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Modelling long-term peatland dynamics. I. Concepts, review, and proposed design

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Abstract

This article reviews the existing conceptual and simulation models for peatlands and develops a model framework for simulating peatland dynamics in boreal regions. Clymo's peat bog growth model has been used as the conceptual foundation in published simulation models, but in these models the structural and functional layers of litter, acrotelm and catotelm are not dynamically integrated. Organic-matter decomposition processes in these layers operate at different rates over various time scales. The processes in more active litter and acrotelm layers largely pre-determine the net peat accumulation in the catotelm. On the basis of evaluating litter and peat-core data, we propose a model design that connects different layers through changing water-table depth, driven by effective moisture. The model framework includes single and double negative exponential decay functions that together produce net peat accumulation or degradation and hence carbon balance. The model is designed to be generic in structure, but can be validated using estimated parameters and observed peat accumulation data for continental western Canada. The objectives of this model exercise are (1) to understand the interactions of different biological and environmental factors in boreal peatlands, and (2) to realistically simulate peat accumulation and decay over the last several millennia using proxy paleoclimate data as drivers and peat profiles for validation. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Northern (boreal and subarctic) peatlands have accumulated on average at a 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 (that includes wetlands) is estimated at 610 Pg (Schimel, 1995), whereas the

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production and respiration flux of global vegetation and soils (including wetlands) is on the order of 60 Pg/year (Schimel, 1995). Although northern peatlands have a relatively low average net accumulation rate at ~ 20 g C per m^2 per year (e.g. Gorham, 1991; Vitt et al., 2000), the relatively large size of their C pool raises concerns that northern peatlands may become significant sources for atmospheric C under a changing climate.

There is also little known about the variability of peatland C fluxes and sequestration through time, especially in response to climate change (Moore et al., 1998). Change of peatlands between C sources (due to net peat degradation) and sinks (due to net peat accumulation) through time would affect significantly 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. Some of the C flux from peatlands to the atmosphere, however, is in the form of highly radiatively active methane (CH_4) rather than CO_2 (Moore and Knowles, 1989; Moore and Roulet, 1993).

Temperature plays a dominant role in control of C dynamics in upland mineral soils, with the decay rate of soil organic matter and consequent C release to the atmosphere increasing with increasing temperature (Trumbore et al., 1996; but see Giardina and Ryan, 2000), as well as through soil thaw in northern ecosystems (Goulden et al., 1998). In many regions, temperature also exerts a strong influence on primary productivity and hence on root and detrital C influx to the soil. In northern peatlands, hydrological changes are also known to 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 photosynthetic production of living plants atop the acrotelm (surface and upper oxic layer) and decomposition of litter and peat in both the

acrotelm and the catotelm (underlying anoxic layer); all of these processes relate positively to temperature (Clymo, 1984; Clymo et al., 1998). As litter and new peat in the acrotelm are exposed to oxygen and varying water levels, they are subject to a relatively high decay rate. Once in the catotelm, the decay rate declines sharply and becomes less dependent on surface environmental conditions over time. The rate of peat passage from acrotelm to catotelm, therefore, largely 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 nonlinear relations with thermal and moisture conditions.

Due to the complex interactions involved in peatland dynamics, a simulation model is useful in order to facilitate the understanding of processes and to make projections. Because peatlands are ecosystems bordering between uplands and aquatic ecosystems, they have some special features that cannot be handled in standard ways as for other ecosystems (e.g. Parton et al., 1987; Mitsch et al., 1988). Unlike upland vegetation and soils, peatlands support limited productivity but accumulate large amounts of organic materials in their waterlogged peat column. The objectives of this article are to review existing conceptual and simulation peat models and to lay out a plan for further model development.

2. Overview of peatland models

Peatland models can be roughly grouped into two basic categories—conceptual models and simulation models. Conceptual models describe relationships of different processes and can be used to examine the consequences of various assumptions (Clymo, 1992). A simulation model is built upon the conceptual model, and its purpose is to mimic and reproduce the behavior of real-world systems, through changing a parameter or a set of parameters over time. However, sometimes this division is not straightforward.

