WORKING PAPER

LARGE-SCALE DISTURBANCE IN BOREAL FOREST DYNAMICS: FIRE, BOG AND SUBSTRATE EFFECTS

Brian E. McLaren

November 1989
WP-89-96

PUBLICATION NUMBER 106 of the
Biosphere Dynamics Project

IIASA
International Institute
for Applied Systems Analysis

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ABOUT THE AUTHOR

Brian E. McLaren was part of the Young Scientist's Summer Program in IIASA in 1989, from the Department of Botany, University of Toronto, Canada M5S 1A1. The following study is one result of Mr. McLaren's participation, with 22 other student and professional scientists, in the global modeling studies conducted in IIASA's Biosphere Dynamics Project throughout the summer of 1989. In addition to producing the current manuscript to define potential new routines for adding realism to available models of boreal forest dynamics, Mr. McLaren coordinated the entry of Chinese and Russian temperature and precipitation data into the project climate data base and aided in the translation into English and the editing of several forestry papers by Russian and Chinese colleagues.

FOREWORD

IIASA's projects within the Environment Program are devoted to investigating the interaction of human development activities and the environment, particularly in terms of the sustainable development of the biosphere. The research is policy-oriented, interdisciplinary, international in scope and heavily dependent on collaboration with a network of research scientists and institutes in many countries. The importance of IIASA's Environment Program stems from the fact that the many components of the planetary life-support systems are being threatened by increasing human activity, and that these problems are not susceptible to solution by singular governments or even, international agencies. Instead, resolution of the difficulties will demand concerted and cooperative actions by many governments and agencies, based on valid understanding of the earth's environmental systems. Establishment of a basis for international cooperation, and production of accurate global environmental perceptions are both hallmarks of IIASA's Environment Program.

Foremost among the global environmental issues of concern are those involving increasing concentrations of greenhouse gases and changing climate. Problem solutions will only become apparent after collection and analysis of pertinent data, testing of relevant hypotheses, genesis of mitigation strategies and investigation of the efficacy of the strategies which are developed. All of these activities can support development of, or be supported by, the appropriate mathematical models of the biosphere. Therefore, the Biosphere Dynamics Project has been focused on the creation of models which can describe the vegetation dynamics portion of the biosphere. The models are being designed to define the biotic and ecological results of measures suggested to slow or stop increases in greenhouse gases. The models must be capable of documenting whether, and if so, by how much, vegetational communities would benefit from mitigation actions, as well as describing how the terrestrial biosphere will respond in its role as carbon source and sink.

One such study is aimed at examining the potential future responses of the world's boreal forests to changes in global climate and atmospheric chemistry. The first step is to incorporate known environment-ecosystem relationships into mathematical models, exemplified by the content of this working paper. The incorporation into models of environmental processes which control the composition and dynamics of northern boreal forests must begin with the critical features of permafrost distribution and dynamics and their interrelationships with vegetation cover. The current working paper provides an essential element in our work to produce a globally-comprehensive mathematical model of boreal forest dynamics, and constitutes a basis for broader studies to be implemented during the summer of 1990 at IIASA.

Bo R. Döös, Leader
IIASA Environment Program

ABSTRACT

This literature survey summarizes the work of authors describing flooding and fire disturbances in forest ecosystems. The development of patterned or aapa bogs in the boreal forest is interpreted as a regional phenomenon closely related to precipitation, soil processes, permafrost and fluctuations in the water table. Peat accumulation is described as a balance between production and decomposition of boreal mosses, with some mention made of ericaceous vascular plants. Factors listed influencing production and decay include physical climate and nutrient concentrations in groundwater. Similar relationships are quantified between physical climate and the probability of forest fire ignition, its spread and its impact on vegetation and organics in the boreal forest. While not all modelling work summarized in this paper was originally written for the boreal forest region, the intention is to adapt a range of models to two subroutines, relating fire occurrence and bog development to the physical climate and the vegetation structure of a Boreal Forest Stand Simulator, thereby incorporating disturbance into a dynamic computer model.

CONTENTS

LARGE-SCALE DISTURBANCE IN BOREAL FOREST DYNAMICS: FIRE, BOG AND SUBSTRATE EFFECTS

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1. INTRODUCTION

This review is intended as a basis for developing subroutines which are to simulate disturbance in the boreal forest. The disturbance regimes described include both bog dynamics in terms of production and decomposition, and the occurrence and effects of forest fire in the boreal forest.

