions. In both cases, however, the requirement at the level of the individual cell is the same - a stable, near-zero WTD.

Under a wet climate, increasing precipitation and/or decreasing evapotranspiration would cause the water-table (WT) to rise (WTD < 0) and local factors may buffer/maintain the stability of WTD. Under a dry climate, lowered soil permeability, through decomposition of organic matter, or deposition of fine clay or charcoal particles, may reduce water infiltration and raise the WT. A drying climate may also initiate peatlands through terrestrialisation of former lakes; terrestrialised peatlands will not be considered here, as they would require an additional submodel for lake water level which in turn would require information on basin characteristics beyond those required for paludified sites.

3. Fen Growth and Fen Peat Water-Table Submodel

Fens will experience vertical accretion and lateral expansion after initiation in a cell. The lateral expansion simply increases the number of fen cells on the landscape. The rate of lateral expansion is a function of the substrate slope; Almquist-Jacobson and Foster (1995) suggest that, in Swedish bogs, lateral expansion will be inhibited if the slope is greater than 0.5%. The parameters can be determined empirically. In a Finnish peatland, the field data were fitted to an exponential function of the form $G = a * S^b$ (where G is the rate of lateral expansion, S is the terrain slope, and a and b are the empirically-determined constants) (Korhola et al., 1996). The maximum rate (G) for that site was estimated at 6 m per year (Korhola et al., 1996).

Vertical peat accretion/growth uses Clymo's (1984) conceptual model: $dM/dt = p - \alpha M$ (see above). The α and p values can be measured and estimated empirically from field data, and they can also be modeled as a function of temperatures and other environmental factors. The peatland hydrology model will be developed with available hydrograph data. The compromise would be to implement a much simplified empirical model rather than a full process-based model.

4. Bog Initiation and Bog Peat Water-Table Submodel

The critical condition for initiation of bogs is the hydrological isolation of the peatland surface from surrounding groundwater, such that all nutrients come from atmospheric deposition (wet or dry) and no nutrient-rich groundwater reaches the peat surface in that cell. Sufficient precipitation is needed to flush existing nutrients from the peat. The poor nutrient status is the key for bog initiation, which may be approximated by distance from surrounding mineral soil (D), height difference between peatland surface in the cell and at the peatland margin (ΔH), or low nutrient content of the water supply (NU).

5. Bog Growth Submodel

The bog growth model will be based on Clymo's (1984) peat growth model: $dM/dt = p - \alpha M$. Again the parameters can be estimated empirically from field data. For both fen and bog growth models, the realistic implementation of the acrotelm - catotelm connection will be a key issue and needs further investigation.

DYNAMIC PEAT GROWTH SIMULATION MODEL: A PLAN FOR PHASE I

In Phase 1 of model development, the model will not be spatially explicit and will in fact be a one-dimensional representation of a single peat column. The peat will be assumed to be initiated when the water table is steady at or near the soil surface for some user-specified duration; only vertical growth and decay will be simulated.

Based on Clymo's conceptual model, the acrotelm and catotelm division will be determined by the maximum WTD (lowest summer water table). There will be an exponential rate of decay in both the acrotelm and the catotelm, but the rates will be distinct for each layer. The peat mass will add to the surface of the acrotelm from living plants as primary production, but with a very high decay rate. Peat accumulation will actually occur in the catotelm because of its slow rate of decay. The WTD and subsequently the residence time of peat in the acrotelm will determine the rate of peat mass transfer from the acrotelm to the catotelm. Figure 3 summarizes the basic structure of the Phase 1 model.

The model is eventually to simulate the production and decay processes in acrotelm and catotelm and water and carbon exchange processes between these two layers. The Phase 1 model is able to simulate initiation, accumulation, degradation and termination of peatlands, through prescribed changes in WTD using invariant productivity and decay rate parameters from western Canada, assuming changes in temperature-dependent production and decay rates cancel each other. In this model, WTD seems to be extremely important in controlling the passage of peat mass from acrotelm to catotelm and eventually net peat accumulation. Preliminary results show that even

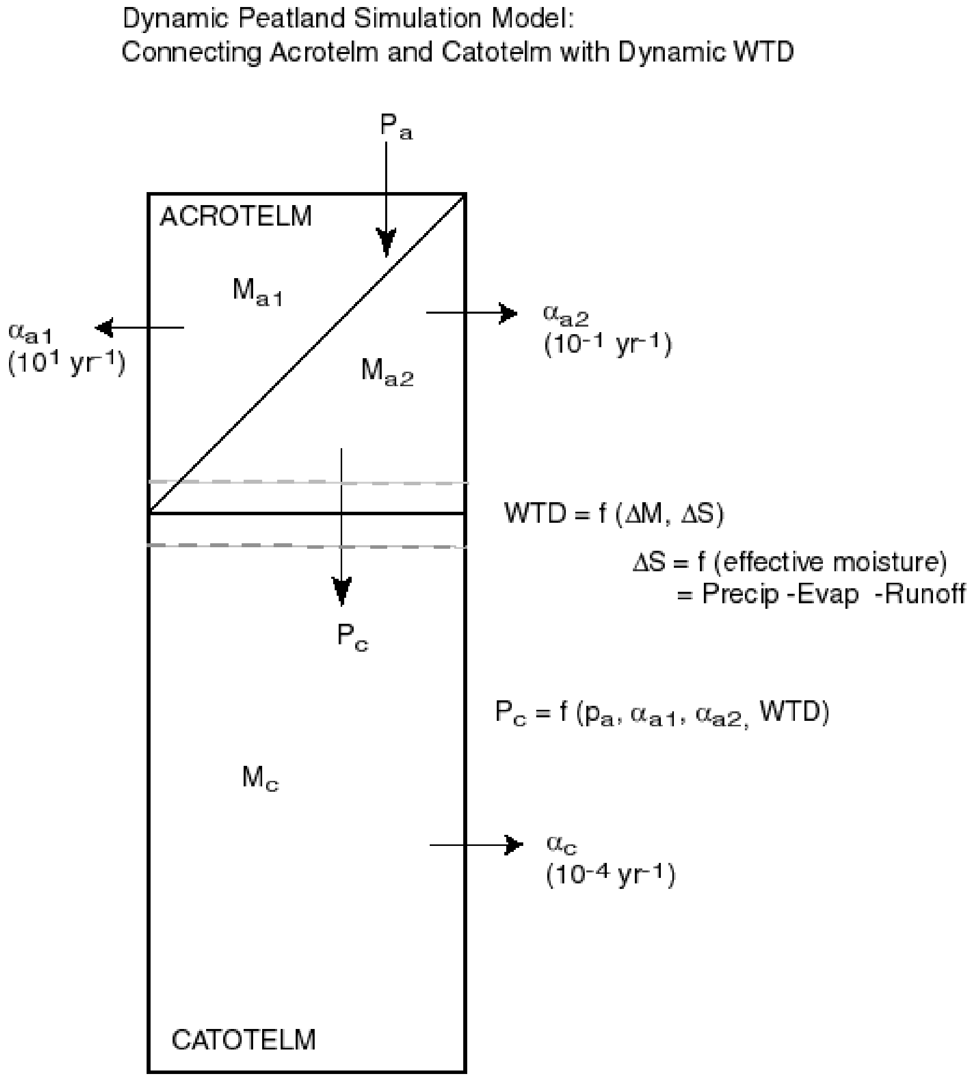


Figure 3. Model design for Phase I: one-dimensional peat growth simulation model with dynamically changing water-table depth.

moderate change in WTD of a few centimeters at decade and century-scales would dramatically change the net peat accumulation. A simulation driven by periodic fluctuations of effective moisture/WTD over the last several thousand years reproduces patterns of peat accumulation that are observed in many peat profiles.

In Phase 2, a WTD sub-model will be developed and calibrated using climate and hydrological observation data to generate a realistic WTD driver. An empirical relationship between temperatures and production/decay rates will be developed to facilitate simulation with dynamically changing production and decay rates. The calibrated peat temperature and moisture sub-models could be used to more realistically project future changes in boreal peatland C storage under different climate warming scenarios, and eventually under different land use options.

Available hydrograph data from central Alberta peatlands (G.R. Hillman, 1998, personal comm.; Szumigalski, 1995; Thormann, 1995) suggest that annual WTD in bogs has low inter-annual and intra-annual variability, but that variability is much higher in fens. The difficulty is to simulate realistic change in WTD based on climate data and peat self-regulation mechanisms. The lack of water balance monitoring data from this region hampers realistic modelling of WTD changes, but the paired on-site measurements of WTD and precipitation at a few sites for a period of up to four years provides necessary data for a compromise, semi-empirical treatment of climate-driven WTD change.

It would be reasonable to use a constant (relative) catotelm decay rate (as in a single exponential model), but, for the acrotelm, a varied decay rate would be more desirable (such as a double or triple exponential model, treating peat as a two or three compartment system with different decay rates for each compartment). Acrotelm decay rates should also be environment-dependent (e.g., temperature). In Phase 1, the model has been implemented with a single acrotelm decay rate.

The Phase 1 model is being used to test hypotheses regarding the importance of water table fluctuations in peatland dynamics. This has allowed us to identify a key issue for realistic implementation of the eventual model: how to realistically and dynamically connect the acrotelm and catotelm through changing WTD. We are in the process of getting new data and re-analyzing available data to explore the dynamics of the acrotelm/catotelm boundary in greater detail, particularly in terms of changing decay rates and bulk density. Hydrological models that may be of use in this regard are summarized in the Appendix.

Apps et al (1994) have proposed a draft design of a peatland carbon dynamics model, based on the approach used in the upland soil submodel of the CBM-CFS2 model (Kurz et al., 1992; Kurz and Apps, in press). This approach does not readily allow the addition of water table fluctuations and is therefore not well suited to our present needs.

DATA EVALUATION AND PARAMETER ESTIMATES

The Acrotelm

1. Productivity and Environmental Relations

The net primary production (NPP) is the initial input to peatlands through fixation of atmospheric CO_2 by photosynthesis. In spite of very different plant communities and vegetation covers for different types of peatlands, the NPP as reported in the literature does not vary widely. Mitsch and Gosselink (1993) estimated NPP at 560 g m^{-2} yr^{-1} for northern bogs. C. Campbell et al.'s compilation (in preparation) shows a mean NPP of 522 g m^{-2} yr^{-1} (348 +/- 184 aboveground; an additional 50% [174 g m^{-2} yr^{-1}] assumed for belowground) for non-permafrost peatlands (bogs and fens) in continental Canada. Using Gorham's (1991) estimates for the catotelm and Clymo's (1984) overall percentage of input from acrotelm to catotelm (10-20%), the productivity in the acrotelm would be 400-800 g m^{-2} yr^{-1} (mean 533 g m^{-2} yr^{-1}).

Climate and other environmental factors influence the NPP in a peatland. There is a documented positive effect of water table on NPP for a lacustrine sedge fen (extreme-rich fen) in central Alberta (Thormann et al., 1998). Their field data from 1991 to 1994 suggest an 11 g m^{-2} yr^{-1} increase in total NPP with a 1 cm increase in water table. Thormann and Bayley's (1997a) results show that a 22.4 cm increase in WT caused a 326% increase in herb NPP in 1993-94; and Szumigalski and Bayley (1997) show a 14 cm decrease in WT causing a 40% decrease in herb NPP at the same site in 1991-92. There appears to be no observed or reported effect of WTD on NPP in bogs, presumably due to the more stable WTD at an inter-annual scale, and therefore the greater difficulty of observing such a relationship without direct experimental manipulation of the water table.

There is a documented effect of temperature on moss NPP in bogs. Moore (1989) combined his own field data and other data from the literature and found that a one-degree increase in mean annual temperature (MAT) could cause a 17 g m^{-2} yr^{-1} increase in *Sphagnum* NPP. He reported the regression relation: *Sphagnum* NPP = 187 + 17.2 * MAT (n = 60; $r^2 = 0.307$) (Fig. 4). Thormann et al. (1998) also reported a positive relation between moss NPP and summer temperatures, suggesting a 41 g m^{-2} yr^{-1} increase in moss NPP with a one degree increase in summer temperature. These relationships are, however, quite weak; in the case of Thormann et al.'s study, the data are from a single site observed for only four years. In the case of Moore's study, the results are heavily leveraged by the small number of sites at the cold end of the spectrum - the more numerous warmer sites show a greater variation than do the few cold sites, suggesting the result may in part be an artifact of the uneven data distribution. With the data used in Moore's study, it would perhaps be more useful to draw a bounding curve rather than a regression line (Fig. 4). This would suggest not so much the unlikely linear relationship with temperature, but rather would suggest the intuitive temperature limitation of growth in cold environments, and the corresponding lack of temperature limitation in warmer environments which would therefore be controlled by other factors. Even in the cold environment, it is unclear whether the limitation is truly one of temperature, or simply one of growing season duration.

Hilbert et al. (submitted) hypothesised a quadratic peat productivity function, suggesting that plant growth peaks at some intermediate value of the limiting environmental condition and decreases to zero for either greater or lower environmental values. Their functional relation is in the form of $P = k (E – E_{min})(E_{max} – E)$, where k is a coefficient determining the maximum productivity, and E_{max} and E_{min} is maximum and minimum environmental conditions at which growth equals zero. They specifically used WTD as the major environmental variable.

In the proposed model, 550 g m^{-2} yr^{-1} will be a reasonable base NPP. The effective moisture and subsequent WTD will be the major environmental driver. Temperature will not be explicitly represented in the first phase of model development, which will ignore permafrost and therefore those regions where mean annual temperature is low enough for temperature to be significantly limiting according to the bounding curve on Figure 4 (permafrost is exceedingly rare in areas with a mean annual temperature above 0°C; Vitt et al., 1994). Environmental relations can be treated either empirically or theoretically. Severe data limitations preclude an empirical treatment. The extrapolation of relationships built upon a limited range of environmental variability could easily result in unstable model behaviours. In contrast, a purely hypothetical growth function would run the risk of being unverifiable through field data. Therefore, the middle ground and a compromise approach would be the preferred route: theoretically based extrapolation of empirical relationship.

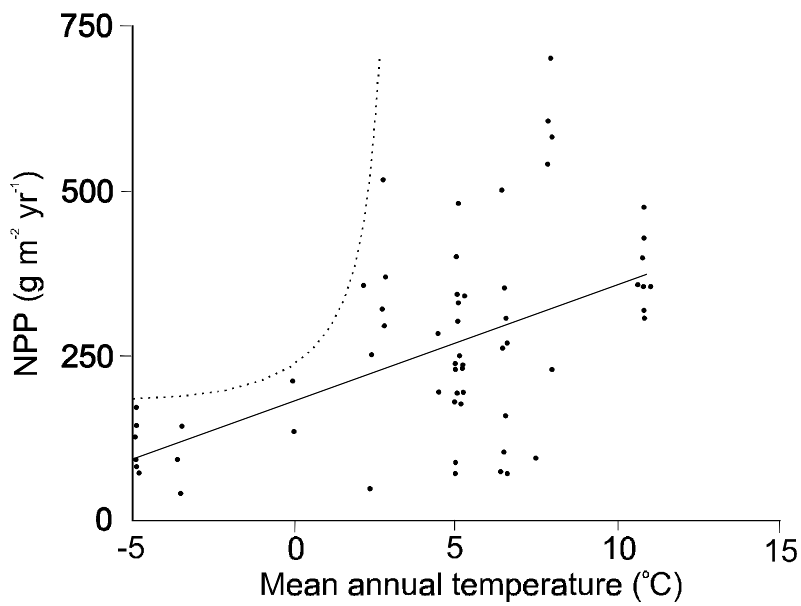


Figure 4. Example of the statistical relationship between net primary production (NPP) and environment factors (temperature in this case) (modified from Moore, 1989). Solid line is originally reported regression line; dotted line shows possible boundary of temperature limitation. See text for detail.