2.1. Conceptual models

Four conceptual models of peat growth and development are reviewed here (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 (1978) peat growth model, which has been further developed in Clymo (1984), Clymo et al. (1998). The Clymo model treats the accumulating peat as a two-layer system, i.e. the acrotelm (thin, oxic, upper layer) and the catotelm (thick, anoxic, underlying layer) (Ivanov, 1981; Ingram, 1978). The boundary between these two layers is approximately at the mean depth of the lowest summer water table (maximum WTD) for bogs (Clymo, 1984), but may be determined by variables other than WTD in rich fens. The major feature of this model is the use of a proportional decay function (e.g. a single exponential model, Jenny et al., 1949; Olson, 1963) 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. The constant decay model implicitly 'assumes that the combination of chemistry, proportions, environment in the peat, and microbial activity result in a constant proportional rate' (Clymo, personal communication, 1999). This treatment is supported by limited field data of moss decay measurements in the litter layer and acrotelm and by a number of catotelm peat profiles (see summary in Clymo, 1984). It is also theoretically realistic in terms of mathematical and biological behaviours (Wieder and Lang, 1982). 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 quadratically with proportion remaining) (see Table 1 for a summary of mathematical formulation and biological consequences).

There are two main aspects in which the peatlands of western Canada differ from the raised bogs that inform the basic Clymo model, (1) they are dominantly fens; and (2) they are in a conti-

ental climate. The continental climate has a relatively limited water supply, with strong seasonal and inter-annual variability. While several western Canadian fens have been moderately well studied (see Vitt et al., 1994, 2000), more data will be needed to fully establish the functional differences between continental fens/bogs and the more maritime bogs envisaged by Clymo and others. Yu et al. (2000) suggested that the convex pattern observed in continental fens might result from gradual decline in the peat-transfer rates from the acrotelm to catotelm, as a result of decreased vegetation production and/or increased acrotelm decomposition, due to autogenic vertical growth of peatlands. Kilian et al. (2000) suggested that the peat age–depth relations may be linear, if considering possible dating errors and/or variable botanical composition and accumulation rates of different peat sections.

Ingram (1982) model is more hydrologically oriented and is a 2-D 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. Ingram's model fits well with small raised bogs, but 'fails badly for large diameter (several kilometers) bogs', which might need to incorporate interactions between the catotelm and the acrotelm (Clymo, personal communication, 1999). Almquist-Jacobson and Foster (1995) attempted to integrate peat hydrology, bog growth and differentiation of surface features into a single model, as also done by Clymo (1984). Like the Ingram model, it represents a 2-D raised bog. The major difference is that while the Ingram model mainly represents internal processes, the model of Almquist-Jacobson and Foster includes explicit representation of external processes.

Kirkby et al. (1995) proposed a peatland model to predict the form and distribution of peat mires, which incorporates climate (net rainfall or effective moisture, i.e. precipitation–evaporation) into peatland biology (decomposition) and hydrology model. As in Clymo's model, their biological component deals with productivity and decomposition in the acrotelm and catotelm, but on the basis of peat depth rather than mass. The model recognizes the importance of the acrotelm depth in

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), Clymo (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, $\alpha = \alpha_Q(m_t/m_0)^2$	$M_t = (p/\alpha_Q) \frac{1}{((1 + 2\alpha_Q T)^{1/2} - 1)}$; no limit	
Hydraulic/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 determining 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)
Modified hydraulic model	Net rainfall and its variability determines peatland height	$H = L\{[R - \Delta R(1-r)]/K\}^{1/2}$, where $r = [(\pi p_a/\alpha_a \Delta R)]^{2/3}$	Sinusoidal variation in net rainfall and water table; the acrotelm depth determined by moisture deficit	High net rainfall (moist climate) increases the bog height; high variability in effective moisture reduces the bog height	Kirkby et al. (1995)

Note: M , cumulated peat mass; m , mass of particular peat parcel; 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; R , average net rainfall (rainfall-evapotranspiration); ΔR , half-amplitude of variation in net rainfall; p_a , biomass addition rate to the acrotelm; α_a , acrotelm peat decay rate.

determining net peat accumulation. Its main assumption is that the acrotelm depth can be represented by maximum moisture deficit depth and the moisture deficit can be estimated by a sinusoidal variation in net rainfall through the year. The approach used in the hydrological component incorporates climatic factors (i.e. effective moisture/net rainfall). Because in developing their model they assume at equilibrium the acrotelm and catotelm peat stops growing, the biological processes do not explicitly involve in peatland dynamics. Thus, the model is basically a modified version of Ingram's hydraulic model, but explicitly defines the net recharge rate as a function of average rainfall and of amplitude of variation in net rainfall. The model has been used to predict sites with suitable conditions for the initiation and growth of peat in Europe.

