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A model of organic matter accumulation in a developing fen/raised bog complex

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A mechanistic simulation model of organic matter accumulation for a developing fen/raised bog complex in Ireland is presented. Parameter/variable values have been primarily drawn from the published literature. The development of the theoretical considerations of fen peat as a substratum to a raised bog is evaluated using the model. Terrestrialization is the pathway of hydroseral succession. The conceptual model treats peat growth as the accumulation of a series of parcels comprising both a labile and a non-labile component. The fen phase of the model uses a discrete description of organic matter accumulation while the raised bog phase uses a continuous description. Both phases use a constant decay rate. The model integrates changes in net primary productivity and aerobic decay to simulate four climatic periods. The model generates outputs for peat depth and mass with time and profiles of bulk density with depth. Results over a simulated period of 10 000 years demonstrate how changes in surface net primary productivity and aerobic decay can change the rate of peat accumulation in the developing fen/raised bog complex. Sensitivity analysis showed that the most important parameters influencing simulated depth and mass were the labile fraction in organic matter (raised bog) followed by net primary productivity (raised bog). The potential significance of underlying fen peat as a proportion of the total depth and mass of a developing fen/raised bog complex was evaluated and shown to be substantially diminished after 5 000 years. It was established that the model predictions corresponded well with data for Irish Midland bogs and given suitable adjustment of values, could potentially simulate Fennoscandian conditions as well.

Keywords: Climate, mires, peat, peatlands, *Sphagnum* productivity

INTRODUCTION

Models have been developed in recent years to address the issue of vegetational succession and organic matter (OM) accumulation in wetland ecosystems (Clymo 1978, Wildi 1978, Straškraba et al. 1988, Logofet & Alexandrov 1988, Bakker 1994). Clymo (1984 & 1992a) and Clymo et al.

(1998) describe various models of fen/bog carbon accumulation and depth using decay functions where the rate of change of decay exhibited either a 'constant', 'linear' or 'quadratic' response in relation to the proportion of original dry mass still remaining. The model presented here, synthesises elements of earlier model development and uses a constant rate of decay. The model introduces response to climate change and a new mechanism for determining dry bulk density as a decay control process. The objective of the model development at this stage is prediction of peat accumulation and facilitation of hypothesis development about the factors controlling the nature and magnitude of bog development. The model represents a mechanistic and deterministic approach to simulating OM accumulation in a developing fen/raised bog complex. The model and its output are analysed in terms of closeness of prediction to field data and the tenability of the assumptions used.

Background — The developing peatland

Gore (1983) describes fens as mires that are under the influence of surface water derived predominantly from outside their own immediate limits. In contrast, raised bogs are typically defined as obtaining their water supply solely through precipitation. Thus the main difference between fens and raised bogs lies in the origin and chemistry of their respective water supplies. Fens may develop through paludification, i.e. the swamping of river flood-plains or forest soils, or they may develop through terrestrialization or the infilling of shallow lakes (Gore 1983).

Terrestrialization – fen development

There are many pathways of raised bog development that have been described by various authors (Weber 1908, Walker 1970, Tallis 1983). Although there is no single preferred pathway for hydroseral succession, the majority of sequences involve a reed swamp stage and a final ombrotrophic bog stage (Walker 1970). Indeed, Gore (1983) observed that the presence of *Equisetum fluviatile*, *Phragmites australis* and *Carex* spp. among the oldest identifiable plant remains in bogs as strongly suggesting that they originated from overgrown shallow lakes. This paper describes the developmental sequence as one of general terrestrialization (Weber 1908).

The accumulation of OM on the lake floor inhibits the mass movement of oxygenated lake water into the sediments, and since the rate of oxygen diffusion in water is 10^4 less than in air, anaerobic conditions quickly arise (Clymo 1992a & 1992b). The input of OM to the anaerobic fen peat accumulating system is a function of the net primary productivity (NPP) of the fen plant community and of the removal of material through aerobic decomposition and runoff processes. Aerobic decay removes OM from the system through either gaseous emissions or losses in solution. All decay is associated with loss of physical structure and/or change of chemical state (Swift et al. 1979). These processes are very active in the fen waters above the lake floor where there is a relatively high degree of oxygen present and mass movement with fen lake water (Thormann & Bayley 1997). The depth and flow rate of the fen lake waters, as well as the nature and time for the transit of OM are important in controlling the quality and quantity of OM that enters the anaerobic lake floor deposit.

Fen peat accumulates during terrestrialization, in many cases raising the accumulating surface above the influence of ground water and thus removing it from a topogenous environment. With this change in the hydrosere, a transitional zone develops where plant communities of one seral stage begin to decline and are replaced by a terrestrial ombrotrophic plant community in the form of a raised bog (Gore 1983, Tallis 1983).