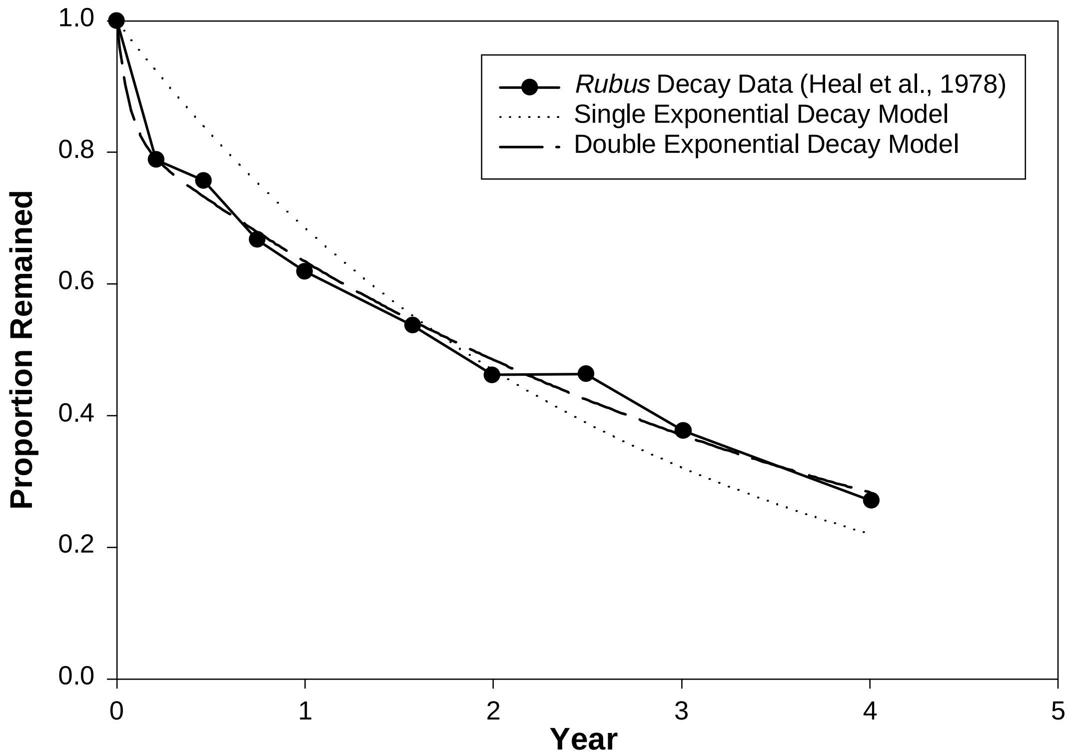
2. *Decay Rates and Environmental Controls*

The selection of a decay model is one of the distinguishing features in the conceptual and simulation models. There are basically two criteria to guide model selection: biologically and mathematically meaningful behaviours. Wieder and Lang (1982) reviewed the advantages and disadvantages of different statistical methods for analysing decomposition data. If the proportion of initial mass remaining at time t is $X = f(t)$, the two decomposition rates can be defined as (1) absolute decomposition rate, which is the first derivative of X with respect to t, (dX/dt), and (2) relative decomposition rate, $[(dX)/(dt*X)]$ (Wieder and Lang, 1982). The most realistic models appear to be one of the exponential models, in terms of both mathematical and biological behaviour.

For a single exponential decay function (Jenny et al. 1949; Olson, 1963), $X = e^{-kt}$. The consequences of this model are (1) the absolute decay rate decreases linearly as the amount of substrate remaining declines, and (2) the relative decay rate remains constant. This fits the biology of litter decomposition. For a double exponential decay model, $X = A*e^{-k1*t} + (1 - A) * e^{-k2*t}$, which assumes that litter can be partitioned into two components: a relatively easily decomposed or labile fraction (A) and a more recalcitrant fraction (1-A). Each fraction decomposes at a different rate (k_1, k_2), with $k_1 > k_2$. The consequences are (1) the overall relative rate tends to decline, approaching k_2 over time, and (2) the overall absolute rate decreases non-linearly over time.

A double exponential decay model appears to be biologically more realistic (e.g., Wieder and Lang, 1982) and could be later adapted to make the peatland model more compatible with the CBM-CFS2 forest carbon budget model (Kurz et al., 1992; Kurz and Apps, in press). The CBM-CFS2 model uses four pools to represent soil organic carbon: very fast, fast, medium and slow pools. Each pool consists of different plant materials and has a different decomposition rate. In a forested peatland, the ability to implement two or more compartments (moss, sedge, forest litters, etc.) is certainly desirable, especially when more detailed data are available.

For a single exponential model, the appropriate peat decay constant is in the range of 0.01 – 0.8 yr^{-1} (Clymo, 1984). For comparison, the constants for the four pools in the upland soils in the CBM-CFS2 model are: 0.5 (very fast), 0.14 (fast), 0.037 (medium) and 0.0068 yr^{-1} (slow). Litter bag decomposition data have been fitted to the single and double exponential models. Decomposition measurements of *Rubus chamaemorus* leaves over a period of four years (Heal et al., 1978) indicate that the double exponential curve fit is much better than is the single exponential fit (Fig. 5). *Carex aquatilis* decomposition measurements in an open rich fen show a decay rate of 0.015 day^{-1} (5.4 yr^{-1} for a 365-day year, or 1.5 yr^{-1} for a 100-day decomposition season), with four data points over 100 days (Thormann, 1995). *Carex* in another open rich fen shows a decay rate of 0.60 yr^{-1} with three data points over a two-year period (Szumigalski and Bayley, 1996). Rochefort et al. (1990) measured decomposition of three *Sphagnum* species in a poor fen over three years with five data points at the Experimental Lakes Area, Ontario.



SingleExp Model: y= exp(-a*x)

Adj Rsqr = 0.92979734

Coefficient	Std. Error	t	P
a = 0.3785	0.0320	11.8454	<0.0001

$\alpha = 0.38\ yr^{-1}$

DoubleExp Model: y=a*exp(-b*x)+(1-a)*exp(-c*x)

Adj Rsqr = 0.99030045

Coefficient	Std. Error	t	P
a = 0.1707	0.0212	8.0409	<0.0001
b = 15.3824	18.1117	0.8493	0.4238
c = 0.2685	0.0156	17.1664	<0.0001

(18% Fast Component: $\alpha 1 = 15.4\ yr^{-1}$)
(82% Slow Component: $\alpha 2 = 0.27\ yr^{-1}$)

Figure 5. Decomposition of *Rubus* leaves (data from Heal et al., 1978) and fitted curves using single exponential decay and double exponential decay models. The exercise seems to support the use of a double exponential decay model, which provides a second decay term significantly greater than zero.

The decay rate is believed to be a function of temperature fluctuations and mean temperatures (Clymo, 1984). There are limited data, however, to build a reliable functional relationship. The oxygen consumption rate of decomposing *Rubus* leaves, as a proxy of decomposition, shows an exponential relation between decomposition and temperature, $\alpha_T = 142 * (-0.86 + e^{0.0324T})$ (Rosswall, 1974). From data for surface (0-10 cm) fen peat in Hogg et al. (1992), there might be a relation of $\alpha_T = 0.072 * e^{0.0635T}$. Szumigalski and Bayley (1996) found a negative relationship between rate of material loss and water level. The decay rate is 0.62 yr^{-1} when the water level is 40 cm below the peat surface, but the decay rate is 0.40 yr^{-1} when the water level reaches the peat surface. This likely represents the transition from aerobic to anaerobic decomposition with saturation.

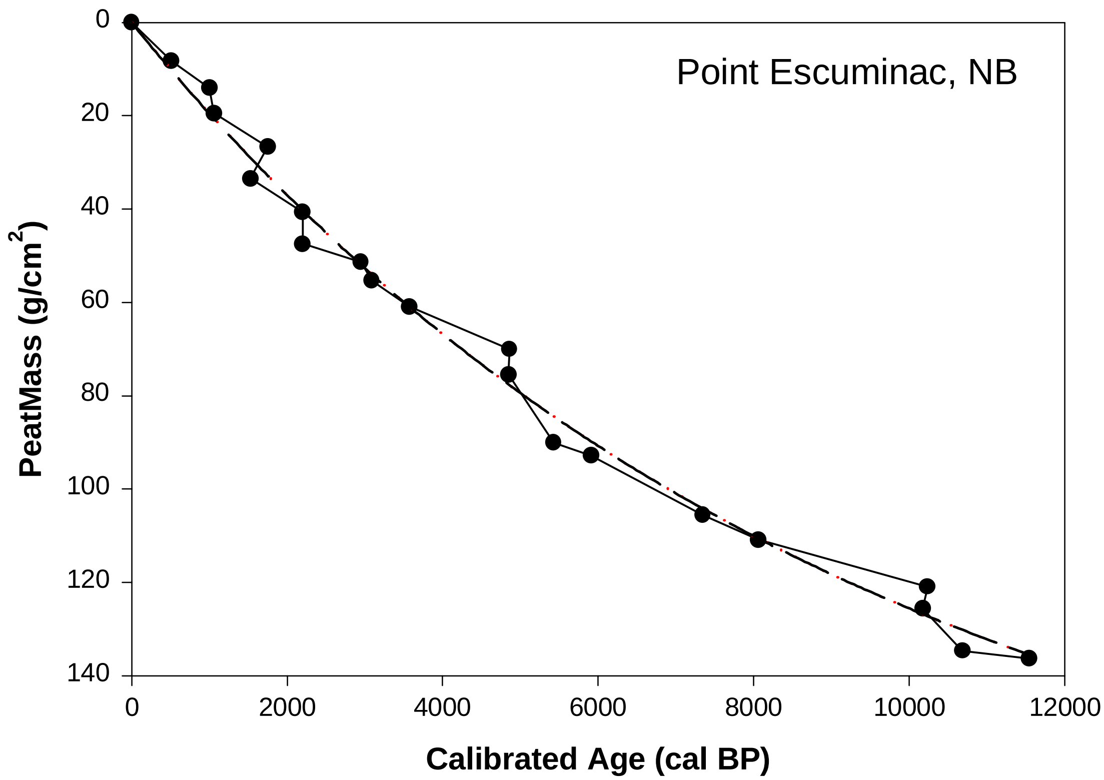
The Catotelm

1. Insights and Parameters Estimated from Dated Peat Profiles

Most of the potential peat generated by NPP is decayed prior to entry into the catotelm. The rate of peat addition to the catotelm is estimated at 10-20% of NPP, with a range of 36 – 78 g m^{-2} yr^{-1} (Clymo, 1984; Gorham, 1991). For a single exponential decay model, the constant decay rate is in the range of 0.7 – 5.5 x 10^{-4} yr^{-1} (Clymo, 1984). The significance of different models is further discussed below.

Two computer programs (KGraph and SigmaPlot) were used to estimate p_c and α_c numerically. The results from the two programs are identical, but SigmaPlot also reports statistical significance results. The curve fitting exercises were carried out for data from Point Escuminac, NB (Fig. 6; Warner et al., 1991, 1993), Draved Mose, Denmark (Fig. 7; Aaby and Tauber, 1975) and 14 sites in western Canada (Vitt et al., in preparation), based on both single exponential [$M = (p_c/\alpha_c)(1 - e^{-\alpha_c t})$] and double exponential [$M = (p_{c1}/\alpha_{c1})(1 - e^{-\alpha_{c1} t}) + (p_{c2}/\alpha_{c2})(1 - e^{-\alpha_{c2} t})$] decay models. In the models, the rate of peat addition (p_c) determines the general slope of the curve, and the decay constant (α) determines the curvature.

Using apparent depth and ^{14}C dates for Point Escuminac, p_c is estimated to be 0.072 cm yr^{-1} (+/- 0.004) [for a density of 0.28 g cm^{-3}, p_c would be 201.6 g m^{-2} yr^{-1}] and α_c = 0.0000683 (+/- 0.0000239) yr^{-1}. The reported values in Warner et al. (1993) are 190 g m^{-2} yr^{-1} (+/- 11.2) and 0.000109 (+/-0.000009) yr^{-1}. The difference may be due to using ^{14}C rather than calibrated ages. Fig. 6 shows the updated values using calibrated ages and a uniform bulk density value (the original estimates may have used bulk density values for individual depths, but these down-core bulk density data were not published). Another fitting exercise was carried out on the data from Draved Mose in Denmark, the best-dated bog core for a concave age-depth curve in the world. There are 55 ^{14}C dates from Draved Mose Bog (Aaby and Tauber, 1975). Here, the ages were first calibrated using CALIB Rev. 4.0 (Stuiver et al., 1998). The estimated values are 69 g m^{-2} yr^{-1} for the peat addition



Single Exponential Model: y= (a/b)*(1-exp(-b*x))

Adj Rsqr = 0.99108771

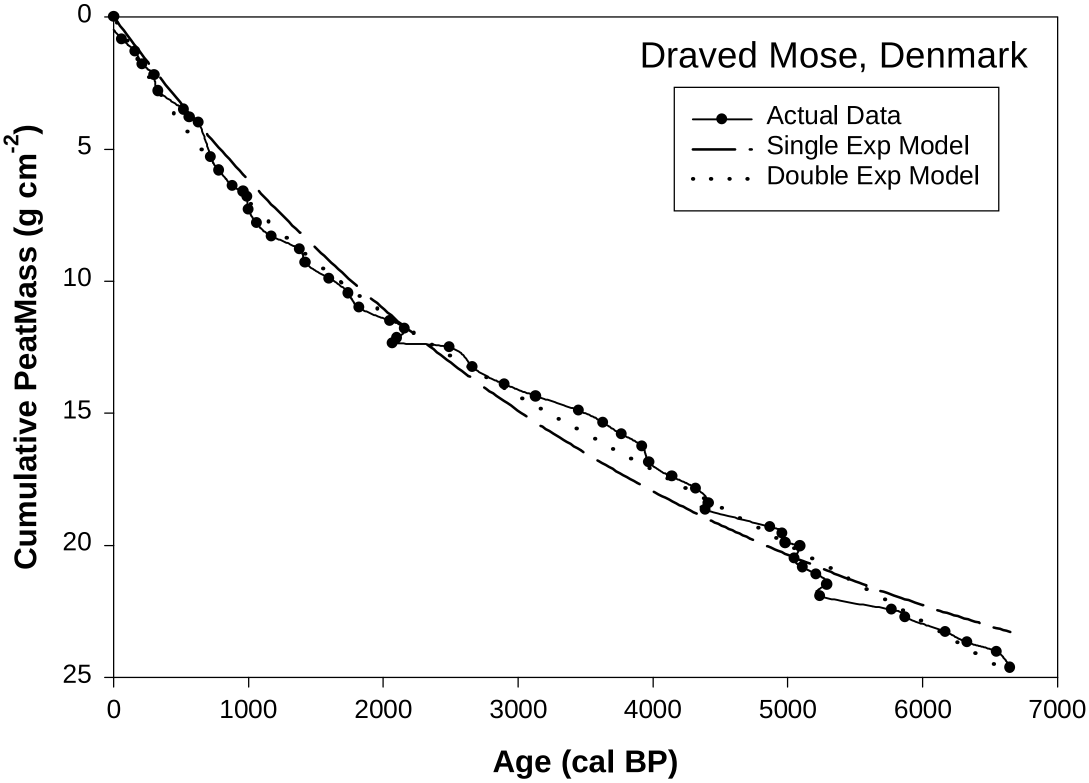
Coefficient	Std. Error	t	P
a = 0.0206	0.0007	27.5332	<0.0001
b = 0.0001	0.0000	10.7106	<0.0001

Double Exponential Model: y=(a/b)*(1-exp(-b*x))+(c/d)*(1-exp(-d*x))

Adj Rsqr = 0.99004133

Coefficient	Std. Error	t	P
a = 0.0087	18245.7169	0.0000	1.000
b = 0.0001	3.8904	0.0000	1.000
c = 0.0119	18245.7138	0.0000	1.000
d = 0.0001	2.8557	0.0000	1.000

Figure 6. Peat mass – age plot for Point Escuminac, New Brunswick (data from Warner et al., 1991; 1993) and fitted curves using single and double exponential models (both overlay each other). The statistical results of the curve fitting exercise suggest that the single exponential model is sufficient to describe the relation, and a double model is not needed because the second decay term is not significantly different from zero (therefore the double exponential model is not significantly different from the single exponential model)



Single Exponential Model: y= (a/b)*(1-exp(-b*x))

Adj Rsqr = 0.98867407

Coefficient	Std. Error	t	P
a = 0.069288	0.0020	35.5289	<0.0001
b = 0.000235	0.0000	16.0701	<0.0001

Double Exponential Model: y=(a/b)*(1-exp(-b*x))+(c/d)*(1-exp(-d*x))

Adj Rsqr = 0.99614282

Coefficient	Std. Error	t	P
a = 0.0756	0.0051	14.8053	<0.0001
b = 0.0009	0.0002	3.9221	0.0003
c = 0.0188	0.0078	2.4264	0.0188
d = -0.0001	0.0001	-1.0162	0.3143

Figure 7. Peat mass – age plot for Draved Mose, Denmark (data from Aaby and Tauber, 1975) and fitted curves using single and double exponential models.

rate and 0.00024 yr^{-1} for the constant decay rate. The results from Draved Mose are similar to those reported in Clymo (1984) at 64 g m^{-2} yr^{-1} and 0.00019 yr^{-1}. From these two well-dated bog sites, we conclude that despite the greater degree of realism it theoretically carries, a double exponential decay model is not needed, because with available quality of data the second fitted decay parameter is not statistically different from zero.