The boreal forest, or taiga, is a zone extending around the globe in subpolar latitudes, below the treeline but north of the deciduous forest zone. It forms an important natural and economic resource for Canada, some of the United States, Scandinavia, the USSR and a small part of China. It is composed of hardy species of Pine (*Pinus*), spruce (*Picea*), larch (*Larix*) and fir (*Abies*), mixed, usually after disturbance, with deciduous hardwoods such as birches (*Betula*), poplar (*Populus*), willow (*Salix*) and alder (*Alnus*). However, mosses and lichens form an important part of the groundcover along with a limited number of herbs. Mosses, especially *Sphagnum* associated with wetlands, are also invaders following disturbance.

Large-scale disturbance is a common feature of boreal forest dynamics. Usually, disturbance by fire is characterized by mortality of spruce crowns and groundcover, and is followed by a succession of hardwoods or pines with serotinous cones. Disturbance caused by changes to the water table, for example accompanying the development of permafrost pans in soil, after iron-pan forming soil processes cause a perched water table, or after flooding brought about by blocked drainage systems, is characterized in comparison by similar tree mortality, but also by increased growth rates of mosses, often leading to the accelerated accumulation of organic matter on the forest floor.

Many positive and negative feedback loops exist in the relationship between these three important components of the boreal forest, namely the active soil organic layer, the boreal forest trees, and the physical process of fire. For example, the formation of wetlands and a thick accumulation of organic material inhibits the growth of pine, birch and poplar, causing these hardwoods to die. On the other hand, deciduous litter produced by birch and poplar can limit the establishment of mosses. Often, however, hydrarchic succession will complete itself by the invasion of a moisture tolerant species over a former bog (in North America, *Larix laricina* or *Picea mariana*; in Eurasia, *Larix dahurica* and other larch species). Fire and the species composition of the boreal forest are also closely related. Certain species of spruce and pine have reproductive strategies geared to invading cleared areas after a burn. They reach sexual maturity very early, so that in areas with frequent fire recurrence, these species come to dominate. Similarly, poplars have evolved rapid means of clonal propagation allowing them to invade burned sites in large numbers, forming short-lived, dense deciduous stands in recently burned areas. In turn, the litter produced by boreal forests can be an important determinant of fire regime. The relationship of fuels to fire intensity and spread is discussed in detail towards the end of this paper. Finally, an important relationship exists between soil organic matter and fire. In the boreal forest, cool temperatures result in very slow rates of decomposition. After some time, large amounts of forest nutrients may become stored in a partly decomposed litter and organic material. These nutrients are only released as ash following a forest fire. A large accumulation of organic material inhibiting a forest cover, such as a peat bog, can, on the other hand, form a barrier to the spread of a forest fire.

An important driving force for the interrelationships described above is, as in all ecosystems, the physical climate. Cooler temperatures and slow evapotranspiration rates typically occurring in the boreal forest often promote saturated soils leading to moss accumulation. However, prolonged periods in summer without rain and with low relative humidity can result in increased burn frequency. Small fluctuations in climate can change the delicate balances between growth of trees, accumulation and decomposition of organic material, and the occurrence of fires.

It is apparent from the above paragraphs that boreal forest interactions, while part of a relatively simple global ecosystem, can be complex to describe. Many mathematical relationships between boreal forest components have been derived by those interested in quantifying forest processes, either to better understand the functioning of the biosphere, or to predict resource capacity of an ecosystem. In many instances discussed in this paper, mathematical relationships among components in the boreal forest have been combined into mathematical models, processed by microcomputers. The reason for developing simulations of an ecosystem are twofold. First, if statistical forest growth models properly approximate natural species relationships and other dynamic biological processes, then it is a good indication that these processes have been realistically parameterized. A model is a test of our biological understanding. Second, running a model under controlled changes of specific parameters can simulate scenarios expected in a dynamic future. A common reason for creating ecosystem models is to simulate a forest stand, to test its trueness to reality, and then to alter the temperature regime in the driving climatic parameters. This possibility allows prediction of future forest changes given the global warming anticipated with the CO_2 greenhouse effect.