Raised bog growth

The raised bog accumulates OM due to water logged conditions (now ombrotrophic) that reduce the rate of decay. Most raised bogs comprise an aerobic upper layer called the acrotelm (100–500 mm deep), the lower parts of which may be seasonally anaerobic, and a deeper anaerobic layer of variable depth, called the catotelm (Ingram 1978, Clymo 1992a, 1992b). The rate of input of OM to the acrotelm is equivalent to the NPP of the peatland vegetation. As with the fen, material

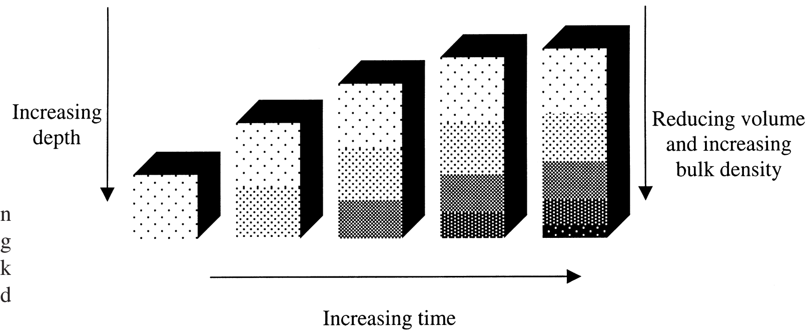

Fig. 1. Schematic representation of the parcel concept showing reduced volume, increased bulk density with depth and increased total core mass with time.

that survives decomposition in the acrotelm ultimately enters the catotelm. The depth of the acrotelm, the duration OM residence in this zone and the nature of the OM are important in controlling the quality and quantity of OM that enters the catotelm.

MATERIALS AND METHODS

Model structure

Fen (minerotrophic) and raised bog (ombrotrophic) accumulation is represented by a series of parcels of dead OM stacked one on top of the other (Fig. 1). Peat accumulates annually through the addition of a new discrete parcel of OM. Older parcels are covered and become deeper in the profile. OM is composed of fractions that vary in their susceptibility to breakdown. It has been assumed for simplicity that the dead plant OM deposited at the surface of the developing fen/raised bog is composed of a labile and a non-labile component. The labile component is assumed to be easily digested by micro-organisms and the non-labile component is assumed to be indigestible or refractory. The labile OM within each parcel decays with time, thus its mass and volume decrease with time. The model structure (Fig. 2) will be considered in terms of the development stages being simulated.

Fen peat accumulation

Annual parcels of dead OM (equivalent to fen NPP) are deposited at the surface of the lake. The parcels are subject to runoff and aerobic decay over one year before being passed to the anaerobic process zone at the bottom of the lake (Fig. 2: fen depth less than lake depth). The annual deposition and accumulation of dead OM at the bottom of the lake represents a potentially infinite sequence of parcels. Where a constant mass of OM is deposited annually, comprising both a labile component, m, and a non-labile component, x, and the rate of decay, α, is constant, then the sequence of annual deposits may be described as a geometric series. Such a situation does not lend itself to direct analytical solution. However, the inclusion of the refractory component may be addressed satisfactorily through an iterative modelling program. A geometric series incorporating a non-labile component may be represented by:

$$(m + x) + (mr + x) + (mr^2 + x) + \ldots (mr^{t-1} + x) + \ldots \qquad (1)$$

where, the common ratio $r = 1 - \alpha$.

The sum, S_t, of the first, t, terms of such a series is given by:

$$S_t = \frac{m(1-r^t)}{(1-r)} + tx \qquad (2)$$

The model uses this discrete process description to simulate and evaluate changes in fen lake depth with time. The threshold of fen lake depth is used to define vegetational progression. Once the lake has been filled (Fig. 2: fen depth greater than lake depth) it is assumed that ombrotrophic conditions prevail, that *Sphagnum* species dominate the vegetation and raised bog development starts.