There are 14 peat profiles with a minimum of three ^{14}C dates (maximum of 6 dates at Lesser Slave Lake) (Vitt et al., in preparation). These were used to estimate peat addition rates to the catotelm and decay rates based on a single exponential decay model (Fig. 8). Seven profiles show concave age – depth (mass) curves for this model, three appear to be not concave in shape but may yield reasonable estimates when the origin is forced at depth = 0, time = 0, and the remaining four profiles show convex curves and yield biologically meaningless negative decay rates. The estimated values from individual sites and from a combined data set are reported in Table 3. As argued in Clymo et al. (1998), the function parameter fitting (FPF) method seems to be more robust in dealing with the multiple core data with large variations. If so, then we could use all the available basal dates (as in Halsey et al., 1998) for FPF fitting, which would provide significantly better estimates of parameters. This work is in progress.

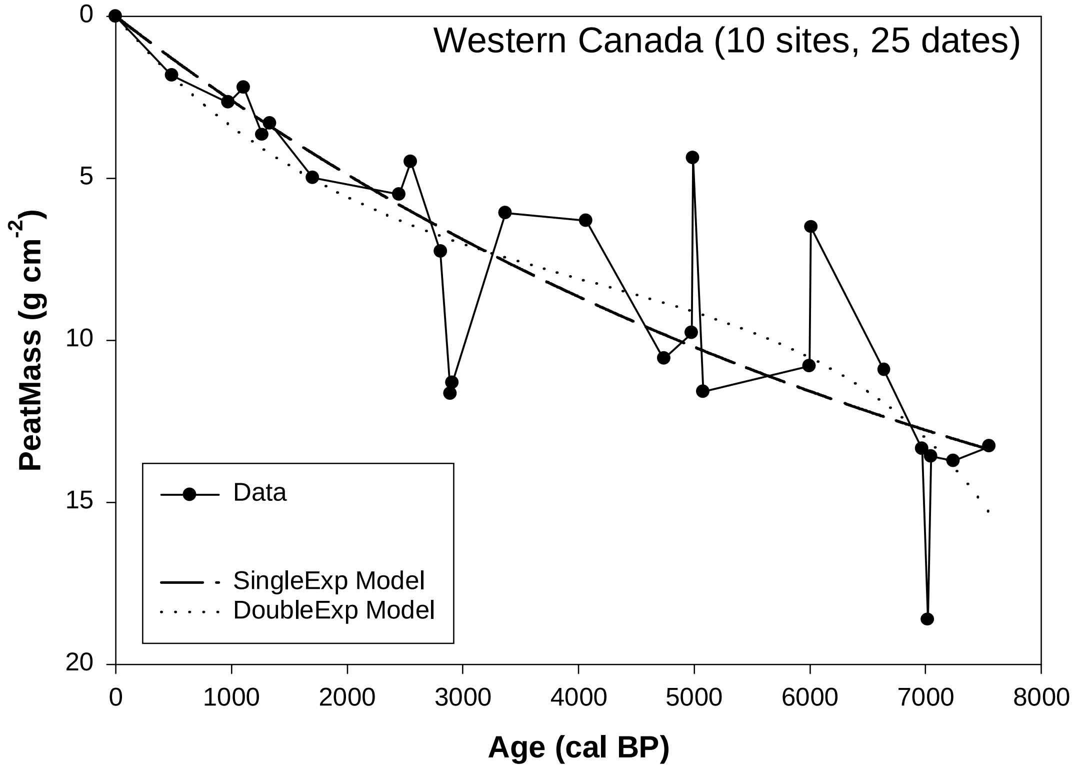
Gorham (1991) estimated that the catotelm long-term average accumulation rate for all boreal and subarctic peatlands, based on 138 basal ^{14}C dates, is 0.5 mm yr^{-1} (from current peat depth/basal age), i.e., 56 g m^{-2} yr^{-1} with an estimated average bulk density of 0.112 g cm^{-3}. The long-term average accumulation rates are 0.54 mm yr^{-1} for boreal Canada, 0.31 mm yr^{-1} for subarctic Canada, and 0.48 mm yr^{-1} for Canada overall. Treating these 38 dated boreal peat cores as from a single profile, the estimated peat addition and decay rates are 80 g m^{-2} yr^{-1} and 0.00014 yr^{-1}, respectively.

2. Decay Models and Significance

Based on a Finnish peatlands database of 310 bogs and fens, Clymo et al. (1998) estimated that the peat addition rate to the catotelm is 0.0021 kmol C m^{-2} yr^{-1} (0.0021 x 12.011/0.52 = 48.5 gC m^{-2} yr^{-1}) and the decay rate is 3.7 x 10^{-5} yr^{-1} using a linear decay model (assuming proportional decay constant decreasing linearly with remaining peat mass). It appears that different decay models (constant, linear or quadratic) do not make much difference for individual peat profiles, because these profiles usually have less variation. However, if using pooled data from different peat profiles, the greater variation, presumably caused by site–specific factors, would cause significantly different estimates. As argued by Clymo et al. (1998), their newly developed FPF method would provide more reliable estimates because this method considers uncertainty from both peat mass measurements and age measurements. This may therefore provide better estimates and is in progress.

Table 3. Parameter estimates for sites in western Canada (data from Vitt et al., in preparation).

Site Name	**Peat Type**	**# ^{14}C Dates**	**Location**	**Catotelm p ($g/m^2/yr$)**	**Catotelm α ($x10^{-4}/yr$)**
Concave					
Gypsumville Bog, Man.	Bog	3	51 46N 98 30 W	33.75	1.9
Legend Lake, AB	Bog	3	57 26N 112 57W	17.3	2.6
Mariana Lakes Site 16, AB		3		18.7	0.16
89-18A, AB	Plateau	4	58 18N 119 17W	20.3	0.89
79km Bog (Wathaman), Sas.	Bog	3	56 57N 103 34W	26.1	0.99
Steve81-18A, AB	Patterned fen	3	54 45N 115 52W	44.2	1.4
Steve89-16A (Zama), AB		3	59 7N 118 9W	27.6	1.7
Not obviously concave					
Buffalo Narrows, Sas.		3	55 56N 108 34W	17.6	1.3
Steve81-8A (site 4), AB	fen	3	52 51N 116 28W	23.9	0.43
Steve81-11A (site 5), AB	fen	3	53 20N 117 28W	47.7	2.3
Mean (plot all)				**27.72 (23)**	**1.37 (0.64)**
Convex					
Beuval Bog, SAS.	Bog	3	54 40N 107 49W	17.3	-2.4
Steve WC2 (site 7a), AB	Horizontal Fen	3	53 26N 116 04W	7.3	-1.1
La Ronge, SAS.	Bog?	3	54 57N 105 15W	10.5	-2.4
Lesser Slave Lake, AB	Bog	6	55 0N 114 09W	17.8	-0.28



Single Exponential Model: Peat= (p/α)*(1-exp(-α*Age))

Adj Rsqr = 0.71711302

Coefficient	Std. Error	t	P
p = 0.002769;	0.0006	4.4975	0.0001
α = 0.0001288;	0.0001	1.4893	0.1494

Double Exponential Model: Peat = (p1/α1)*(1-exp(-α1*Age))+(p2/α2)*(1-exp(-α2*Age))

Adj Rsqr = 0.70000523

Coefficient	Std. Error	t	P
p1 = 0.004231	0.0021	2.0473	0.0528
α1 = 0.000467	0.0006	0.8226	0.4195
p2 = 0.000017	0.0002	0.1051	0.9173
α2 = -0.000748	0.0012	-0.6350	0.5319

Figure 8. Peat mass – age plot for 10 sites in continental western Canada (total 25 ^{14}C dates; data from Vitt et al., in preparation) and fitted curves when treating all these dates as coming from a single peat profile.

PEAT PROFILES AND PEAT ACCUMULATION

Effects and Significance of Changing Peat Addition and Decay Rates

Based on Clymo's conceptual model, there are two variables determining long-term peat accumulation in the catotelm: the rate of peat addition and the decay rate. Both variables likely change over time, but the peat addition rate is likely to be more variable than is the decay rate. The addition rate is determined at the acrotelm - catotelm interface, which usually lies 20-50 cm below the peat surface, where variations in environmental conditions such as temperature and moisture condition would certainly affect the peat addition rate. In contrast, the decay rate is determined all along the peat profile, the deeper peat being less susceptible to environmental influences from the surface. In addition, using a single exponential model, there are very different influences of peat addition rate and decay rate on the overall peat accumulation, specifically the shape of the age-peat depth curve.

The peat addition rate significantly affects young peat as well as old peat (Fig. 9), and decreasing the addition rate will move the curves upward; for that interval of peat the data points would be above the fitted curve (representing the long-term average p). In contrast, the decay rate affects older peat much more significantly than it does younger peat (Fig. 10), and increasing the decay rate will similarly shift the curve upward and cause the data points to lie above the fitted curve. Overall, the curve is more sensitive to changes in the rate of addition; therefore, the decay rate is more "conservative" and more determined by old peat.

Here we briefly discuss the hypothesis that the wiggles, or departures from a smooth curve, in peat age-depth curves are caused by changes in the peat addition rate. If the assumption that the anaerobic decay rate remains constant over thousands of years is valid, then change in the peat addition rate could be used to explain the century-scale or millennial-scale variation in peat age-depth curves, assuming the roughness was not caused by dating errors. Constant proportional decay seems to be a reasonable assumption considering the damped variation of temperature in peat. Figures 11 and 12 illustrate the possible climate inference and interpretation of sample age-depth profiles.

The results from Draved Mose (Fig. 11) suggest an interval from ca. 5000 to 2500 cal yr BP during which there was a lower-than-mean peat addition rate, and therefore most likely either lower-than-mean NPP or higher-than-mean acrotelm decomposition; either condition would be caused by a relative lowering of the water table, which would in turn result from a drier climate. This corresponds to the known dry sub-boreal period of northwestern Europe, providing some confidence that the assumptions listed above are valid.

Figure 12, showing the grouped dates from western Canadian peat deposits, is somewhat harder to interpret in a straightforward manner, because multiple sites are included.

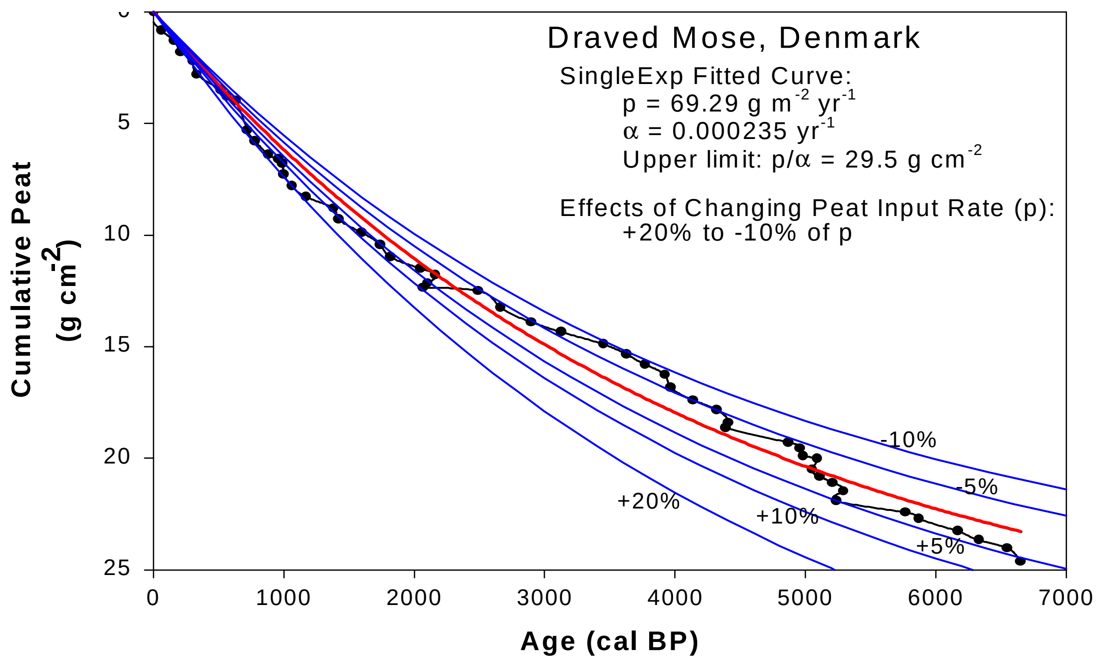


Figure 9. Effects of changing the peat addition rate to the catotelm on the shape of peat mass – age profile, using the Draved Mose peat profile as an example (data from Aaby and Tauber, 1975). Increasing the addition rate causes deeper peat, i.e., the curve moves downward. The central thick curve is fitted by single exponential model.

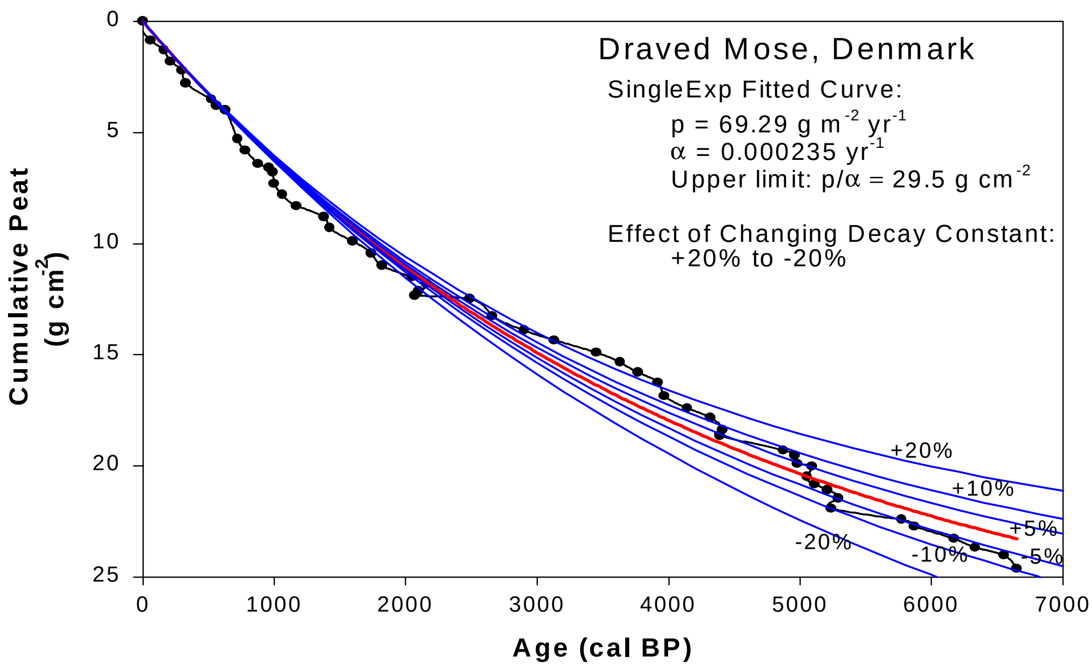


Figure 10. Effects of changing the peat decay rate in the catotelm on the shape of peat mass – age profile, using the Draved Mose peat profile as an example (data from Aaby and Tauber, 1975). Increasing the decay rate causes shallower peat, i.e., the curve moves upward. Compare with Fig. 9, changing addition rate tends to affect both young and old peat, but changing decay rate tends to affect more significantly old peat.