The present Boreal Forest Stand Simulator model has been developed from the general gap-model family for which JABOWA is the prototype. Spatial gap models simulate annual changes among a small plot of trees by calculating growth increments for individual trees, by tabulating the addition of new saplings to the stand and by recording the death of trees (Shugart 1984). For the boreal forest, the first applicable model with documentation is FORSKA (Leemans and Prentice 1989); a recent successor has been named FORBOR. The improvements of these models for the boreal forest include calculation of a vertical leaf area distribution for individual tree crowns allowing for realistic light attenuation between individual trees growing at high latitiudes; improved tree growth equations; and also mortality probability which increases when volume increase/leaf area becomes subcritical. Annual changes on a series of simulated approximately 30 m diameter plots are calculated using a variety of subroutines which include, for example, TVXT, to calculate the growth and probability of death of each tree; STAND, to record stand characteristics such as density, basal area, leaf area index and biomass; and SKOT, which allows sprout growth from dead trees, and removal of dead trees from the living array. Running a series of independent plots allows calculation of mean and variance of forest simulations. Timescale is such that subroutines are called annually or biannually. Some of the processes involving natural catastrophe, mortality, etc. are modelled stochastically, while others are deterministic (Leemans and Prentice 1989). Climate and soil moisture relationships are the major extrinsic forcings in the Boreal Stand Simulator. Life history information regarding specific tree species, such as maximum height and age, leaf area index, and tolerance to shade and nutrient stress, is also important. Disturbance to the boreal forest is handled minimally by the FORBOR model.

In this paper, an attempt is made to describe some features of disturbance to forest growth in the boreal region. Parameters which explain variation in bog bryophyte and vascular plant growth and decay are sought, with the eventual hope of linking them to the existing climatic and soil parameters of the Boreal Forest Stand Simulator (Section 2). Similarly, a review of literature concerning the modelling of forest fires is undertaken (Section 3), with the hope of linking previous models to the climatic parameters of the Boreal Forest Stand Simulator.

2. BOREAL FOREST BOGS

2.1. Introduction

Models describing changes to boreal forest floor organic layers with relation to permafrost-induced soil flooding (Bonan 1988a) are the first simple algorithms used in a Boreal Forest Stand Simulator which might have application to moss growth in general, including bog production. Forest floor characteristics from spruce forests in the uplands of interior Alaska were used to parameterize a simple subroutine for moss accumulation as a balance between production and decomposition (Bonan 1988b):

$$dw/dt = P_{max} - a\,w \tag{1}$$

$$w(t) = P_{max}/a\,[\,1 - e^{-at}\,] + w(0)\,e^{-at}\,, \tag{2}$$

and maximum forest floor biomass as t approaches infinity is:

$$\lim w(t) = P_{max}/a = 10\ \mathrm{kgm}^{-2} \tag{3}$$

where w = peat biomass,
P_{max} = annual production, 0.2 kgm^{-2},
and a = annual decomposition rate, 0.02.

The figures above were derived from previous study of interior Alaska, and depth of moss accumulation is similarly calculated from an empirically derived conversion factor. No variation due to external factors is allowed for annual moss production. Because the model was actually designed for permafrost areas of the northern boreal forest, one equation was used to model changes in decomposition rate with soil temperature, as depth of summer thaw, x (in metres):

$$a = 0.024 * 1.642^{(x-0.5)/0.5} \tag{4}$$

Finally, just as moss growth is not limited by external factors in the Bonan model, tree growth is also not limited as it would be by bog enlargement. Only three simple limits to moss growth are included: The percent of the growing season in which water content is below the wilting point is used to limit moss growth in relation to soil moisture conditions. Mosses are not allowed to grow if this value exceeds 10%. Secondly, because moss productivity is reduced by high light levels, mosses are not allowed to grow if available light on the forest floor exceeds 75%. Thirdly, deciduous leaf litter inhibits the establishment and growth of mosses, so that where the deciduous leaf area is greater than 50% of the total leaf area, mosses are not allowed to become established (Bonan 1988b).

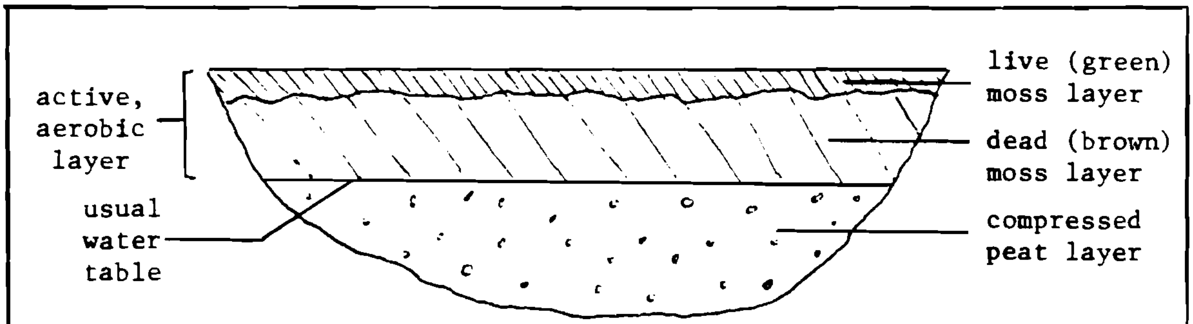


Figure 1. Typical bog cross-section, showing three-layered structure useful in considering moss and peat dynamics separately.