2.2. Simulation models

Here we review published simulation models for peatlands (Table 2). The model design based on Forrester (1961) system modelling approach is an integrated whole system model (Clymo, 1992). The model requires several parameters that may be difficult to obtain, and no validation or test of the model has been provided. Wildi (1978) model, on the other hand, is designed for testing a specific site. It requires a large number of site-specific parameters, including nutrient information. It simulates a 2-D cross-section of the peatland and is designed for investigating controls on bog form.

Winston (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 2-D 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 3-D peat initiation, growth and expansion model. There are no explicit climate or water table drivers in this model.

Hilbert et al. (2000) model the interactions between different components of a peatland using a system dynamics approach. This model shows two possible steady-state configurations for a peat-

land, depending on water relations, to which the authors ascribe the characters of bogs and fens. There are no interactions between the acrotelm and the catotelm. Like Clymo's and other models, however, it is also developed for regions with an oceanic climate. This model can be seen as an outgrowth of Clymo conceptual model, but with significant improvement by adding further explicit functional relationships.

Wieder (2001) presented an empirical model based on ^{210}Pb -dated peat cores, which used depth-dependent decay rates of near-surface (acrotelm) peat to evaluate peatland carbon balance during the last 100–200 years. Frohling et al. (2001) developed a cohort-based peat decomposition model (PDM), in which long-term peat accumulation is directly related to decomposition rates of fresh vegetation litter. The model considers two vegetation types (vascular, and mosses) and root input from vascular plants to deep peat for bogs and fens. The PDM is a static model, assuming constant vegetation production and constant initial litter decomposition. The acrotelm and catotelm are integrated by use of prescribed anoxic factors and bulk density profiles.

3. Dynamic three-dimensional peatland initiation, expansion, and decay model

3.1. Conceptual design of a simulation model

Because of the 3-D nature of peatlands (e.g. Korhola et al., 1996), an ideal model would consider peatland initiation from mineral soils, lateral expansion of peatlands and vertical growth. Obviously, soil characteristics and peatland hydrology play important roles in the initiation of fens, transformation of fens to bogs, and lateral expansion of both fens and bogs. We here present a preliminary design of a grid-based, spatially explicit peatland dynamic model (Fig. 1).

At any time, there are four basic types of land cover (grid-cells), (1) non-peat mineral soils, (2) fen peat, either *Sphagnum*- or brown moss-dominated; (3) bog peat, always *Sphagnum*-dominated; and (4) open water. The simulation starts from a non-peat mineral soil landscape as represented by

Table 2
Summary of peat bog simulation models

Model	Assumption	State variable	Number of parameters	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	Climate (energy inputs, moistures)	Clymo (1992) based on methodology in Forrester (1961)	Complex design; potentially including all the aspects of peatland system; numerous unspecified functional relations and parameters
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 nine submodels along a pre-defined slope	20	No explicit drivers; objective is to distribute modelled variables spatially over time	Wildi (1978)	Site-specific (because of slope specification); nutrients as explicit state variable; simulating equilibrium distribution of five state variables along a slope (nine 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 (1982), Clymo (1984) models, with some modified assumptions; strictly speaking, a 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

Table 2 (Continued)

Model	Assumption	State variable	Number of parameters	Driver factor	References	Comments
Topography-driven 3-D model	Terrain slope determines the rate of lateral expansion; vertical peat growth follows Clymo's assumptions	Using 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; no climate and hydrology drivers; objective is to use estimated parameters to reconstruct an observed peat bog
Nonlinear dynamic model: PAM	Net water input determines the bog height and WTD; plant growth rate is a quadratic (unimodal) function of WTD	Catotelm peat depth, WTD	Hydrology-related rates (drainage, evaporation, maximum and minimum water table, peat water content); production rate, decay rate, maximum growth rate	Climate moisture condition (precipitation); assumption –consequence testing	Hilbert et al. (2000)	A simulation exploring the possible multiple equilibrium states caused by nonlinear dynamics; the hypothetical growth function is a key assumption; no interaction between acrotelm and catotelm (constant bulk density)
Cohort-based PDM	Decomposition rates of deep peat can be related to decomposition of surface vegetation litter	Peat mass and depth; decomposibility of peat cohorts	NPP, litter allocation and decay rates; rooting depth and distribution; WTD; peatland age; bulk density profile	Vegetation NPP and litter decomposition rates	Frolking et al. (2001)	Static model integrating the acrotelm and catotelm with use of prescribed anoxic factors and bulk density profiles

a digital elevation model (DEM), and soil moisture dynamics are simulated. The mineral soil moisture model determines 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 to bog cells. Disturbances and climate change are to be part of the peatland dynamic model, which should be capable of degrading and even terminating a simulated peatland. An excessively rapid climatic moistening could flood the peatland, producing open water, releasing CH_4 and CO_2 .