Raised peat accumulation

The initial establishment of raised peat is repre-

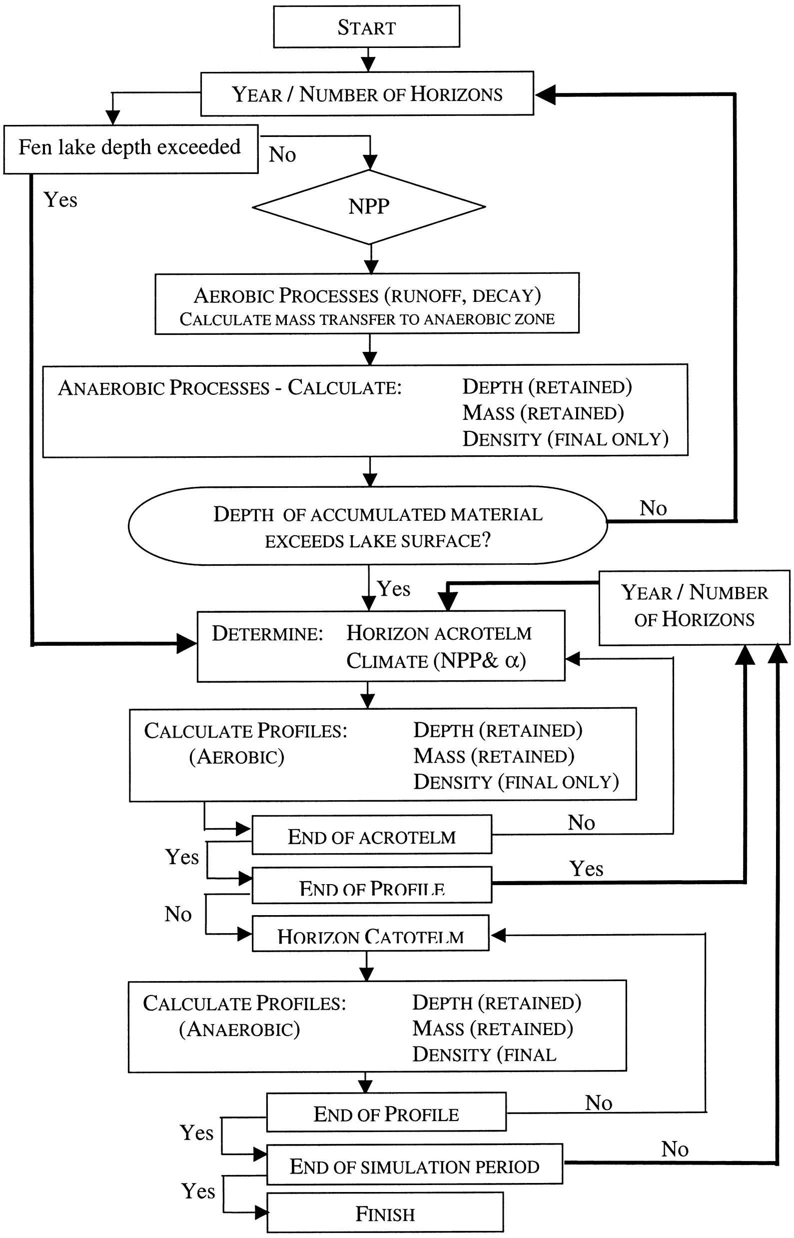

Fig. 2. Flowchart of the model showing operation flow and modular structure.

sented by a non-accumulating layer of aerobically decomposing *Sphagnum* peat, the acrotelm, and a peat accumulating and anaerobically decomposing layer, the catotelm (Ingram 1978). The acrotelm is characterised in the model by the weighted average bulk density of a parcel of OM being less than a critical value, which based on published data, may be taken to define the boundary between the acrotelm and the catotelm (Clymo 1984, 1992a). Labile decomposition on its own accounts for changes in parcel bulk density. This model representation ignores the additional process of structural collapse of the plant matrices near the boundary with the catotelm (i.e. the position of the permanent water table during a dry summer) (Clymo 1992a, 1992b). The mass of labile OM is assumed to decay with time and the rate of loss is directly proportional to the amount of material remaining, such that

$$\frac{dm}{dt} = -\alpha m \qquad (3)$$

where, α, is the decay parameter and, t, is time.

It follows from (3) that:

$$m = m_o e^{-\alpha t} \qquad (4)$$

where, m_o, represents the original labile mass of OM. Additionally, the model describes the removal of labile and non-labile OM in the acrotelm through runoff. As the mass of the labile fraction of each parcel of OM within the acrotelm is removed by decay, the volume of labile material decreases and the weighted average bulk density increases. Consequently, as raised peat development proceeds, the critical bulk density is reached and the parcel enters the catotelm (Fig. 2: end of acrotelm). Further decomposition is then treated as anaerobic. In this way the model generates an acrotelm/catotelm boundary. The decrease in the volume of the labile component within a parcel, and hence total parcel volume, determines the depth contribution of each parcel to the depth of the core as their horizontal area is deemed to remain constant. Raised peat depth is the sum of the volume of the individual parcels. Raised peat mass is the sum of the masses of the individual parcels.

The simulated climate sequence

Changes in NPP and aerobic decay were selected as the means of integrating changes in climate over time for the raised bog. These parameters were chosen because there is stratigraphical evidence of wetland NPP responding to shifts in climate in the past (Hammond 1981). Additionally, aerobic decay has a significant influence on the passage of OM to the peat accumulating anaerobic zone, and is considered to be climatically sensitive (Clymo 1984, Doyle & Dowding 1990). However, in the preliminary model, only one rate was designated for fen NPP and aerobic decay and thus climatic responses were confined to the raised bog phase. The raised bog phase of the model uses changes in NPP and aerobic decay to simulate a maximum of four climatic periods for Ireland of 500, 2 400, and 2 600 years with a final balancing period (3 000 years in the initial model run). In establishing NPP and aerobic decay as indices of climate change reference was made to the climatic chronology of the Holocene in Ireland (i.e. Late boreal, Atlantic, Sub-boreal and Sub-Atlantic periods). The initial model run presented in this paper was for 10 000 years and covered the four simulated climatic periods.

Modification of NPP and aerobic decay in the raised bog

Based on published literature (Table 1) an average NPP for raised bog development was ca. 500 g m^{-2} yr^{-1} and the average aerobic decay rate was 0.06 yr^{-1} (Clymo 1984, Madden & Doyle 1990). During the Late boreal (500 years), temperatures were at their highest since glaciation although precipitation was low relative to current rates (Hammond 1981). Thus the initial NPP attributed to this period in the model was 300 g m^{-2} yr^{-1} dry mass (Table 1) which represents a relatively low value when compared with contemporary Irish NPP measures (Madden & Doyle 1990). During the Atlantic period (2 400 years) the climatic shift was towards a warm but wet environment. To reflect this climatic shift the NPP value was increased to 450 g m^{-2} yr^{-1} dry mass (Table 1). The Sub-boreal (2 600 years) was associated with initially warm but drier conditions which then deteriorate towards wet and cooler conditions and is associated with a major phase of bog development (Mitchell 1986). The NPP value used to reflect these influences, particularly the higher precipitation towards the end of the period was 650 g m^{-2} yr^{-1} dry mass (Table 1). Finally, a NPP value of 400 g m^{-2} yr^{-1} dry mass (Table 1) was used to describe inputs during the Sub-Atlantic (2 500 years) which was a period characterised by an increase in wetness but further falling temperatures (Hammond 1981).