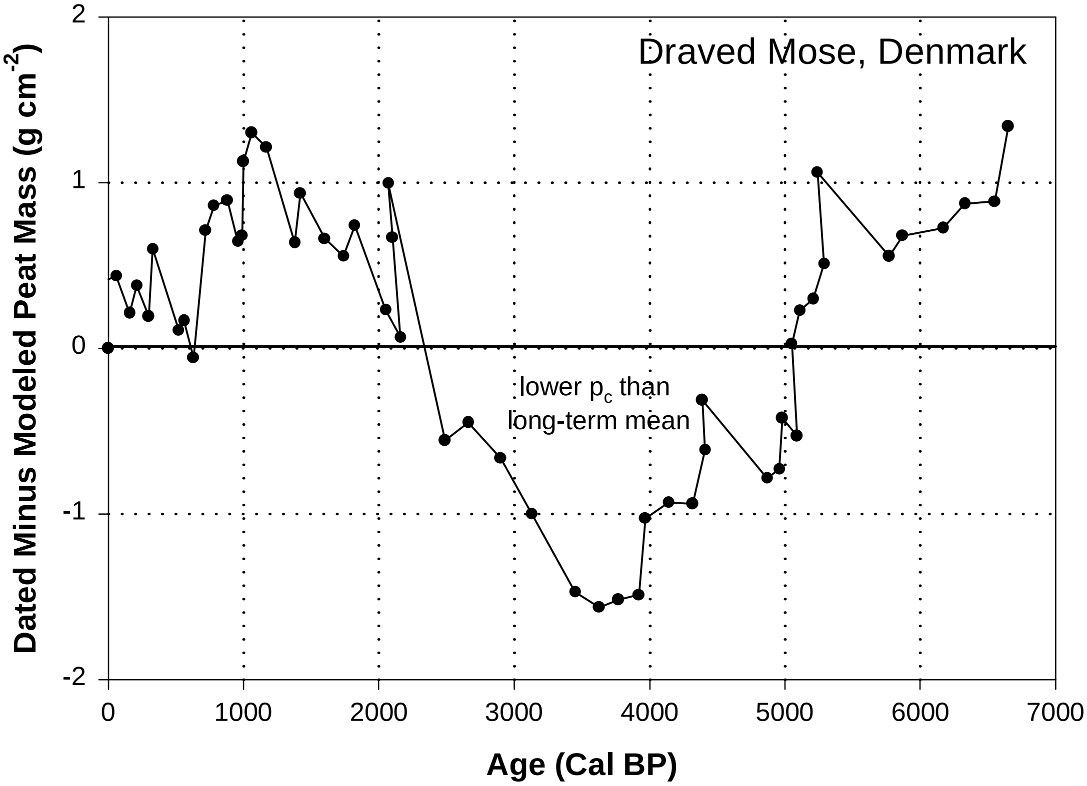


Figure 11. Difference between dated peat mass and modeled peat mass (using single exponential model, see Figs. 7, 9 and 10) at Draved Mose (data from Aaby and Tauber, 1975). Assuming a constant decay rate and the fitted curve representing a long-term average of addition rate for the last seven thousand years, the lower peat mass accumulation from 5000 to 2500 BP may suggest a lowered peat addition rate, possibly caused by lowered NPP, lowered water table, higher acrotelm decay rate or any combination of these factors.

Nevertheless, Figure 12 is not inconsistent with the known mid-Holocene aridity of the western interior of Canada (e.g., Schweger and Hickman, 1989).

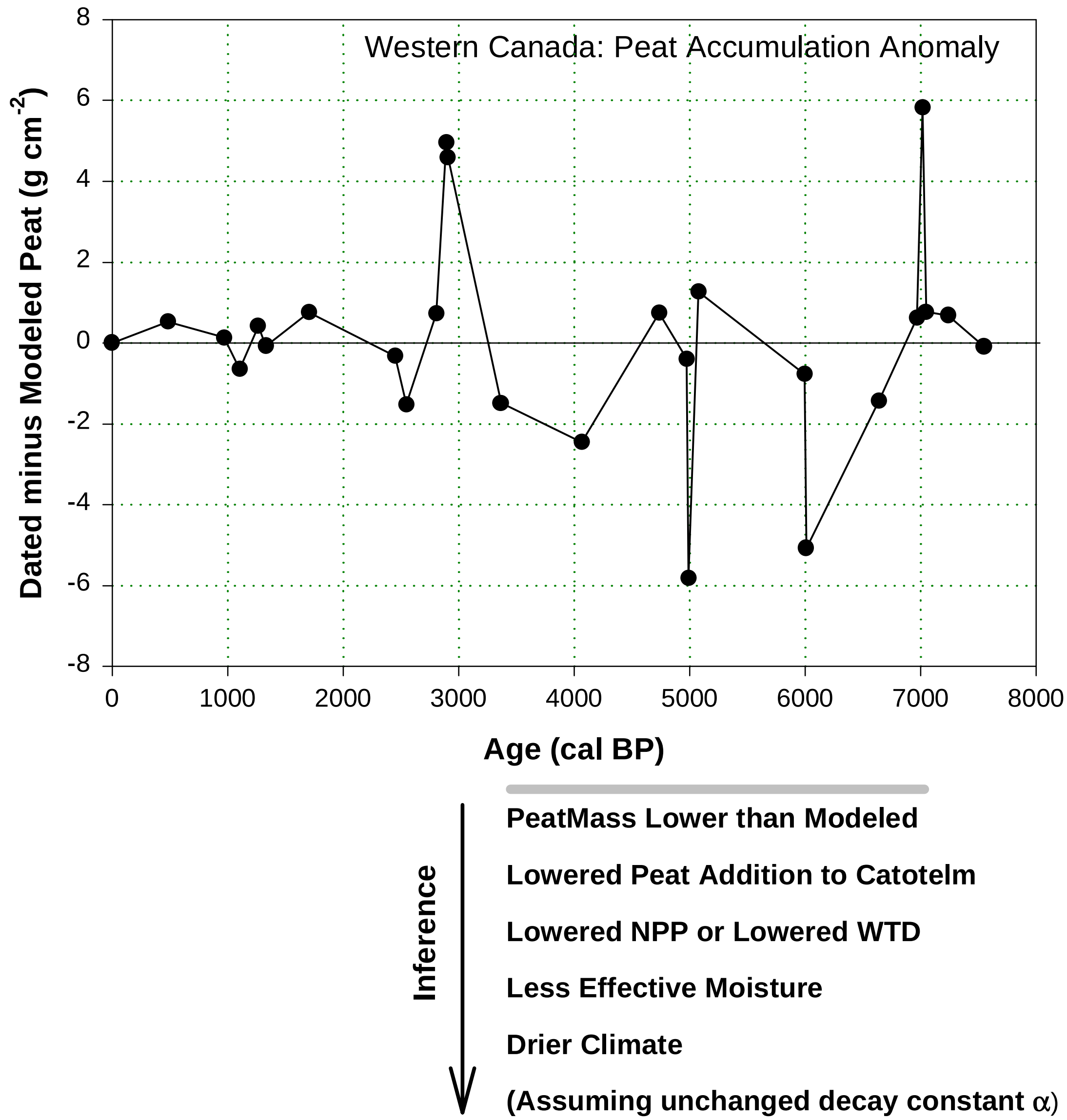


Figure 12. Difference between dated peat mass and modeled peat mass (using single exponential model, see Fig. 8) in continental western Canada (data from Vitt et al., in preparation). See note on this figure and Fig. 11 caption for detail about possible climate inference. The inferred relative dry period during the mid-Holocene (7000 – 3500 BP) is comparable with other independent paleoclimate records in this region, which may also be time-transgressive spatially (see Schweger and Hickman, 1989).

Temporal Variation of Peat Accumulation Rates

We can further analyse the Draved Mose peat profile to gain some understanding of long-term peat accumulation rates. Figure 13 illustrates the change of absolute peat accumulation rate as calculated from each dated point, with a single exponential regression and a linear regression. The present rate of accumulation at the top of the peat column is 0.069 cm yr^{-1}. At the base of the peat profile, the apparent rate is 0.015 cm yr^{-1}; the mean apparent rate over 6650 years is 0.037 cm yr^{-1}. The discrepancy between the modern rate and the apparent past rate does not necessarily reflect an actual change in catotelm production through time, but rather is caused by the decay through time of the older peat; thus, the peat formed between 6000 and 6500 years ago undoubtedly accumulated faster than is apparent from these data, but has been subject to 6000 years more decay than has the more

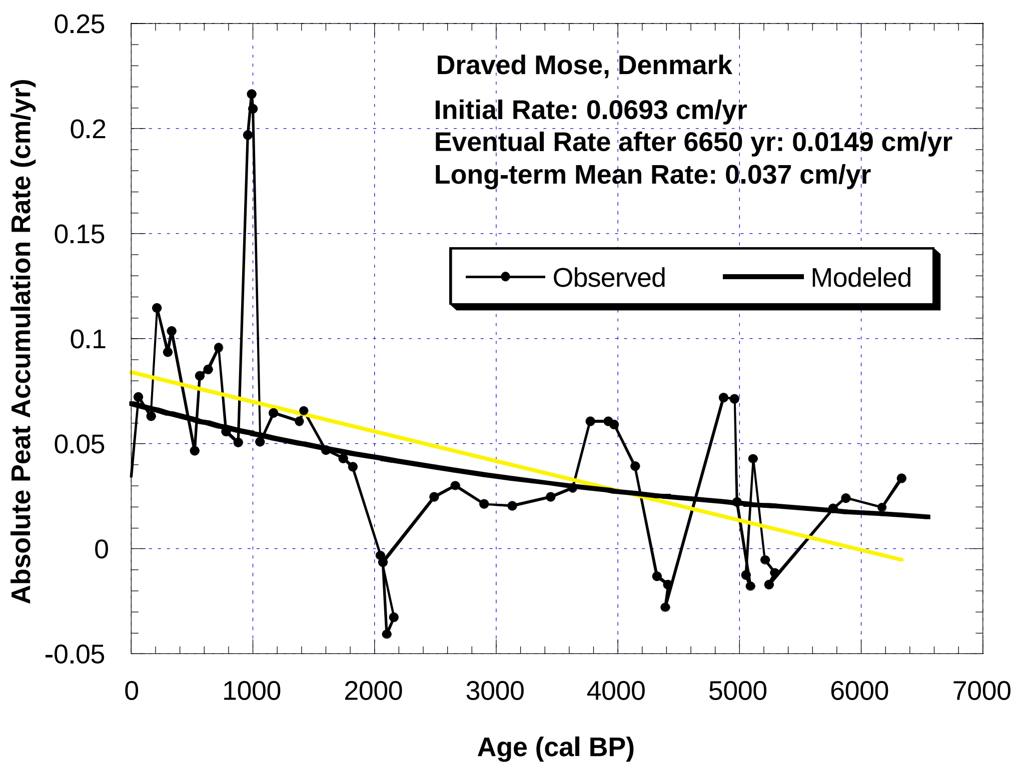


Figure 13. Change of absolute peat accumulation rate over time, using Draved Mose as an example (data from Aaby and Tauber, 1975). The wiggled line is calculated from each pair of dated horizons, the smooth curve is derived from modeled results using a single exponential model, and the straight gray line is a regression line of observed data points. This figure shows that the accumulation rate decreases over time from an initial maximum peat addition rate of 0.069 cm yr^{-1} to an eventual rate of 0.015 cm yr^{-1}, with a mean of 0.037 cm yr^{-1}. The rates are based on the measured smooth curve.

recently formed peat at the top of the profile. This gives the appearance of the catotelm production rate having changed through time, when in fact it is simply the result of aging of the peat.

Figure 7 shows the cumulative peat mass through time; its rate of accumulation appears to increase through time to the present, as a result of this same decay process operating on an ever-increasing peat column. This is a direct consequence of the asymptotic catotelm production and the exponential peat decay processes. Thus the usual practice of calculating peat accumulation rates by dividing peat depth/mass between two dated horizons by the time span can be misleading, particularly when comparing peat of different ages.

PEATLAND HYDROLOGY AND WATER-TABLE DYNAMICS

Water Balance Data and Water-Table Measurements

Because water-table depth (WTD) has been identified as one important factor controlling the rate of peat addition to the catotelm, we have explored and tried to understand the WTD dynamics at different temporal scales. It appears that there is no water balance data available on peatlands for western Canada. Thus it is difficult to implement a full quantitative WTD dynamics model as a driver for a dynamic peatland simulation model. There are some WTD measurements, however, from several peatlands in Alberta, mainly from fens. From these data, we might gain some insights about the WTD dynamics in fens as well as in bogs, and develop a semi-quantitative empirical model to link WTD with climate (effective moisture). The model validation could then be driven by proxy effective moisture from independent paleoclimate and paleolimnological data sets. This aspect of linking peatland hydrology with climate requires further exploration.

For central Alberta, there are peatland hydrograph data available from several University of Alberta theses and subsequent publications. Most of them have no on-site precipitation measurements, but precipitation data from nearby weather stations can be used. The limited WTD data from bogs might be of more value, to contrast the difference of WTD dynamics between bogs and fens, if any.

A. R. Szumigalski's thesis (1995) provides water-table hydrograph data for bogs, poor fens, wooded rich fens, sedge fens and extreme-rich fens in central Alberta, north of Edmonton. Observations were made over two growing seasons (1991 and 1992). With observations starting in early June 1991, the WTD reached a minimum (high water table) in late June and then increased (lower WT) gradually until mid-October. In 1992, the WTD gradually declined with fluctuations from beginning of observation (mid-May) to October. In both years, the bog had greatest WTD at 33-52 cm (mean 42 cm), followed by the wooded-rich fen at 29 cm (13-39 cm), the poor-fen at 24 cm (12-34 cm), the extreme-rich fen at 12 cm (35 to –5 cm, 1992 only), and the sedge fen at 0 cm (16 to -20 cm). All peatlands show about same magnitude fluctuations seasonally, except the extreme-rich fen, which had a dramatic drop-down in July and August 1992 from 0 to 35 cm. The WTD data were compared with precipitation data from the nearby Athabasca 2 weather station. In 1991, precipitation events over 10 mm were rare, but there was frequent precipitation in June, so the WTD curves are relatively smooth. In 1992, there were many precipitation events with more than 10 mm, and they spread over the entire growing season, which presumably caused the greater fluctuations in WTD and the gradual decline over the season. The bottom line is that WTD does vary with precipitation, so should be predictable from precipitation data at a seasonal time scale.

M.N. Thormann (1995, thesis) made observations, in part on the same peatlands, during the growing seasons of 1993 and 1994 (also Thormann and Bayley, 1997a). The peatlands include floating sedge fens, lacustrine sedge fens, riverine sedge fens, riverine marsh and lacustrine marsh. He also compared the WTD with precipitation records from the Athabasca 2 station. The years 1991 and 1992 were dry (258 and 235 mm May-August precipitation, respectively), but 1993 and 1994 were wet (434 and 322 mm May-August precipitation, respectively). In 1993, precipitation occurred primarily in late July and early August, with up to 55 mm in a single event. In contrast, WTD in fens was more stable in 1993 at about 0 cm, but marshes showed greater fluctuations with WTD as much as 30 cm above the peat surface in a riverine marsh and about 30 cm below in a lacustrine marsh. Precipitation was fairly evenly spread throughout the 1994 growing season, but WTD in fens showed greater fluctuations. Overall high WT in early season and low WT in late season occurred in 1994. Thormann (1995) indicated the bog WTD was 28-50 cm (mean 40 cm) in 1993 and 33-51 cm (mean 45 cm) in 1994, though no hydrograph data were presented.