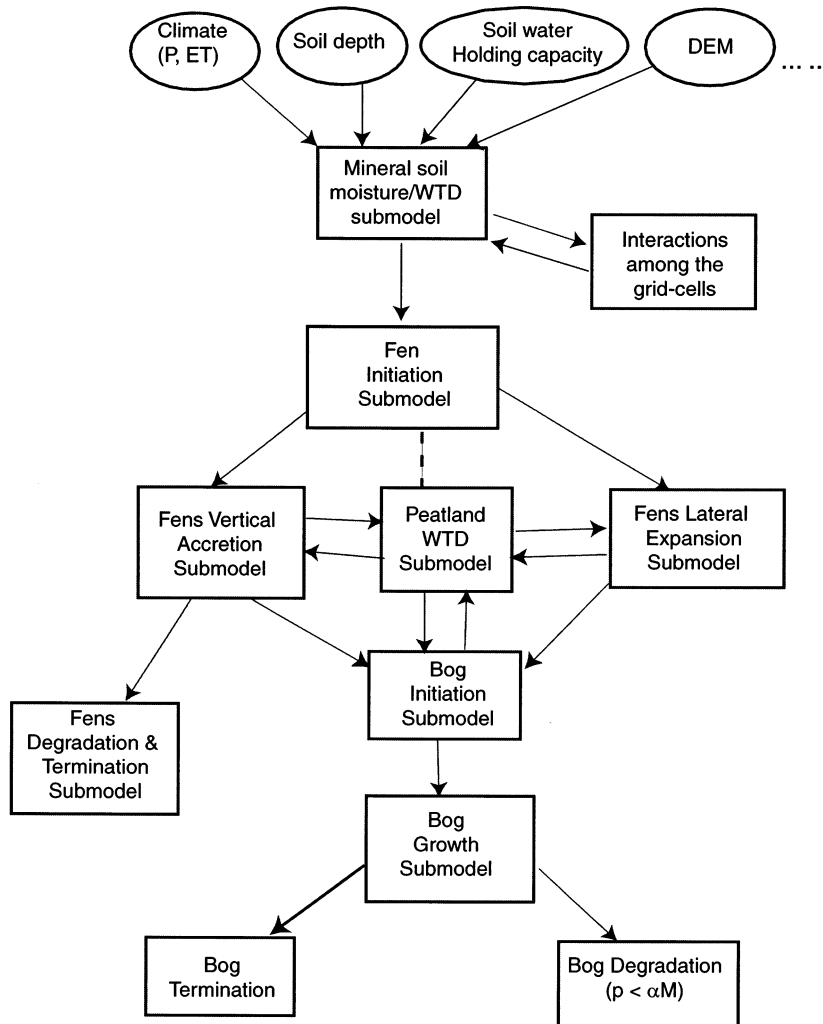


Fig. 1. Conceptual design of a 3-D peatland simulation model, which considers peatland initiation, vertical growth and lateral expansion. The model can be dynamically driven by climate variables (e.g. effective moisture).

All calculations are performed on individual cells. For the mineral soil moisture submodel the time steps are monthly, and the outputs are summarised and averaged at the end of each year, 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 owing to the slow nature of peatland growth.

3.2. Model structure

3.2.1. 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 DEM, coupled with one of several existing distributed watershed hydrology models, such as TOPMODEL (Beven and Kirkby, 1979) and its subsequent development (see Yu and Campbell, 1998 for a review). The submodel can have three soil layers, as in Potter (1997), each with its own soil moisture holding capacity.

The validation and calibration of the submodel need, at a minimum, complete water budget data for several years from one site. For our purposes, precipitation and evaporation will be climate drivers for the model. We need to test the behavior 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.

3.2.2. Fen initiation submodel

The critical conditions for fens to initiate from mineral soils are (1) high water table (WTD ≈ 0); and (2) relatively stable water table ($\Delta(\text{WTD})/\Delta t \approx 0$ for a certain period of time) to cause peat accumulation (Zoltai and Vitt, 1990). 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.