The enzymatic response of decay demonstrates a non-linear relationship with temperature and moisture. However, NPP also demonstrates a similar non-linear relationship with temperature and moisture in that it is driven by physiological activity. It was therefore assumed that variation in aerobic decay was proportional to NPP. Thus based on the NPP measures outlined above, the average aerobic decay rate of 0.06 yr^{-1} was modified to give 0.036, 0.054, 0.078 and 0.048 yr^{-1} for the four climatic periods respectively.

Variation of NPP and aerobic decay based on their assumed relationship with climatic conditions represents a simplified and somewhat arbitrary modification of these parameter values. However, it is reasonable to assume that temperature and rainfall effects would influence NPP and aerobic decay. Thus the relative values used attempt to take account of the recorded climatic conditions and are not contrary to established theory on plant growth and microbial activity. A more complex simulation of the live plant/microbial dynamics is beyond the current scope of this paper.

Parameters and variables

Important variables and parameters that influence peat dynamics were identified from a review of the published literature. The parameters and variables used in the model are summarised in Table 1. The initial parameter and variable values used to generate the preliminary set of results were based on ranges commonly reported in the literature (Table 1) and are not site specific.

Model output

The model output provides profiles of total peat depth and mass with time for both the fen peat and raised peat strata. The model also generates a profile of bulk density with depth for the fen/raised bog complex at the end of the simulated period. In the model run the integration interval was annual for the fen and every 100 years for the raised bog phase, with outputs generated at each interval. The model has been programmed in Visual Basic 6.

Table 1. Parameter and variable values used in the initial simulation run of the model.

Parameter/ variable	Meaning	Values	Units	Literature references used in estimation of parameter and variable values
α_{af}	Aerobic decay rate (fen)	0.4	yr^{-1}	Heal & French (1974); Thormann & Bayley (1997)
α_{cf}	Anaerobic decay rate (fen)	0.0008	yr^{-1}	Clymo (1984, 1992a, 1992b & 1998)
α_{a1rb}	Aerobic decay rate (raised bog)	0.036	yr^{-1}	Clymo (1965, 1978); Lieffers (1988)
α_{a2rb}	Aerobic decay rate (raised bog)	0.054	yr^{-1}	Clymo (1965, 1978); Lieffers (1988)
α_{a3rb}	Aerobic decay rate (raised bog)	0.078	yr^{-1}	Clymo (1965, 1978); Lieffers (1988)
α_{a4rb}	Aerobic decay rate (raised bog)	0.048	yr^{-1}	Clymo (1965, 1978); Lieffers (1988)
α_{crb}	Anaerobic decay rate (raised bog)	0.0008	yr^{-1}	Clymo (1984, 1992a, 1992b & 1998)
D_b	Surface bulk density (dry)	0.05	$Mg\ m^{-3}$	Tolonen (1977); Clymo (1978 & 1984)
D_{bc}	Critical bulk density	0.065	$Mg\ m^{-3}$	Clymo (1978, 1992a & 1984)
D_{Lrb}	Labile density (raised bog)	0.043	$Mg\ m^{-3}$	Tolonen (1977); Clymo (1978 & 1984)
D_{NLrb}	Non-labile density (raised bog)	0.1	$Mg\ m^{-3}$	Tolonen (1977); Clymo (1978 & 1984)
D_{Lf}	Labile density (fen)	0.043	$Mg\ m^{-3}$	Tolonen (1977); Clymo (1978 & 1984)
D_{NLf}	Non-labile density (fen)	0.11	$Mg\ m^{-3}$	Tolonen (1977); Clymo (1978 & 1984)
LF_f	Labile fraction in NPP (fen)	0.8	$g\ g^{-1}$	Heal & French (1974); Malmer & Wallen (1999)
NLF_f	Non-labile fraction in NPP (fen)	0.2	$g\ g^{-1}$	Heal & French (1974); Malmer & Wallen (1999)
LF_{rb}	Labile fraction in NPP (raised bog)	0.75	$g\ g^{-1}$	Clymo (1983); Flaig et al. 1975
NLF_{rb}	Non-labile fraction in NPP (raised bog)	0.25	$g\ g^{-1}$	Clymo (1983); Flaig et al. 1975
L	Lake depth	3.0	m	Mitchell (1976, 1986); Mitchell & Ryan (1997)
NPP_f	Fen net primary productivity	600	$g\ m^{-2}\ yr^{-1}$	Bradbury & Grace (1983); Madden & Doyle (1990)
NPP_{rb1}	Raised bog net primary productivity	300	$g\ m^{-2}\ yr^{-1}$	Bradbury & Grace (1983); Madden & Doyle (1990)
NPP_{rb2}	Raised bog net primary productivity	450	$g\ m^{-2}\ yr^{-1}$	Bradbury & Grace (1983); Madden & Doyle (1990)
NPP_{rb3}	Raised bog net primary productivity	650	$g\ m^{-2}\ yr^{-1}$	Bradbury & Grace (1983); Madden & Doyle (1990)
NPP_{rb4}	Raised bog net primary productivity	400	$g\ m^{-2}\ yr^{-1}$	Bradbury & Grace (1983); Madden & Doyle (1990)
R_f	Runoff coefficient (fen)	0.6	yr^{-1}	Thormann & Bayley (1997)
R_{rb}	Runoff coefficient (raised bog)	0.2	yr^{-1}	Verry & Urban (1992)