H.L. Wind-Mulder (1998) made WTD and on-site precipitation measurements on a bog/poor fen complex near Seba Beech in central Alberta for four years from 1992 to 1995. She found that WTD in natural virgin peatlands is more consistent within and between years than it is in harvested peatlands. The WTD ranged from an annual mean of 20 cm in a dry year to 6 cm in wet years. In terms of WTD responses to precipitation events, water level in natural peatlands rises slowly in response to a rainfall event, while the harvested peatland water table responds dramatically to the rainfall event (p. 90). This implies that natural virgin peatlands have self-regulating mechanisms (buffering effect of the intact acrotelm) to resist external perturbations such as rainfall events, and that these mechanisms are absent in the harvested peatland. Presumably this mechanism relies on the non-linear interactions of different components within the peatland systems.

In summary, bogs have more temporally stable annual mean WTD, presumably due to their stronger self-regulating mechanism, despite variable precipitation over time. The fens WTD varied seasonally and inter-annually. Thormann et al. (1998) showed that in lacustrine fens, the WTD changed from 7.1 cm above the surface (1991) to 6.8 cm below the surface in 1992, 2.8 cm below in 1993, and 19.6 cm above again in 1994. In bogs, the WTD was always below the peat surface and changes from 40 cm in 1991 to 43.4 cm in 1992, 39.6 cm in 1993, and 44.5 cm in 1994.

Treed Fens at Wolf Creek, Alberta

Wolf Creek (30 km southeast of Edson, Alberta) is a treed fen. The site is one of several peatland sites for peatland drainage and forestry experiments (Hillman, 1997). Here we use the WTD and on-site precipitation measurements from a control site (#2). There are over 7500 observations from this site at one reading every 1.5 hours over 5 growing seasons from 1987 to 1991 (Fig. 14 shows the daily WTD and rainfall records). Fortunately, among these 5 years of measurements, 1988 was dry, with growing season (15 May to 3 October) precipitation of 298 mm compared to the climate normal of 361 mm from May to September (1951-80 climate record). 1990 on the other hand was a wet year, with 423 mm of precipitation for the same period (Fig. 15). The WTD response to these years was different, with the WTD reaching much greater values in the dry year than in the wet year, and with a much more pronounced mode of WTD values in the dry year than in the wet year, which can be seen to have had a more variable WTD.

Figure 16 is an alternative way to show the response of WTD to rainfall events. Usually WT rises abruptly after a rainfall event, and then gradually declines in the following days due to evapotranspiration and runoff; this response is clearly lagged behind the rainfall event. Figs. 17a, b and c show more details of the daily variations of WTD. The WT appears to peak at noon, presumably in response to insolation and temperature driven evapotranspiration (hydraulic lift). In springtime, WT rises abruptly in the late morning and remains high in the afternoon, but gradually declines into the night. This is probably caused by the melting of snow and ice on warm afternoons. On some summer days, WT seems to decline more rapidly in the afternoon, probably due to elevated evapotranspiration at that time.

Self-Organized WTD Dynamics in Peatlands and Scaling-up Issues

The WTD time series from Wolf Creek can be analysed statistically to gain some insights into the dynamic behaviour of peatland hydrology. The time-series of WTD observations seems to show a similar pattern of the abrupt rising of WT after a rainfall event and then gradual drawdown due to runoff and/or evapotranspiration at quite different time scales: 500 days, 100 days, 30 days, 1 week, and 1 day (Fig. 18). The power spectral analysis of this time series shows power-law behaviour of peatland hydrology dynamics. The preliminary results from each of two years of time-series records show that log (frequency) vs. log (power spectra) plots have a non-flat spectrum with scaling exponents of –1 to -2; this is quite different from white noise (flat spectrum; with scaling exponent close to 0). The scaling exponents are -1.2 for the 1990 time series and -1.4 for the 1988 time series (Fig. 19), suggesting that the power spectrum is proportional to $f^{-1.2}$ and $f^{-1.4}$, respectively, where f is frequency. Figure 20 shows the power spectra of all five-year WTD time series.

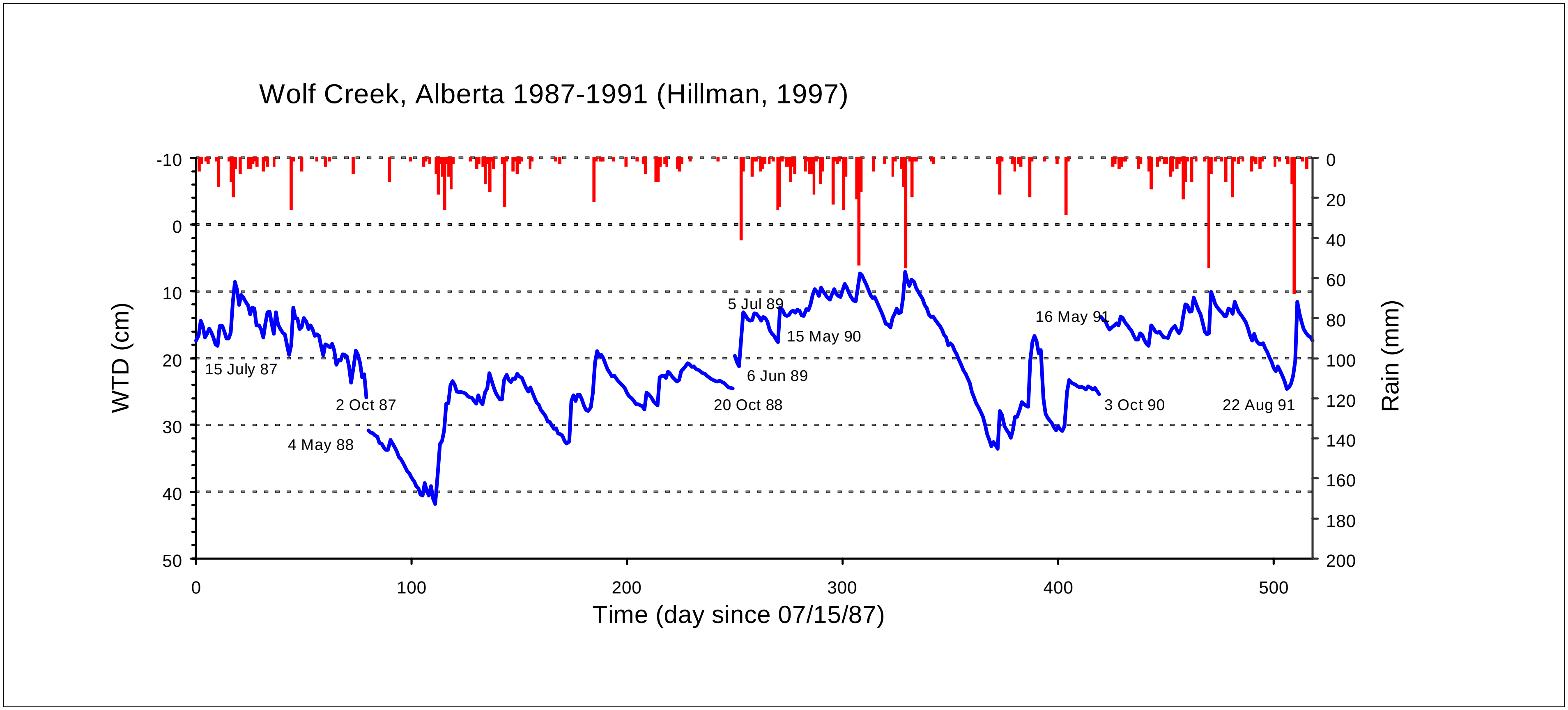


Figure 14. Hydrograph of water-table fluctuations (lower curves) and on-site precipitation (upper bars) at a treed fen site in central Alberta (control #2, Wolf Creek, Alberta) (data from Hillman, 1997). The original measurements were carried out every one and half hours, with total over 7500 readings over five growth seasons (mostly from May to October) from 1987 to 1991. The figure shows the daily variations of WTD and rainfall amount. The normal precipitation (1951-1980) for the region is 536 mm annually, 361 mm of which is during May to September and 150 mm of which are snowfalls. This period has a dry year (1988) with growing season rainfall of 298 mm and a wet year (1990) with growing season rainfall of 423 mm. See text for more discussion.

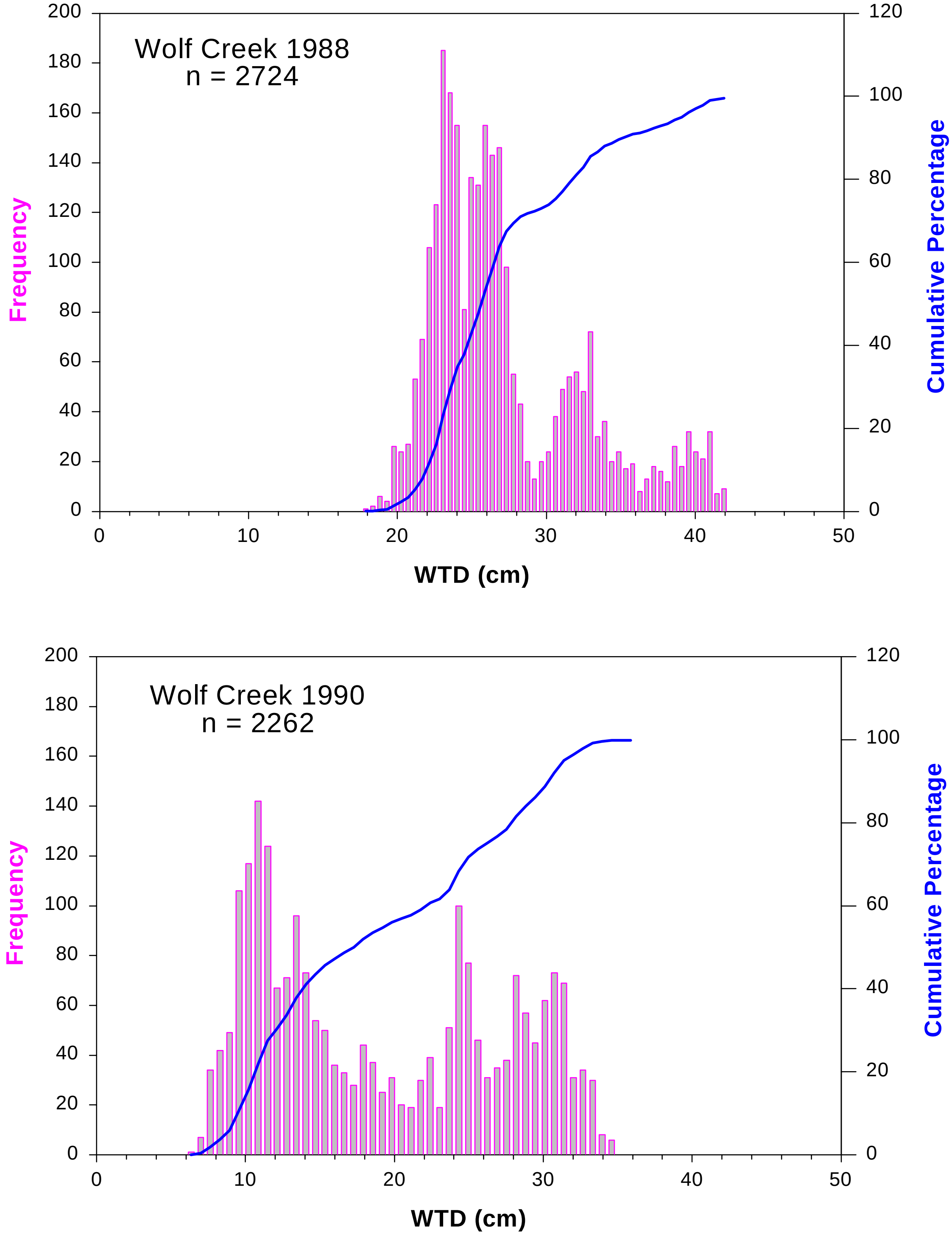


Figure 15. WTD frequency (bars) and cumulative percentage (curves) for 1988 and 1990 at Wolf Creek site (data from Hillman, 1997). In 1988, the WTD is at 22-28 cm for 60% of the time, and in 1990 water level is higher, wider spread but concentrated at 10-15 cm for 40% of the time.

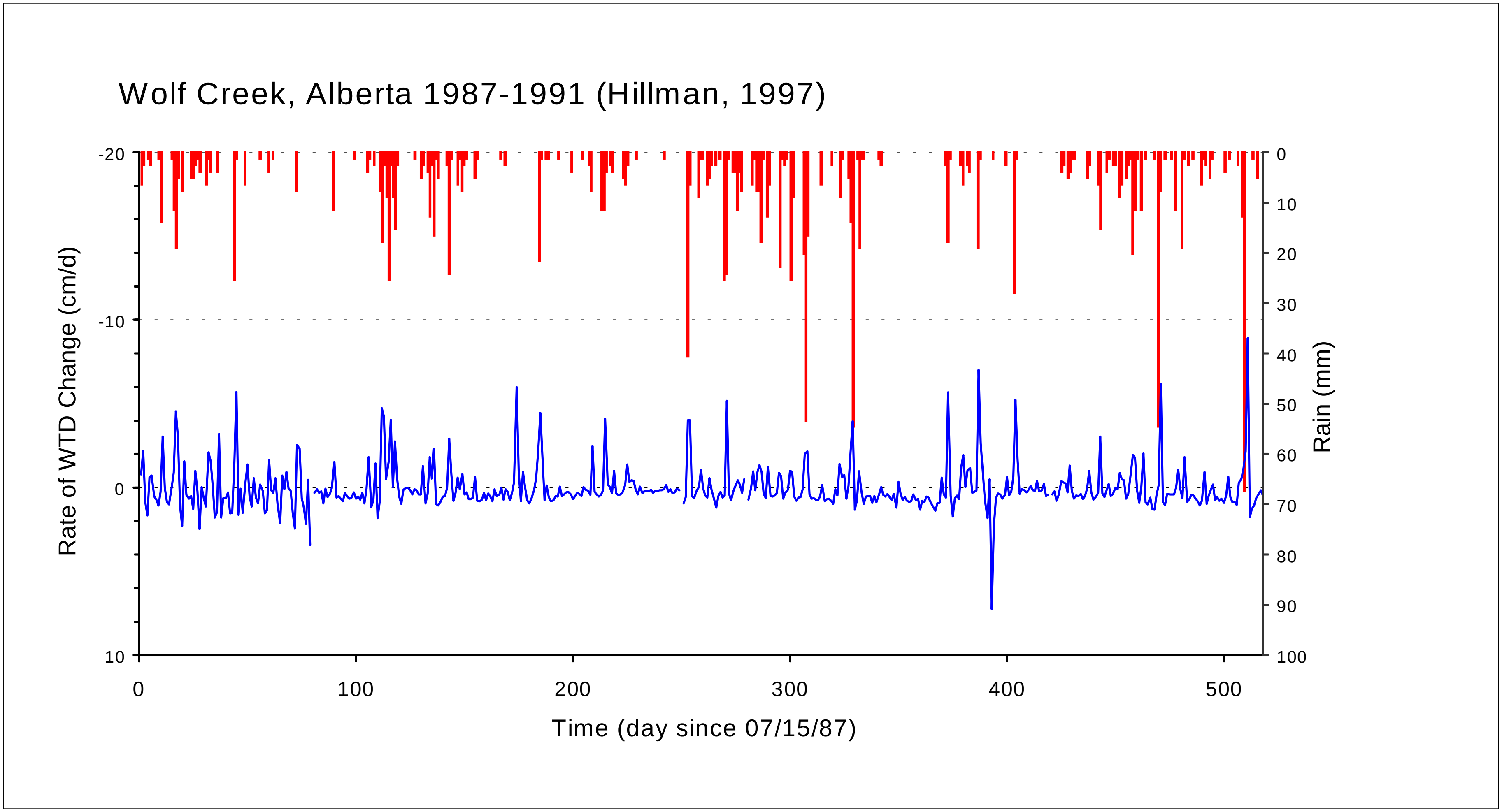


Figure 16. Daily rate of WTD change (curves) in response to rainfall events (bars) at Wolf Creek, Alberta (data from Hillman, 1997).