Two different scenarios could produce conditions suitable for initiating fen peat, (1) regional climate changes and (2) change of local hydrologic conditions. Under a wet climate, increasing precipitation and/or decreasing evapotranspiration would cause the water table to rise (WTD approaching 0) and local factors may buffer/maintain the stability of water table. Under a dry climate, lowered soil permeability, through decomposition of organic matter, or deposition of fine clay or other fine particles, may reduce water infiltration and raise the water table. In both cases, however, the requirement at the level of the individual cell is the same—a stable and high water table. A drying climate may also initiate peatlands through terrestrialisation of former lakes; however, 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.

3.2.3. 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. Under a constant climate, 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%. In a Finnish peatland, the field data were fitted to a power function of the form $G = a \times S^b$ (where G is the rate of lateral expansion in m/year; S is the terrain slope, and two parameters $a = 773.6$ m/year and $b = -1.17845$ are the empirically determined constants) (Korhola et al., 1996). The maximum rate (G) for that Finnish site was estimated at 6 m/year, with slope S close to 0 (Korhola et al., 1996 and references therein).

Vertical peat accretion/growth uses Clymo (1984) conceptual model: $dM/dt = p - \alpha M$ (see Table 1). The α and p values can be measured and estimated empirically from field data, and they

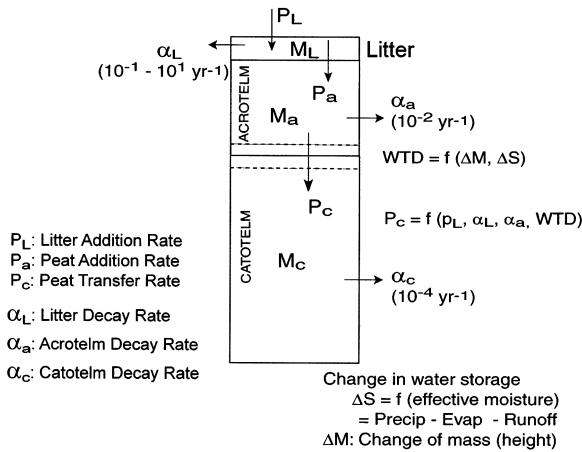


Fig. 2. Model design for phase I: 1-D peat growth simulation model with dynamically changing WTD. The model consists of three structural and functional layers, litter, acrotelm and catotelm. Biological and chemical processes occur more actively in the top two layers, driven by effective moisture (WTD) among other environmental factors, than in the catotelm.

can also be modelled as a function of temperatures and other environmental factors. The peatland hydrology model will be developed with available hydrograph data. The compromise adopted here is to implement a much-simplified empirical model rather than a full process-based hydrology model.

3.2.4. 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 no nutrient-rich groundwater reaches the peat surface in that cell and all nutrients come from atmospheric deposition (wet or dry). 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, height difference between peatland surface in the cell and at the peatland margin, or low nutrient content of the water supply.

3.2.5. Bog growth submodel

The bog growth model will be based on Clymo (1984) peat growth model. 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.

4. Dynamic peat growth simulation model: phase I

4.1. A three-layer model: assembling litter, acrotelm, and catotelm components

In phase I of model development, the model will not be spatially explicit and will in fact be a 1-D 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 certain duration; only vertical growth and decay will be simulated. Fig. 2 summarises the basic structure of the phase I model.

Functionally, there are three layers in a peat column, (1) living vascular plants and mosses (the litter layer); (2) the acrotelm; and (3) the catotelm. Net primary production (NPP) is the initial input to peatlands through fixation of atmospheric CO_2 by photosynthesis. In a mature peatland ecosystem (in a steady state), the addition of dead plant material as litter to the peatland is equal to NPP. The decomposition processes of litter, however, are likely different initially, including leaching of soluble organic materials as dissolved organic carbon (DOC), which warrants the separate treatments of litter and acrotelm peat (see Yu et al., 2001 for detailed discussion). After initial decomposition, the litter enters the acrotelm as new peat. Based on Clymo's conceptual model, the acrotelm and catotelm division is determined by the maximum WTD (lowest summer water table). Both the acrotelm and the catotelm peat will experience decomposition, but the rates will be distinct for each layer. The aerobic decay rate is relatively high in the acrotelm. Peat accumulation will actually occur in the catotelm because of its slow anaerobic decay rate (2 or 3 orders of magni-

tude lower than in the acrotelm) (Clymo, 1984). The nature of the peatland, including vegetation type and consequent NPP and litter quality, and climate and hydrology, will determine the rate of litter addition to the acrotelm peat. The WTD and consequently the residence time of peat in the acrotelm will determine the rate of peat mass transfer from the acrotelm to the catotelm. That transfer rate, coupled with the resulting relatively constant anaerobic decay rate of the catotelm peat, will eventually determine the long-term peat accumulation rate.