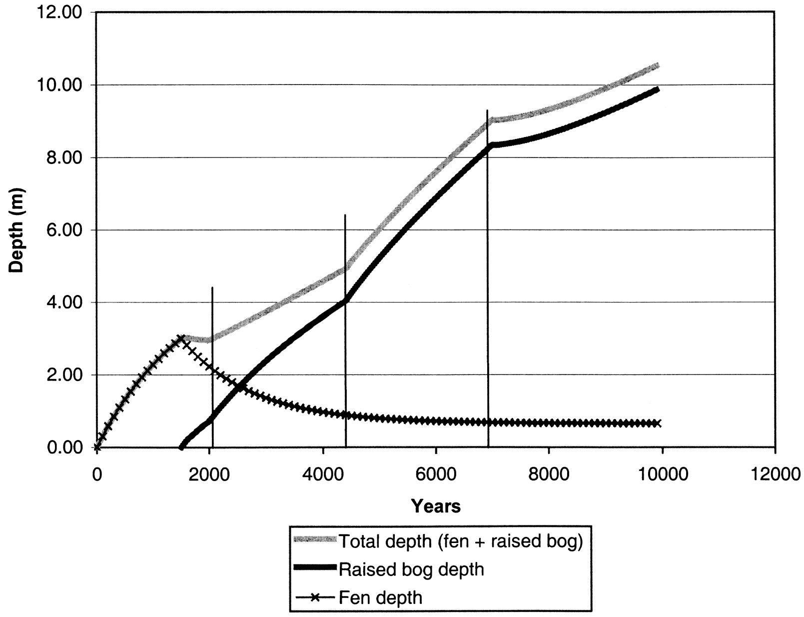

Fig. 3. Growth in depth for a fen/raised bog complex with climate change.

Sensitivity analysis

The model was initially run using values estimated from the literature (Table 1). Sensitivity analysis was then performed to identify those parameters and variables of greatest influence on model output. The procedure adopted for sensitivity analysis was to increase and decrease the initial simulation value for each parameter or variable by 10% requiring 32 simulations. Only one parameter or variable was modified for any given run of the model except for α_{rb} and NPP_{rb} which were modified collectively. In each case the impact on acrotelm depth as well as total depth and cumulative mass at 500, 5 000 and 9 000 years were recorded.

RESULTS

The estimated growth in depth and mass for a fen/raised bog complex was projected for 10 000 years, based on the values in (Table 1) (Figs. 3 and 4). The transition from fen to raised bog occurred after a simulated period of 1 500 years when the peat reached a depth of 3 m (Fig. 3). Ombrotrophic bog development then advanced over 8 500 years embracing the four climate periods (indicated by vertical lines Figs. 3 and 4). The model projected a peat core at the end of the simulation run as having an acrotelm depth of 0.11 m and generated a profile for the increase in bulk density with depth. During the initial 500 years of raised bog development continued decay in the fen peats resulted in a decline in depth of fen OM that approximately matched the increase in raised bog depth. This resulted in no net growth in depth and retarded growth in mass for the combined fen/raised bog complex during this period (Figs. 3 and 4). At the end of the fen (year 1 500), cumulative mass was just below 173 kg m^{-2} (Fig. 4). During the simulated period, year 1 500 to 2 000, the combined fen/raised bog complex gradually increased in mass rising to approximately 188 kg m^{-2} at 2 000 years. When the simulation was run to approximately 5 000 years, decay in the fen was substantially complete, and the profile of total depth and mass for the combined fen/raised bog complex paralleled that of raised bog development on its own. At 5 000 years the total depth was approximately 6 m (Fig. 3) and cumulative mass was approximately 487 kg m^{-2} (Fig. 4). Running the simulation to 10 000 years generated a total peat depth of 10.5 m (Fig. 3) and a cumulative mass of 962 kg m^{-2} (Fig. 4). In contrast, by

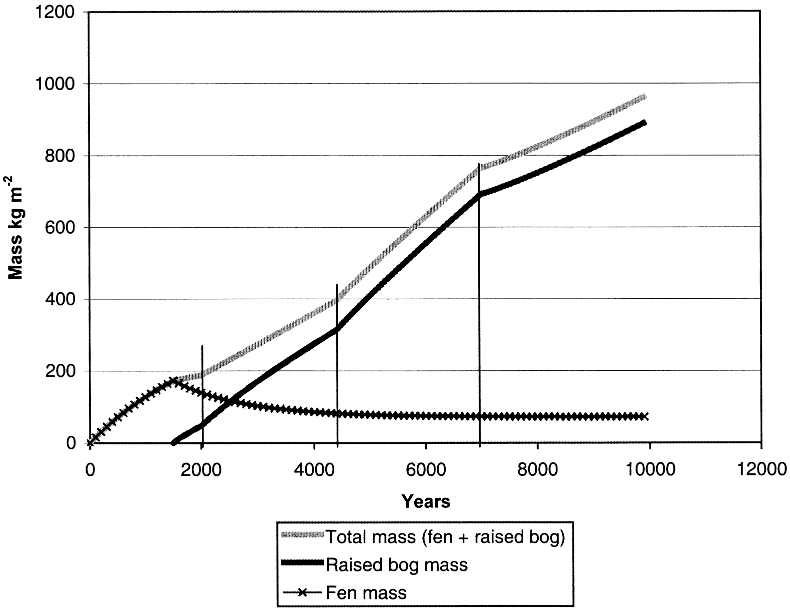

Fig. 4. Growth in mass for a fen/raised bog complex with climate change.

this same point in time the depth and cumulative mass of fen peat which had reached its maximum value at year 1 500 in the simulation run had dropped to 0.7 m and 72 kg m^{-2} respectively (Figs. 3 and 4).