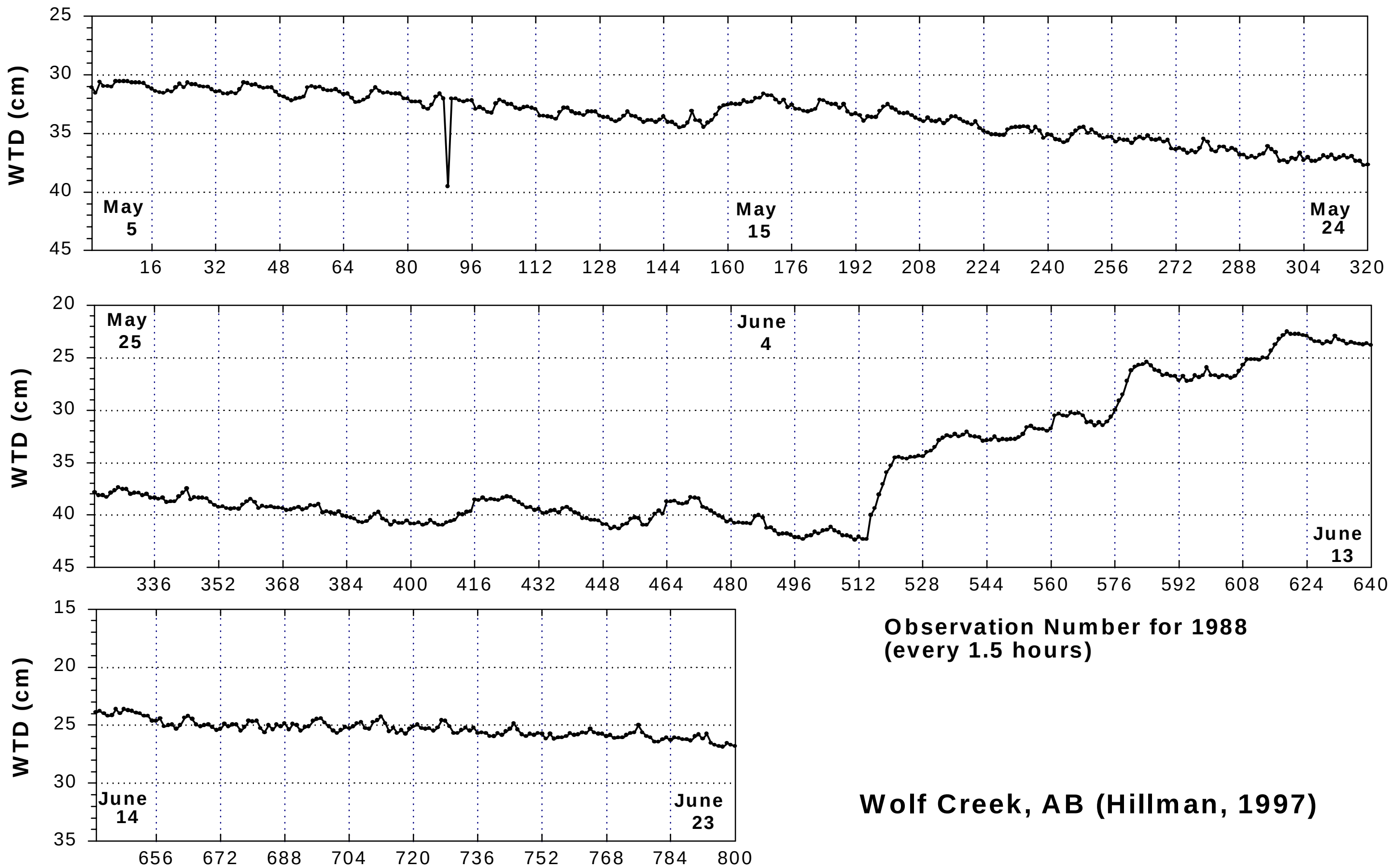


Figure 17. Detailed hydrographs showing the daily change of WTD during the growing season of 1988 at Wolf Creek, Alberta (data from Hillman, 1997). In springtime, the high water table tends to be around noon every day, probably due to melting of snow and ice. Vertical dotted lines are daily boundaries, representing mid-night. This page shows record from 5 May to 23 June.

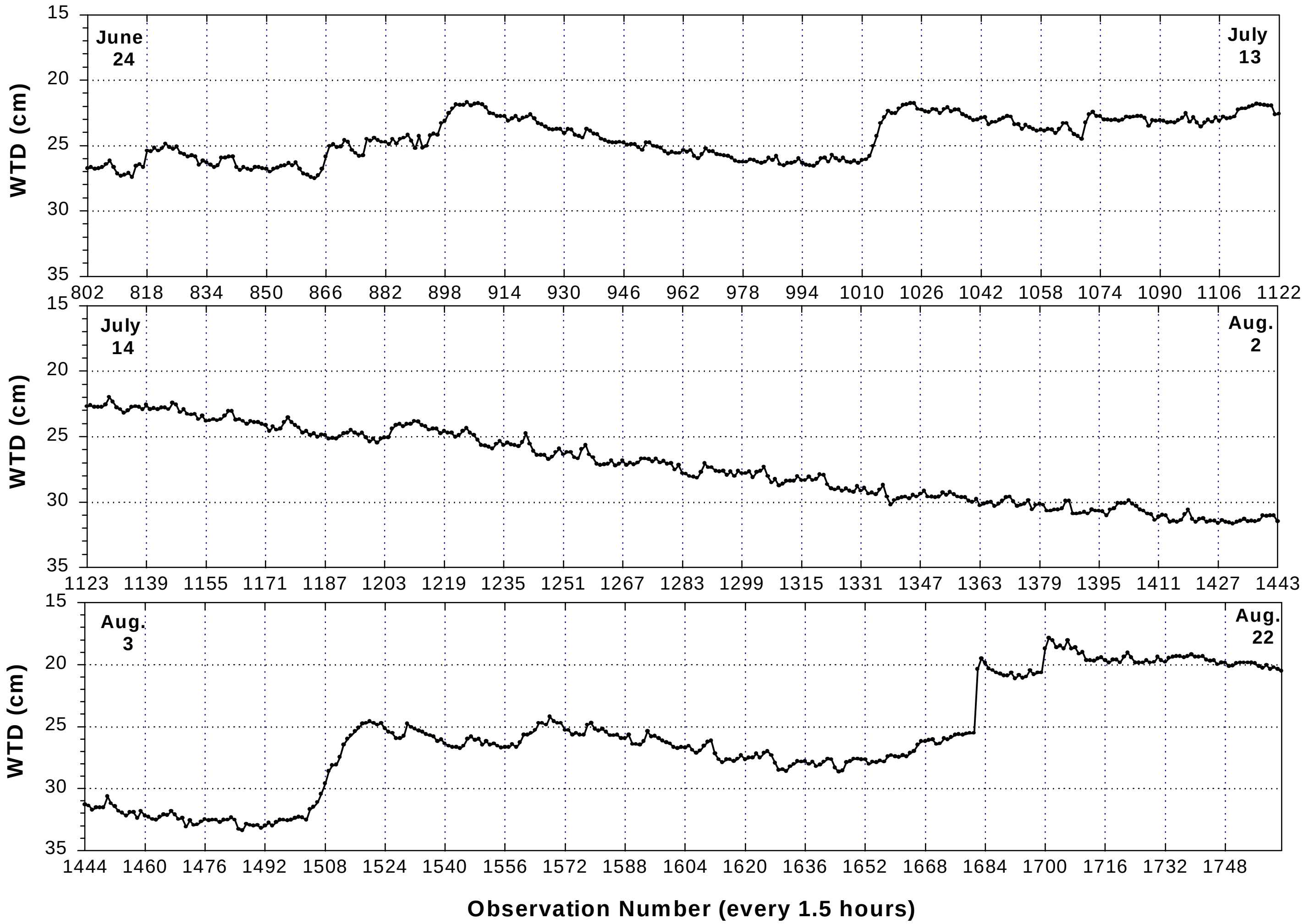


Figure 17. Continued. For summer from 24 June to 22 August.

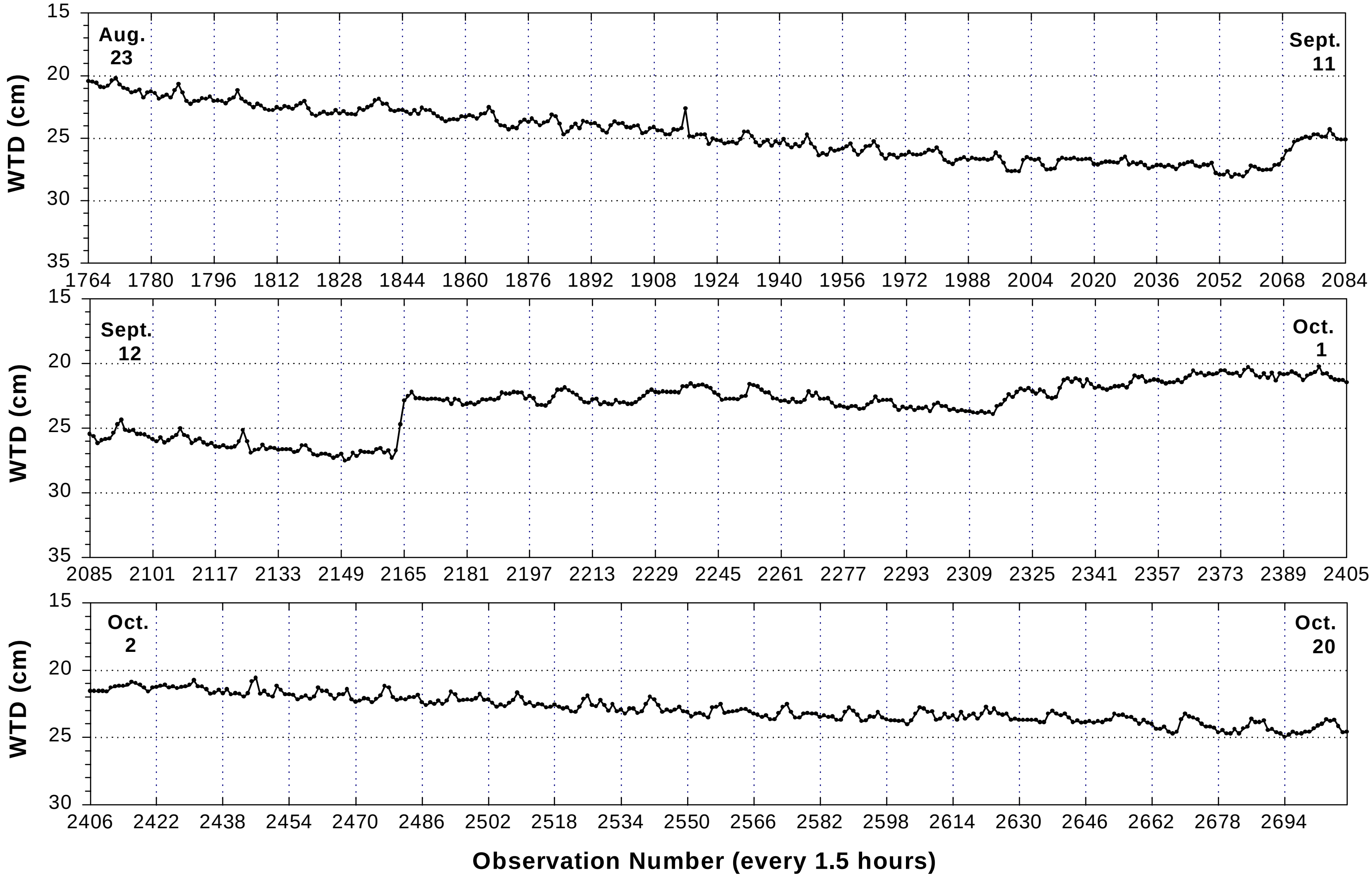


Figure 17. Continued. For autumn from 23 August to 20 October.

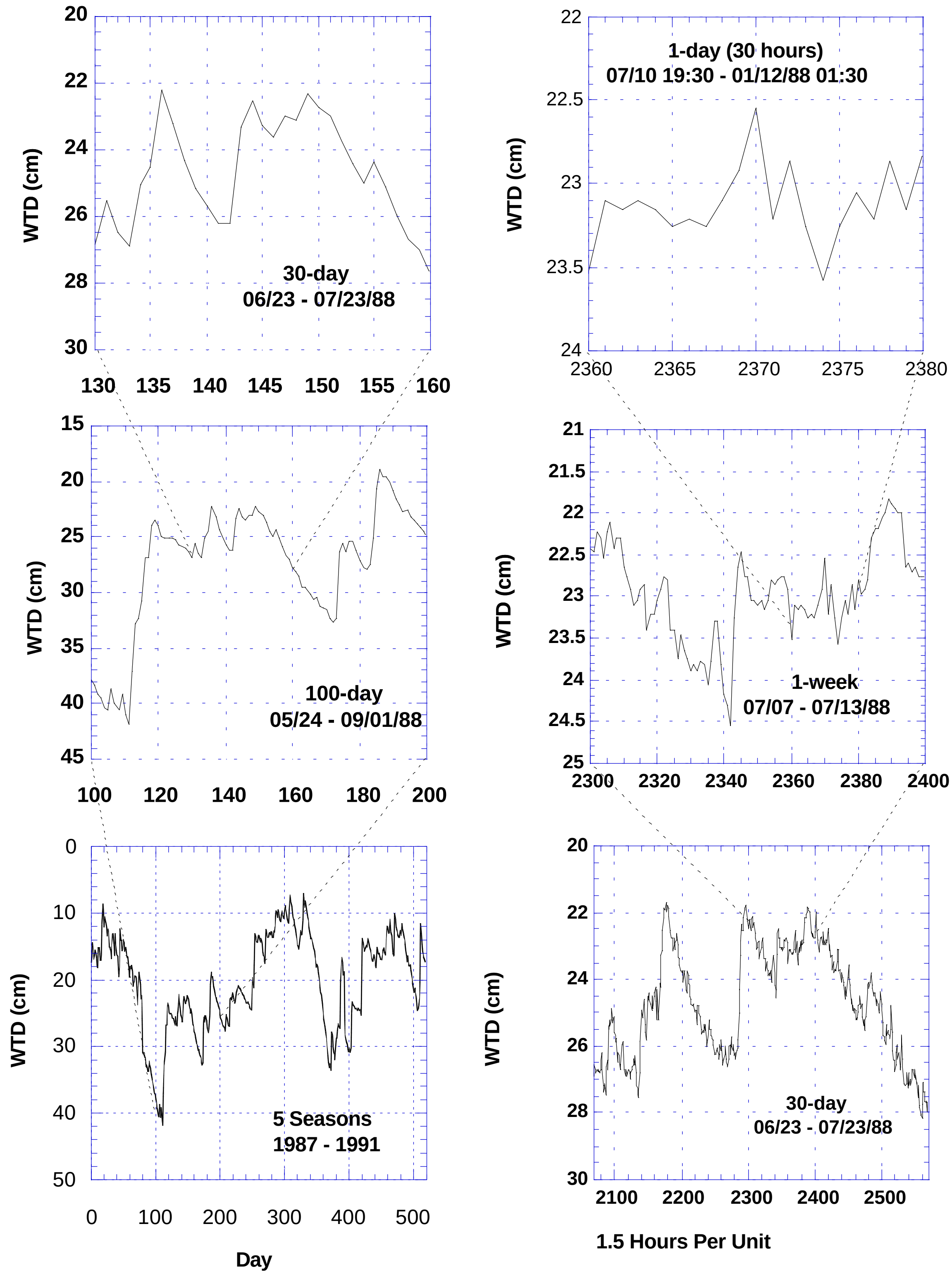


Figure 18. Self-similarity of water-table fluctuations in peatlands at Wolf Creek, Alberta (data from Hillman, 1997). Total record represents growing season (mostly from May to October) for the years 1987-1991.