The model will simulate the production and decay processes of litter, acrotelm and catotelm peat and water and carbon exchange processes among these three layers, with dynamic climate and hydrology drivers. The phase I model is able to simulate 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 (positive) and decay rates (positive) cancel each other. This model is used to test hypotheses regarding the importance of water table fluctuations in peatland dynamics. In this model, WTD seems to be extremely important in controlling the passage of peat mass from the acrotelm to catotelm and eventually net long-term peat accumulation.

4.2. Dynamic acrotelm–catotelm integrator

The pattern in physical properties of peat profiles reflects the underlying processes connecting the acrotelm and catotelm. There is usually a sharp transition in proportion of dry mass, water and gas at or near the water table (i.e. the acrotelm–catotelm boundary) (Clymo, 1984, 1992). This pattern is reflected in the bulk density of the peat, which can be assumed to be a function of compaction and decomposition. The down-core increase of density in the acrotelm is probably caused by a decrease in volume (high compaction potential due to high gas content) that is more rapid than decrease in peat mass (due to decomposition). In the catotelm, however, the decrease in peat volume and mass are both slow and may be at about the same rate, often causing a nearly constant bulk density in deep peat profiles.

A successful connection of the acrotelm and catotelm in a dynamic simulation model needs a functional change in bulk density and decomposition rate as water-table changes, which will transfer peat mass back and forth between the two layers. Unlike a conceptual model, a simulation needs to consider the processes acting on the peat cohorts that move back and forth above and below the acrotelm–catotelm boundary due to fluctuations in the water table (Clymo, 1978). The time scales are quite different for each functional layer; a few years for litter, several decades for the acrotelm, and thousands of years for the catotelm. The processes in litter and acrotelm initially determine the peat input to the catotelm, and the accumulated catotelm peat will respond less to these processes in the layers above but decomposition and other disturbances in the catotelm alone.

5. Summary and further developments

5.1. Clymo's conceptual model

In the absence of new data from continental peatlands (fens as well as bogs) suggesting otherwise (but see Yu et al., 2000), we will build our simulation model on this conceptual foundation. By considering the differences between conceptual and simulation models, the peatlands that show a convex curve of peat age–depth relationship (Ikonen, 1993; Charman et al., 1994; Kuhry and Vitt, 1996; Yu et al., 2000) could be simulated with continuously changing peat addition and transfer rates. In the Clymo model, the concave relationship is a consequence of the assumption of constant peat transfer rates.

5.2. Eventual 3-D and current 1-D 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 1-D simulation model of vertical peatland growth (phase I model) is feasible, based on our current understanding of peatland dynamics. In phase II of model development, 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 temperature 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 project future changes more realistically in boreal peatland C storage under different climate warming scenarios, and eventually under different land use options.

5.3. Selection of decay models and their implications

The majority of published peat profiles show concave peat age–depth curves, suggesting that 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 acrotelm and catotelm, considering the quality of available data. Although fitting exercises show no differences using these decay models, different models have different assumptions and consequences. Limited litter-bag decomposition data suggest that double constant proportional decay rate models are needed in order to adequately account for the rapid initial decay, due partly to very different processes, e.g. leaching, in the initial stage of decomposition (Yu et al., 2001).

5.4. Connecting acrotelm and catotelm through WTD

It is important to implement effectively the transfer of peat mass between acrotelm and catotelm, as this transfer process will determine the peat addition rate to the catotelm and long-term peat accumulation (Clymo, 1984). 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 an index of decay, etc.) around the boundary between acrotelm and

catotelm would make the implementation more realistic.

5.5. Water-table dynamics

Lack of water balance data from fens in continental western Canada prevents direct quantitative dynamic WTD modelling. On the other hand, such direct dynamic modelling might not be necessary, considering the different time 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. WTD is arguably the most important single factor in determining peat accumulation rates, as it affects both production and decay. The model will, therefore, need to consider processes governing WTD in some detail.

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