Sensitivity analysis

Total depth and mass were most notably effected by changes in LF_{rb} where relative differences ranged between approximately 25% and 27% (Fig. 5). When only long term effects were considered (≥ 9 000 years) the model output demonstrated significant sensitivity to changes in NPP (with relative differences of between 8% and 9%) (Fig. 5). The analysis, in respect of the long term projections, of depth with increased and reduced parameter/variable values and of mass with reduced parameter/variable values indicated relative differences of between 5% and 11% with the modified D_{bc} (Fig. 5a, 5c and 5d).

When short term depth effects were considered the parameter/variable to which the model was most sensitive was R_f (with a relative difference of approximately 15%) followed by NPP_f, D_{Lf} and α_{af} in that order (Fig. 5a and 5c). The same analysis in respect of mass showed that the parameter/variable to which the model was most sensitive was again R_f (with a relative difference of approximately 15%) followed in this case by NPP_f, LF_f, α_{af} respectively (Fig. 5b and 5d).

The model output for acrotelm depth demonstrated greatest sensitivity to changes in D_{bc}, D_{Lrb} and LF_{rb} with relative differences ranging between approximately 15% to just below 25% (Fig. 6).

DISCUSSION

Sensitivity analysis

In discussing the output of the model it is first necessary to consider the insights that sensitivity analysis provided in terms of model response to changes in parameter/variable values. With the exception of NPP_{rb} and R_{rb}, the model response, across the selected output measures, was non-linear with respect to the modification in parameter or variable values (Figs. 5 and 6). In particular the model output demonstrated sensitivity to LF_{rb} and NPP_{rb} (Fig. 5) and D_{bc} and D_{Lrb} (Fig. 6), the underlying mechanisms of which will be examined.

Raised bog parameters and variables

Labile fraction: The most significant parameter in terms of its effect on the overall model profile