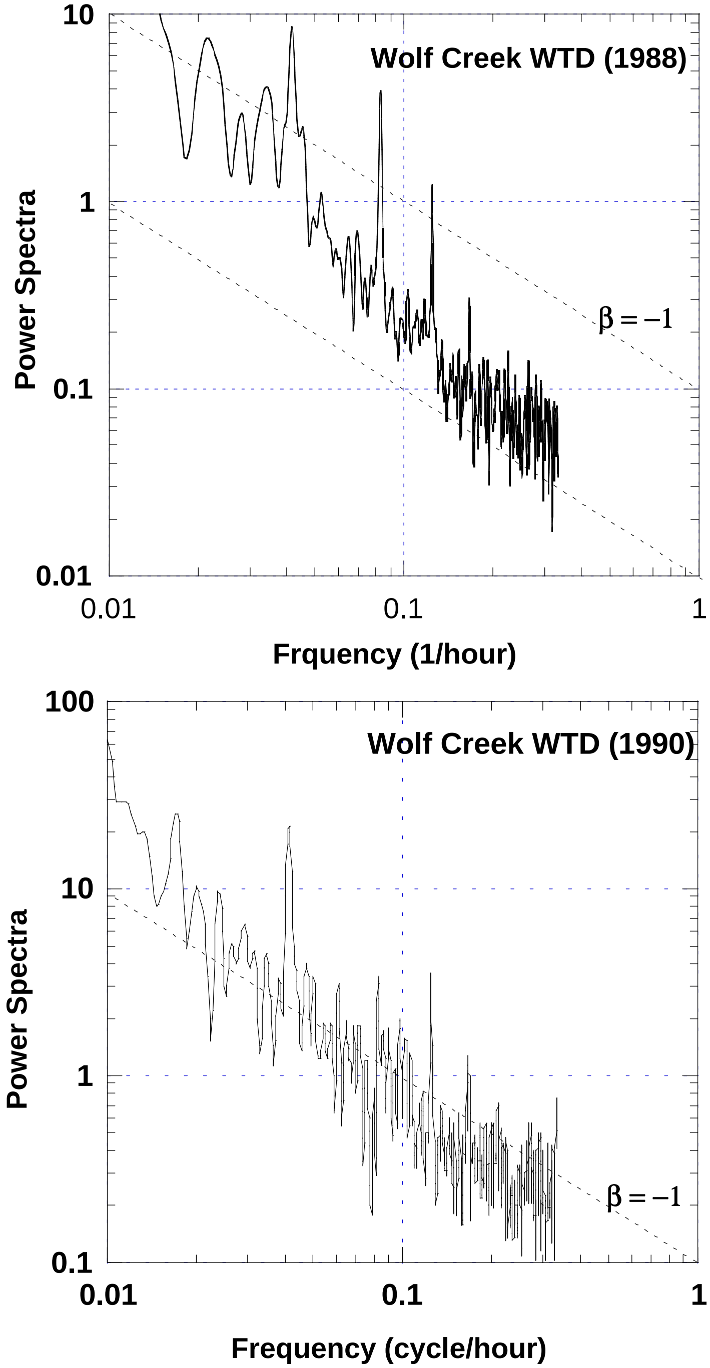


Figure 19. Power spectrum of the WTD time series for 1988 and 1990 in a peatland at Wolf Creek, Alberta (data from Hillman, 1997). The power spectrum is given as a function of frequency from time scales of 3 to 100 hours, as plotted on a log-log scale. The scaling exponent is about –1.4 and –1.2 for 1988 and 1990, respectively, suggesting a relation of $S(f) \propto 1/f^{-1.4}$ and $S(f) \propto 1/f^{-1.2}$. The power-law behavior of peatland WTD dynamics may suggest the presence of fractal-like, self-regulating mechanisms in peatlands.

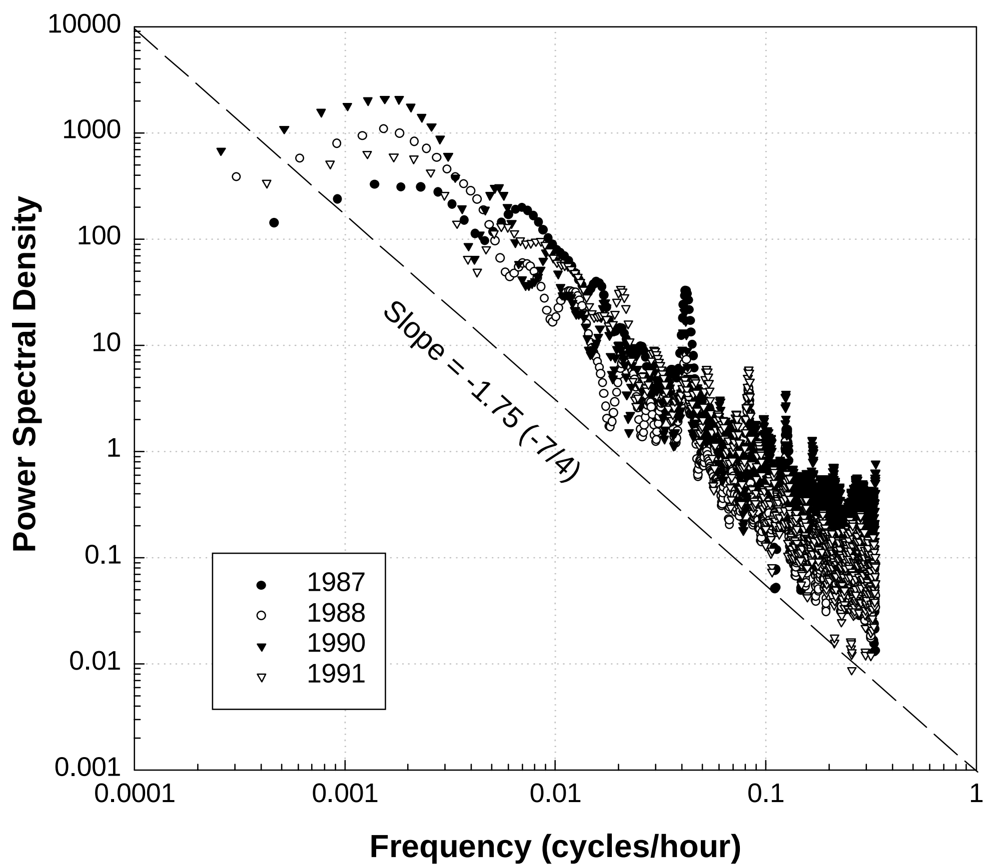


Figure 20. Power spectrum of the WTD time series for 1987, 1988, 1990 and 1991 in a peatland at Wolf Creek, Alberta (data from Hillman, 1997). The power spectrum is given as a function of frequency from time scales of 3 to 3000 hours, as plotted in a log-log scale. The scaling exponent is close to –1.75 (-7/4), suggesting a relation of $S(f) \propto 1/f^{-1.75}$.

These results suggest that self-similar and self-organized behaviours might exist in peatland WTD dynamics. The water-table fluctuations in peatlands seem to be scale-invariant, driven by scale-free internal dynamics. These dynamics might be related to non-linear responses of peatland hydrology to external perturbations, such as rainfall events. Such a fractal-like organization of peatlands has been demonstrated in a simulation model, using two coupled stochastic differential equations (for peat depth and WTD, respectively) (Hilbert et al., submitted). These findings may imply that WTD is driven either by self-organized criticality or by other scale-free (scale-invariant) internal peatland dynamics. This is consistent with the generally held belief that peatlands regulate their own water levels. If so, this has important implications for understanding peatland carbon dynamics and the effects of human disturbances.

Further statistical analysis is planned to compare structures of the power spectra between fens and bogs, between natural virgin peatlands and drained peatlands, and between natural peatlands and harvested peatlands. The anticipated results would be that this self-regulation mechanism only occurs in natural bogs and fens, is stronger in bogs than in fens, and is nearly absent in harvested and drained peatlands. If so, this would imply that harvest and drainage of peatlands destroys their internal self-regulating mechanisms, causing a lack of buffering capacity for these peatlands to resist external perturbations.

SUMMARY AND OUTSTANDING PROBLEMS

1. **Clymo's conceptual model.** Clymo's model is so far the only available model that captures the essential behaviors of peatland systems. This model also appears to be well supported by field data. In the absence of new data from continental peatlands (fens as well as bogs) suggesting otherwise, we will build our simulation model on this conceptual foundation.

2. **Eventual and current models.** The proposed final model is a project requiring well-designed implementation as well as further understanding of the basic peatland processes and their interactions. However, the current one-dimensional simulation model of vertical peatland growth is feasible based on our current understanding of peatlands dynamics.

3. **Selection of decay models and their implications**. The majority of peat profiles show concave age-depth/mass curves, and CO_2 and CH_4 have been observed to evolve from deep peat, suggesting decay in deep peat is an ongoing process. The three decay models (constant, linear and quadratic) seem not to be very different in their ability to account for the variations present in real data (Clymo et al., 1998). Single constant proportional decay rate models seem to be sufficient for the catotelm, considering the quality of available data. Limited decomposition data suggest that double constant proportional decay rate models are needed for the acrotelm, in order to adequately account for the rapid initial decay, due partly to very different processes, e.g., leaching, at this stage of decomposition.

4. **Parameter estimates and data availability.** It appears that estimated parameters (p, α) show a latitudinal gradient in Finland, both decreasing further north, which may be very well due to direct temperature effects (Clymo et al., 1998) or simply to growing season duration. A similar compilation and analysis of peatland data from western Canada would be of great value to gain understanding of the patterns and processes in peatlands of a *continental* region. Effective

moisture would likely be found to be a dominant factor because water is apparently a limiting factor and water availability is near or below the threshold required for the formation and maintenance of peatlands. New data from individual peat profiles with well-dated stratigraphy would be welcome to determine the similarities or differences between oceanic and continental peatlands.

5. **Environmental relations of peat addition and decay.** It appears that a more feasible approach would be to generate hypothetical functional relations, based on the limited available observations and biological theory. It is extremely difficult to generalize from the available data, because of the complexity of the factors involved and the sometimes conflicting results.

6. **Connecting acrotelm and catotelm through WTD.** It is very important to effectively implement the transfer of peat mass between acrotelm and catotelm. This includes applying the appropriate decay rates for transferred peat, and the bulk density values for depth – mass conversion. More detailed examination of stratigraphic data (bulk density variations, chemical composition as index of decay, etc.) around the boundary between acrotelm and catotelm would provide some useful insights and make the implementation more realistic.

7. **Dynamic WTD.** Lack of water balance data from this region prevents direct quantitative dynamic WTD modelling. On the other hand, such direct dynamic modelling might not be necessary, considering the very different temporal scales of observed hydrology data and modelled peatland dynamics. We are mainly interested in long-term peatland dynamics (decadal to millennial). A semi-quantitative empirical relationship between effective moisture and WTD at annual or decadal scales would be sufficient for our purposes, and in many ways perhaps more desirable. The scale-free internal dynamics of peatland hydrology will provide useful insights, which will simplify the implementation of WTD dynamics in the model, and aid in understanding peatland dynamics in general. WTD is arguably the most important single factor in determining pet accumulation rates, as it affects both production and decay. The model will therefore need to give WTD particular attention; a summary of potentially useful hydrological models is provided in the Appendix.

8. **Climate interpretation of peat profiles.** Given the very different effects of rate of peat addition (p) and decay rate (α) on the shape of peat age – depth curves, it appears that p is more likely responsible for the observed variations in the age-depth curves of peat profiles. Because of damped fluctuations of environmental conditions in catotelm peat, decay rate is much less

responsive to climate change. Because of the tendency of decay rate to have greater effect on older peat, change in decay rate is unlikely to be responsible for the relatively short-term (century-scale) rapid variation of peat accumulation. In contrast, the rate of peat addition is determined by plant productivity and decay rate in the acrotelm and is thus dependent on WTD, which very likely responds to changes in climate.

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REFERENCES CITED

Aaby, B. and Tauber, H. 1975. Rates of peat formation in relation to humification and local environment, as shown by studies of a raised bog in Denmark. *Boreas*, **4**: 1 -17.

Almquist-Jacobson, H. and Foster, D.R. 1995. Toward an integrated model for raised-bog development: Theory and field evidence. *Ecology*, **76**: 2503-2516.

Apps, M.J. and others. 1994. A carbon dynamics model of Canadian peatlands: Draft design document. Canadian Forest Service, Northwest Region, Edmonton, AB.

Arp, P.A. and Yin, X.W. 1992. Predicting water fluxes through forests from monthly precipitation and mean monthly air temperature records. *Canadian Journal of Forest Research*, **22**: 864-877.

Baker, J.H. 1972. The rate of production and decomposition of *Chorisodontium aciphyllum* (Hook. F. & Wils.) Broth. *Britain Antarctic Survey Bulletin*, **27**: 123-129.

Beven, K.J. and Kirkby, M.J. 1979. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences-Bulletin*, **24**: 43-69.

Beven, K.J. and Wood, E.F. 1983. Catchment geomorphology and the dynamics of runoff contributing areas. *Journal of Hydrology*, **65**: 139-158.

Campbell, C. and others (in preparation). Spatial patterning of net primary production and carbon sequestration in wetlands of western continental Canada.

Ciais, P., Tans, P.P., Trolier, M., White, J.W.C. and Francey, R.J. 1995. A large northern Hemisphere terrestrial CO_2 sink indicated by the $^{13}C/^{12}C$ ratio of atmospheric CO_2. *Science*, **269**: 1098-1102.

Clymo, R.S. 1978. A model of peat bog growth. In O.W. Heal and D.F. Perkins (eds.), *Production ecology of British moors and montane grasslands*. Springer, Berlin. pp. 183-223.

Clymo, R.S. 1984. The limits to peat bog growth. *Philosophical Transactions of Royal Society, London*, **303B**: 605-654.

Clymo, R.S. 1992. Models of peat growth. *Suo*, **43**: 127-136.

Clymo, R.S., Turunen, J. and Tolonen, K. 1998. Carbon accumulation in peatland. *Oikos*, **81**: 368-388.

Dammon, A.W.H. 1986. Hydrology, development, and biogeography of ombrogenous peat bogs with special reference to nutrient relocation in a western Newfoundland bog. *Canadian Journal of Botany*, **64**: 384-394.

Fan, S., Gloor, M., Mahlman, J., Pacala, S., Sarmiento, J, Takahashi, T. and Tans, P. 1998. A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science*, **282**: 442-446.

Forrester, J.W. 1961. Industrial dynamics. MIT Press, Cambridge, Ma. 464 p.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, **1**: 182-195.

Goulden, M.L., Wofsy, S.C., Harden, J.W., Trumbore, S.E., Crill, P.M., Gower, S.T., Fries, T., Dauber, B.C., Fan, S.-M., Sutton, D.J., Bazzaz, A. and Munger, J.W. 1998. Sensitivity of boreal forest carbon balance to soil thaw. *Science*, **279**: 214-217.

Guertin, D.P., Barten, P.K. and Brooks, K.N. 1987. The peatland hydrologic impact model: development and testing. *Nordic Hydrology*, **18**: 79-100.

Halsey, L.A., Vitt, D.H. and Bauer, I.E. 1998. Peatland initiation during the Holocene in continental western Canada. *Climatic Change*, **40**: 315-342.

Heal, O.W., Latter, P.M. and Howson, G. 1978. A study of the rates of decomposition of organic matter. In O.W. Heal and Perkins, D.F. (eds.), *Production ecology of British moors and montane grasslands*. Springer, pp. 136-159.