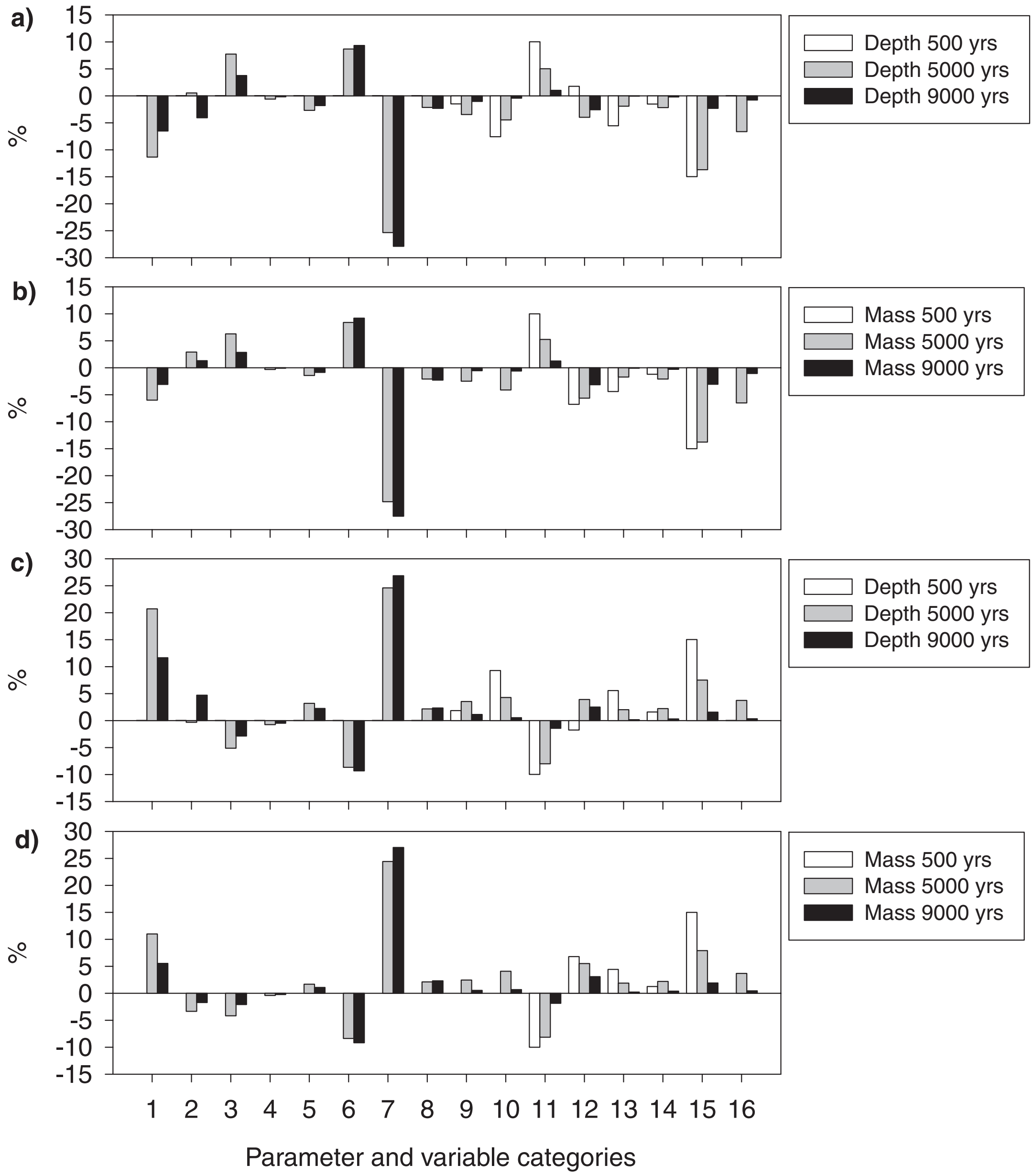

Fig. 5. Sensitivity analysis showing change in depth (graphs a, c) or mass (b, d) compared to the initial simulation run with a 10% increase (a, b) or reduction (c, d) in parameter / variable values. Categories: 1 = Critical bulk density (D_{bc}), 2 = Non-labile density (raised bog) (D_{NLrb}), 3 = Labile density (raised bog) (D_{Lrb}), 4 = Aerobic decay rate (raised bog) (α_{arb}), 5 = Anaerobic decay rate (raised bog) (α_{crb}), 6 = Net primary productivity (raised bog) (NPP_{rb}), 7 = Labile fraction in NPP (raised bog) (LF_{rb}), 8 = Runoff coefficient (raised bog) (R_{rb}), 9 = Non-labile density (fen) (D_{NLf}), 10 = Labile density (fen) (D_{Lf}), 11 = Net primary productivity (fen) (NPP_f), 12 = Labile fraction in NPP (fen) (LF_f), 13 = Aerobic decay rate (fen) (α_{af}), 14 = Anaerobic decay rate (fen) (α_{cf}), 15 = Runoff (fen) (R_f) & 16 = Lake depth (L)

output was LF_{rb}. Increasing LF_{rb} by 10% caused a reduction in the depth and mass of between approximately 25% and 28%, but an increase in the acrotelm depth (ca. 15%). A higher LF_{rb} implies a lower NLF_{rb} and since this material, given time, comes to represent the major component in the

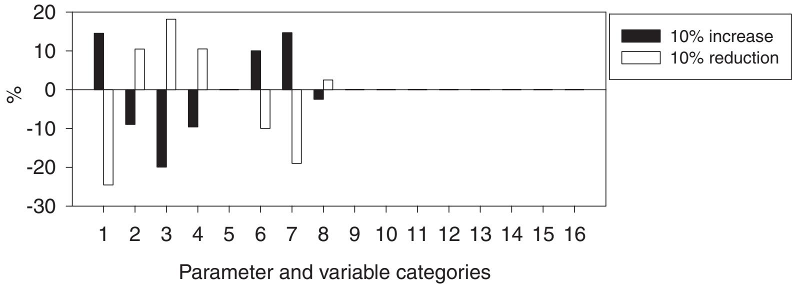

Fig. 6. Sensitivity analysis showing change in acrotelm depth compared to the initial simulation run with a 10% increase/reduction in parameter/variable value. Categories: see Fig. 5.

peat accumulating system, an increase in LF_{rb} would be expected to reduce depth and mass. Similarly, in the acrotelm, the labile mass is increased due to the additional fractions of labile material entering the system which increases volume contribution and thus total parcel volume (height). Additionally, the parcel D_b is reduced delaying the progression to D_{bc} (the trigger for anaerobic decomposition). As a result there are more parcels in the acrotelm and depth is increased (Fig. 6). A similar line of reasoning applies to the situation where the value of LF_{rb} was reduced.

Primary productivity: Changing NPP_{rb} by 10% with respect to the initial simulation value changed acrotelm depth by 10% and total depth and mass projections at 5 000 and 9 000 years by approximately 9% (Figs. 5 and 6). This is the response pattern expected. Increasing NPP_{rb} increased the amount of labile and non-labile material entering the ecosystem and thus increased the depths and masses for all time periods since the parcels were simply larger. The responses were reversed with a decrease in NPP_{rb}. However, modifying NPP_{rb} does not effect the duration that material resides in the acrotelm.

Critical bulk density: The increase in D_{bc} by 10% caused an increase in acrotelm depth of nearly 15% (Fig. 6). This was because the parcel D_b took longer to reach the increased D_{bc} and hence the acrotelm comprised more parcels of OM. Since the catotelm established later and received more highly decomposed OM total depth and cumulative mass at 5 000 and 9 000 years were reduced, despite the acrotelm depth increase (Fig. 5a and 5b). This same analysis applies in reverse where the D_{bc} is reduced.

Labile density: Increasing D_{Lrb} caused a reduction in acrotelm depth of nearly 20% (Fig. 6). This was because labile OM is a significant component in the acrotelm and increasing D_{Lrb} reduced parcel volume such that the acrotelm would occupy less volume (depth). Additionally, because the density of the labile fraction was increased, the D_b of the acrotelm parcels would be increased and thus take less time to reach the D_{bc}. Consequently the acrotelm would comprise fewer parcels of OM which would also decrease depth. A similar line of reasoning applies to the reduction in D_{Lrb}.

Fen parameter and variables

The modification of fen parameters and variables have their greatest impact on the short term scale because the fen completes its development cycle relatively early in the simulation (approximately year 1 500 in the initial simulation run). Clearly the contribution of fen peats to the growing raised bog becomes smaller as time passes (Fig. 5). In relation to the fen and short term model responses to parameter/variable modification, R_f and NPP_f were the most important parameters. Since the R_f is a direct proportion of NPP_f it is more appropriate to consider the impact of NPP_f. As with NPP_{rb}, increasing NPP_f increased the amount of labile and non-labile material entering the ecosystem and thus increased the masses and depths for all time periods. These responses were reversed with a decrease in NPP_f. The evaluation of the other fen parameters D_{Lf} and LF_f are similar to that which applies to their raised bog equivalents. By comparison the modification of the aerobic decay rate (α_{af} and α_{arb}) plays a relatively minor role in determining the shape of the outputs generated by the model.

Fen profiles

The projected duration of fen development (approximately 1 500 years) was shorter than some reported values which have been shown to last up to 4 000 years (Mongan bog) (Parkes, unpublished data, 1999). However, the Bog of Allen (an Irish Midland raised bog) shows fen development as lasting approximately 1 000 years (Mitchell & Ryan 1997). The simulation parameter and variable values generated a fen which existed for a period of time comparable with the early hydroseral phases of Irish raised bogs. Identifying what is significant in controlling the output obtained will guide investigation of specific field sites in terms of trying to identify what the relevant parameter and variable values may have been during the actual local development of such precursor fens.

The projected final depth of fen peat strata at 0.7 m was broadly consistent with data gathered from a selection of Midland bogs in Ireland (Raheenmore, Clara and Mongan bogs) (Bloetjes & van der Meer 1992). In the model the maximum depth of fen peat was set by the depth of the lake. The value used in the initial simulation was based on descriptions of Irish midland topography in the early post-glacial period and represents an average primordial fen lake depth (Mitchell 1986, Mitchell & Ryan 1997). At any specific location, actual depth will depend on lake floor topography. Additionally, the rooting depth of fen plants will limit maximum lake depth although marginal encroachment may allow progressive in-filling of deeper lakes. However, the influence of lake depth on the total depth of the mature bog is relatively minor (Fig. 5).

Raised bog profiles

The model projected a final total peat depth of approximately 10.5 m, raised bog strata of 9.8 m and an acrotelm depth of 0.11 m (Fig. 3). The outputs are consistent with available data for raised bogs in Ireland (Hammond 1981, Bloetjes & van der Meer 1992, Feehan & O'Donovan 1996, Mitchell & Ryan 1997, Barber 1981, Barber & Chambers, unpublished data 1998, Parkes, unpublished data 1999). It is significant to note that the contribution of fen peats to the pattern of raised peat development is substantially reduced after 3 000 years and immaterial after 5 000 years (Figs. 3 and 4).

Rates of peat accumulation responded as NPP varied among climatic periods (Figs. 3 and 4). The model showed that where NPP changed from a higher value to a lower value peat accumulation was retarded. The period of this reduced or even zero rate of peat accumulation varied depending on the magnitude of the changes and the mass of labile material in the peat at that time, but has been shown to last over several hundred years. However, the incorporation of a refractory component in OM ensures that peat growth is never zero. This outcome, while clearly only valid within a specific time frame, is not inconsistent with available evidence (Clymo 1984, Bloetjes & van der Meer 1992, Mitchell & Ryan 1997).

The model projection of cumulative peat mass (173 kg m^{-2} at 1 500 years, 487 kg m^{-2} at 5 000 years and 962 kg m^{-2} at 10 000 years) was greater than reported data for peatland sites in Fennoscandia. Cumulative mass at 5 000 years range from 160–220 kg m^{-2} for sites in Southern Finland and Denmark (Aaby & Tauber 1975, Tolonen 1977). While the model projection was approximately twice these values, data for Mongan bog (an Irish Midland raised bog) shows cumulative masses (assuming an average bulk density of 0.09 Mg m^3) of 180 kg m^{-2} at 1 500 years, 430 kg m^{-2} at 5 000 years and 750 kg m^{-2} at 9 500 years (Barber & Chambers, unpublished data 1998, Parkes, unpublished data 1999). This would suggest that currently the model's output is more consistent with data relating to raised bog development in the Irish Midlands. Given that the model output of depth and mass was reduced by nearly 10% for a 10% reduction in NPP_{rb} (Figs. 5 and 6) suggests that where NPP measures were reduced as might arise where a greater continental influence prevailed (over the last 10 000 years) the depth and mass projections would be reduced making them more comparable to those reported for Fennoscandia. Indeed, Vasander (1982) has reported the contemporary above ground productivity of a south Finnish raised bog at 237 g m^{-2} yr^{-1} which is a value considerably below most of the values used in the initial model run. Additionally, values above

0.8 for the initial labile fraction of OM in NPP have been reported for tundra regions (Heal & French 1974). If these fractional values and modified NPP are used in the model then the depth output approaches 5 m and mass 500 g m^{-2} for a 10 000 year run. This result is much closer to values commonly reported for Fennoscandia. The analysis indicates that the model output can be consistent with data relating to raised bog development in the Irish Midlands (as currently parameterized) but the theory is flexible enough to apply elsewhere.

Conclusion

The model continues to be developed. It introduces a new approach to the determination of bulk density through differential decay and then uses this to control the rate of that decay. Additionally, the model introduces the influence of climate change and examines the contribution of fen peats to the maturing raised bog. Model analysis at this stage is primarily concerned with addressing the issue of whether the assumptions about process are valid and what reliability can be placed on these descriptions. Additionally, this simulation analysis helps raise questions about the possible relationship between parameter and variable values and the influence of prevailing abiotic conditions. To that end this model represents both a synthesis of existing efforts in this area and an advancement in the form of a new tool as an aid to understanding bog development.

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