Hilbert, D.W., Roulet, N. and Moore, T. (submitted). Modelling and analysis of peatlands as dynamical systems. *Journal of Ecology*.

Hillman, G.R. 1997. Effects of engineered drainage on water tables and peat subsidence in an Alberta treed fen. In C.C. Trettin, M.F. Jurgensen, D.F. Grigal, M.R. Gale and J.K. Jeglum (eds.), *Northern Forested Wetlands: Ecology and management*. CRC Lewis Publishers, New York. Pp. 253-272.

Hogg, E.H., Lieffers, V.J. and Wein, R.W. 1992. Potential carbon losses from peat profiles: Effects of temperature, drought cycles, and fire. *Ecological Applications*, **2**: 298-306.

Houghton, R.A., Davidson, E.A. and Woodwell, G.M. 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. *Global Biogeochemical Cycles*, **12**: 25-34.

Ingram, H.A.P. 1978. Soil layers in mires: function and terminology. *Journal of Soil Science,* **29**: 224-227.

Ingram, H.A.P. 1982. Size and shape in raised mire ecosystems: a geophysical model. *Nature*, **297**: 300-303.

Ivanov, K.E. 1981. Water movement in mirelands. (translated from Russian by A. Thomson and H.A.P. Ingram) Academic Press, Toronto, 276 p.

Jenny, H., Gessel, S. and Bingham, F.T. 1949. Comparative study of decomposition rates of organic matter in temperate and tropical regions. *Soil Science,* **68**: 419-432.

Korhola, A., Alm, J., Tolonen, K., Turunen, J. and Jungner, H. 1996. Three-dimensional reconstruction of carbon accumulation and CH_4 emission during nine millennia in a raised mire. *Journal of Quaternary Science*, **11**: 161-165.

Kurz, W.A. and Apps, M.J. (in press). A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. *Ecological Applications*.

Kurz, W.A., Apps, M.J., Webb, T.M. and McNamee, P.J. 1992. The carbon budget of the Canadian forest sector: Phase I. Northwest Region, Forestry Canada, Information Report NOR-X-326.

Lauenroth, W.K., Urban, D.L., Coffin, D.P., Parton, W.J., Shugart, H.H., Kirchner, T.B. and Smith, T.M. 1993. Modeling vegetation structure-ecosystem process interactions across sites and ecosystems. *Ecological Modelling*, **67**: 49-80.

Mitsch, W.J. and Gosselink, J.G. 1993. Wetlands. 2nd Edition, Van Nostrand Reinhold, New York.

Moore, T.R. 1989. Growth and net production of Sphagnum at five fen sites, subarctic eastern Canada. *Canadian Journal of Botany*, **67**: 1203-1207.

Moore, T.R. and Knowles, R. 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science*, **69**: 33-38.

Moore, T.R., Roulet, N.T. and Waddington, J.M 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. *Climatic Change*, **40**: 229-245.

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology*, **44**: 322-331.

Parton, W.J. 1978. Abiotic section of ELM. In G.S. Innis (ed.), *Grassland Simulation Model*, Springer, New York. pp. 31-53.

Poiani, K.A., Johnson, W.C., Swanson, G.A. and Winter, T.C. 1996. Climate change and northern prairie wetlands: Simulations of long-term dynamics. *Limnology and Oceanography*, **41**: 871-881.

Poiani, K.A. and Johnson, W.C. 1993. A spatial simulation model of hydrology and vegetation dynamics in semi-permanent prairie wetlands. *Ecological Applications*, **3**: 279-293.

Post, W.M., Emanuel, W.R., Zinke, P.L. and Stangenberger, A.G. 1982. Soil carbon pools and world life zones. *Nature*, **298**: 156-159.

Potter, C.S. 1997. An ecosystem simulation model for methane production and emission from wetlands. *Global Biogeochemical Cycles*, **11**: 495-506.

Priestly, C.H.B. and Taylor, R.J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, **100**: 81-92.

Rochefori, L., Vitt, D.H. and Bayley, S.E. 1990. Growth, production, and decomposition dynamics of *Sphagnum* under natural and experimentally acidified conditions. *Ecology*, **71**: 1986-2000.

Rosswall, T. 1974. Decomposition of plant litter at Stordalen – a summary. In J.G.K. Flower-Ellis (ed.), *International Biological Programme – Swedish tundra biome progress report 1973*. Swedish Natural Science Research Council, pp. 207-212.

Sharpley, A.N. and Williams, J.R. (eds.). 1990. EPIC – Erosion/productivity impact calculator: 1. Model documentation. USDA Tech. Bull. 1768.

Schimel. D.S. 1995. Terrestrial ecosystems and the carbon cycle. *Global Change Biology*, **1**: 77-91.

Schweger, C.E. and Hickman, M. 1989. Holocene paleohydrology of central Alberta: testing the general-circulation-model climate simulations. *Canadian Journal of Earth Sciences*, **26**: 1826-1833.

Siegel. D.I., Reeve, A.S., Glaser, P.H. and Romanowicz, E.A. 1995. Climate-driven flushing of pore water in peatlands. *Nature*, **374**: 531-533.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J. and Spurk, M. 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon*, **40** (in press).

Szumigalski, A. R. 1995. Production and decomposition of vegetation along a wetland gradient in central Alberta. M.Sc. Thesis, Department of Botany, University of Alberta, Edmonton, Alberta, 117 p.

Szumigalski, A.R. and S.E. Bayley. 1996. Decomposition along a bog to rich fen gradient in central Alberta, Canada. *Canadian Journal of Botany*, **74**: 573-581.

Thormann. M.N. 1995. Primary productivity and decomposition in fens and marshes in the boreal region of Alberta, Canada. M.Sc. Thesis, Department of Botany, University of Alberta, Edmonton, Alberta. 196 p.

Thormann, M.N. and Bayley, S.E. 1997a. Aboveground plant production and nutrient content of the vegetation in six peatlands in Alberta, Canada. *Plant Ecology*, **131**: 1-16.

Thormann, M.N. and Bayley, S.E. 1997b. Aboveground net primary production along a bog-fen-marsh gradient in southern boreal Alberta, Canada. *Ecoscience*, **4**: 374-384.

Thormann, M.N. and Bayley, S.E. 1997b. Decomposition along a moderate-rich fen-marsh peatland gradient in boreal Alberta, Canada. *Wetlands*, **17**: 123-137.

Thormann, M.N., Bayley, S.E. and A.R. Szumigalski, 1998. Effects of hydrologic changes on aboveground production and surface water chemistry in two boreal peatlands in Alberta: Implications for global warming. *Hydrobiologia*, **362**: 171-183.

Trumbore. S.E., Chadwick, O.A. and Amundson, R. 1996. Rapid exchange between soil carbon and atmospheric carbon dioxide driven by temperature change. *Science*, **272**: 393-396.

Vitt, D.H., Halsey, L.A. and Zoltai, S.C. 1994. Bog landforms of continental western Canada in relation to climate and permafrost patterns. *Arctic and Alpine Research*, **26**: 1-13

Vitt, D.H. et al. (in preparation). Spatial and temporal trends in carbon sequestration in peatlands of continental western Canada through the Holocene.

Warner, B.G., Tolonen, K. and Tolonen, M. 1991. A postglacial history of vegetation and bog formation at Point Escuminac, New Brunswick. *Canadian Journal of Earth Sciences*, **28**: 1572-1582.

Warner, B.G., Clymo, R.S. and Tolonen, K. 1993. Implications of peat accumulation at Point Escuminac, New Brunswick. *Quaternary Research*, **39**: 245-248.

Wieder, R.K. and Lang, G.E. 1982. A critique of the analytical methods used in examining decomposition data obtained from litter bags. *Ecology*, **63**: 1636-1642.

Wildi, O. 1978. Simulating the development of peat bogs. *Vegetatio*, **37**: 1-17.

Wind-Mulder, H.L. 1998. Towards the restoration of harvested peatlands: Comparisons of harvested and natural peatlands and examination of revegetation techniques. University of Alberta, Department of Biological Sciences, Ph.D. Dissertation. 211 p.

Winston, R.B. 1994. Models of the geomorphology, hydrology, and development of domed peat bodies. *Geological Society of America Bulletin*, **106**: 1594-1604.

APPENDIX: A Survey of Soil Moisture and Water-Table Models

1. TOPMODEL and related models

A physically based, quasi-distributed hydrological simulation tool (Beven and Kirkby, 1979; Beven and Wood, 1983). The model uses digital elevation data (DEM) as well as spatial information on soil, rain and vegetation for the prediction of soil moisture distribution in the catchment.

Basic assumptions:

TOPMODEL is a set of simple concepts for modeling catchment response involving primarily subsurface flows and dynamic saturated contributing areas. It uses physically based parameters and a spatially distributed topographic index computed from a digital terrain model (DTM). It separates the calculation of spatially averaged dynamics of the catchment and local soil moisture accounting.

Model structure:

There are five basic components in TOPMODEL:

1. initiation based on observed flow;
2. root zone storage, S_r, with maximum storage S_{rmax}, which should be filled before infiltration to the unsaturated zone;
3. distribution of soil moisture deficits over the catchment. Rather than operating on a spatial grid, TOPMODEL evaluates soil moisture deficits at any point i, S_i, for the discrete values of the frequency distribution of the soils/topographic index, $\ln(a_i/T_i\tan\beta_i)$, where a_i is the local upslope drainage area, β_i is the local slope angle and T_i denotes local saturated transmissivity. The static relation between the local values of deficits and averaged over the catchment deficit, S_t has the form: $S_i = S_t + m[\gamma - \ln(a_i/T_i\tan(\beta_i))]$;
4. calculate vertical flux rate recharging the saturated zone; and
5. describe the dynamic change of the catchment average soil moisture deficit, S_t.

In the model, the surface layer of the soil may become saturated in two ways: (1) through excess of rainfall rate over the available storage (saturation from above), and (2) through the rise of the water table level due to drainage from upslope (saturation from below). There are four major ways to form run-off: (1) rainfall intensity exceeds infiltration or storage capacity resulting in overland flow over the entire basin, (2) rainfall intensity exceeds infiltration or storage capacity on a variable area of near-saturated soils, (3) rain falls on stream channels and completely saturated soils, and (4) downslope lateral flow of saturated or unsaturated soil water.

Data requirements:

1. physical parameters: areas of the subcatchments, channel network, stream lengths, slopes, elevation, aspect, and the upslope contributing area from which the flow drains into a given point.
2. Hydrological parameters: infiltration parameters, interception storage specifying the volume to be filled before flow enters the subsurface storage, rainfall events, evapotranspiration, hydrological properties of soil and type of land cover.

The topographic index, in the form of $\ln(a/T\tan\beta)$, is the major attractive feature of the model. The model has a time step of 15 minutes and a spatial resolution of 30 m. TOPMODEL has been integrated with a GIS (usually raster-based GRASS). Also the RHESSys (Regional HydroEcological Simulation System) used in the BOREAS project was based on a combination of algorithms from TOPMODEL, MT-CLIM and FOREST-BGC models. All these models are not grid-based, rather patch- or hillslope-based, partly for computational efficiency.

2. CASA (Carnegie-Ames-Stanford Approach) – modified wetland version

Potter (1997) modified the upland soil moisture submodel in the original CASA model and discussed the basic features of this wetland version WTD submodel. In this model, the average WTD is a function of soil moisture holding capacity, depth to impermeable layers, rainfall, evapotranspiration, and run-on and run-off. It is derived from the existing soil decomposition algorithms of CASA model and has either a daily or monthly time step. The objective of the first version of this model is to simulate the timing of changes in WTD.

The model has three soil layers: S_0, surface ponded water layer (water depth); S_1, surface organic layer; S_2, surface organic mineral layer; and S_3, subsurface mineral layer. The layered soil temperature and WTD are modeled as a function of moisture inputs and field capacity of poorly drained soils. The model estimates the potential evapotranspiration (PET) using algorithms as modified from Priestly and Taylor (1972), $PET = a*(Ta + b)*Rs$, and the rainfall interception by vegetation canopy, $PPT = 0.05\ Vc\ \min(PEP, PPT)$.

Soil water balance is the difference between precipitation (or volumetric percolation) inputs and PET outputs for each layer. It is assumed that all moisture inputs and outputs progress from the surface layer downward. Each layer is assumed to be internally homogeneous with respect to water holding capacity. Inputs from rainfall, snowmelt and water run-on can recharge the soil layer to pore saturation level. Porosity, expressed on a percentage basis, is uniform for the entire soil profile. Excess water percolates through to lower layers until they are filled and water accumulates in a ponded surface layer.

The water run-on rate of surface water to a grid cell location may be either (1) prescribed where measurement information exists, or (2) estimated as a function of flow amount and delay factor related to the moisture retention capacity of the surrounding catchment/sediment. Potter (1997) used a hypothetical run-on flow to simulate CH_4 flux in a wetland.

3. WET_SIM 2.0

Poiani and Johnson (1993) and Poiani et al. (1996) developed a simple wetland hydrology simulation model to deal with semi-permanent prairie wetlands. The major change in Poiani et al. (1996) is from site-specific empirical relationships for surface runoff, seepage inflow, and spring refill caused by snowmelt, to more general, physically-based calculations. Their hydrology submodel calculates monthly water level (only above the surface) using a water budget accounting procedure. The starting water level is assigned for the first month, and the model converts this elevation to water volume given a stage-volume relationship. The water volumes are then calculated monthly, and the volume converts back to water surface elevation for output to a vegetation submodel. The time step is daily.

It uses the budget equation: Vt = Vt-1 + P + M + SO + SS – ET. The evapotranspiration (ET) is calculated from potential ET using the Blaney-Criddle method. The pET is a function of average monthly temperature, crop growth stage coefficient, number of daylight hours per year, and total number of daylight hours for this latitude. Precipitation is treated as snow when monthly temperature is less than 0^oC, assuming uniformed distribution.

Surface runoff and subsurface inflow to the wetland from the contributing watershed are calculated using the Erosion Productivity Impact Calculator (EPIC) model (Sharply and Williams, 1990). Precipitation remaining after runoff enters the soil profile. Flow from one layer to a lower layer occurs when soil water content exceeds field capacity, and excess water drains from the layer until storage returns to field capacity (13%).

4. SOILWAT: Abiotic Section of Grassland Simulation Model (ELM)

Parton (1978) developed a water-flow submodel at a daily time step in the ELM grassland model for IBP. The processes simulated through plant canopy and soil layers include rainfall interception, infiltration of water into soil, rapid and slow soil-water drainage, and evaporation of water from the plant canopy and the soil layers. It uses arbitrary numbers of soil layers, with depth and soil type specified for each layer. It mainly deals with allocation of precipitation, and evapotranspiration water loss.

The generalized version of the SOILWAT model has been used in the integration of vegetation models (STEPPE, ZELIG, or B\VEGOMAT), the CENTURY model and the Water model (Lauenroth et al., 1993). The daily time step outputs are aggregated for exchange with the vegetation and nutrient-cycling modules.

5. ForHyM

Arp and Yin (1992) developed a process-based model to simulate the water fluxes through forests. The model is driven by monthly air temperature, monthly precipitation, and mean snow fraction of total precipitation. The model also requires other site-specific data, including proportions of coniferous and deciduous trees in the forest, thickness of soil layers, and clay fraction of mineral soils.

6. PHIM (Peatland Hydrologic Impact Model)

Guertin et al. (1987) developed the PHIM to simulate the hydrology of natural peatland. The model is designed to predict changes in stormflow, low flow and water yield caused by changes in a watershed such as peatland drainage, peat harvesting, timber harvesting and combination of these land uses. PHIM is a generalized, deterministic, continuous simulation model, which is mainly physically based. There are three submodels based on different land cover types: natural peatland, mined peatland and mineral soil peatland submodels.

The model requires inputs from climatic data (precipitation, maximum and minimum daily air temperature) and descriptive landscape information (e.g., vegetation type, canopy cover, soil depth). The model has been verified using data from three watersheds in northern Minnesota.