Further improvements to this original simulation of moss growth (forest floor dynamics) were later provided, which allow for modelling bog growth (Bonan and Korzukhin 1989). If a bog is envisioned as a three-layered entity (Figure 1), with a layer of live moss and a layer of actively decomposing dead moss supported by a layer of compressed peat, then the Bonan and Korzukhin (1989) moss growth subroutine describes the upper layer dynamics using a variety of improvements over Bonan's (1988a) model. These improvements were based on moss physiology. Equations were derived for live (green) and dead (brown) moss, both in the upper "active layer" (Figure 1), such that:

$$dm_1/dt = q_1 m_1(P_{max} p(L)-(R+b)) \quad (5)$$

and $$dm_2/dt = q_1 b m_1 - a m_2 \quad (6)$$

where m_1 = biomass of green moss
m_2 = biomass of brown moss
q_1 = conversion factor from leaf biomass to surface area
P_{max} = maximum unshaded assimilation per unit leaf area
$p(L)$ = reduction of assimilation as a function of L
L = light intensity
R = respiration rate per unit leaf area
b = decay rate per unit leaf area
and a = annual decomposition rate.

Further observations reveal that the light function, p(l) is a hyperbola, where:

$$p(L) = a_1 \frac{L - a_3}{1 + a_2 p}, \quad (7)$$

and $a_1 = 3.41$, $a_2 = 2.14$ and $a_3 = 0.08$ for a typical moss layer. Also,

$$L = L_0 e^{-k(q1\ m1\ /2)}, \quad (8)$$

where k is a light extinction coefficient, 0.90, and L_0 is the light intensity at the top of the moss layer. Assuming that dm_1/dt is zero for $m_1 = M_1$, the maximum green biomass, and that dm_2/dt is zero for $m_2 = M_2$, the maximum brown biomass, then:

$$q_1 = - \frac{2}{k\ M_1} \ln\left(\frac{a_3 + x}{1 - a_2 x}\right), \quad (9)$$

where $$x = \frac{R + b}{P_{max}\ a_1}; \quad (10)$$

and $$b = (a / q_1) * (M_2 / M_1). \quad (11)$$

The other aspect of the bog, the dynamics of the peat layer, is controlled by the height of the dead moss layer, h_2, in relation to the height of the water table, h, according to the model described by Antonovsky *et al.* (1987). Simply, when $h_2 < h$, anaerobic conditions preclude decomposition of the dead moss, and the bog grows. When $h_2 > h$, the part of the dead moss layer that is above the water table decomposes, while the part below does not.

Later improvements to the model considered tree growth on bogs. Optimal tree growth and regeneration should be reduced as the water table rises and anaerobic soil conditions increase. Species differ in their response to anaerobic soil conditions. This difference is handled in the model by classifying species according to their ability to grow on bogs. It is also possible to model some moss-tree interactions (Bonan and Korzukhin 1989). The first step is to replace the term $P_{max}p(L)$ in Eq. (5) above with:

$$P = P_{max}\ f_1\ f_2\ f_3\ f_4, \quad (12)$$

where f_1 = degree that trees shade moss
f_2 = degree that an open forest canopy limits assimilation
f_3 = deciduous leaf litter effect
and f_4 = soil moisture effect.

A series of values for the above factors are documented for various situations in Bonan and Korzukhin (1989).

Relationships between moss growth and tree survival are further described in the above paper, and included in the life history characteristics of individual tree species. For example, a thick (5-8 cm) moss layer precludes successful regeneration of many species of *Pinus*, *Betula*, *Picea* and *Populus*. Other species such as *Pinus sibirica* require a thick layer of organic material for successful regeneration. From the opposite perspective, mosses thrive in moist, shaded conditions, and as a forest canopy becomes more open, moss productivity declines. If, however, the canopy is too dense, mosses will be shaded out. Including these restrictions in the forest simulation resulted in the following results when running the model:

- on extremely cold, wet sites, a thick moss layer develops, precluding tree growth
- on slightly warmer sites, a thick (20-30 cm) moss layer still dominates the vegetation, but *Picea* can grow
- on warm, mesic sites the forest is initially dominated by *Betula* and *Populus*, and trees of these species prevent the formation of a moss layer; as they die and are replaced by longer-lived, shade-tolerant *Picea* trees, a thin (5-10 cm) moss layer grows on the forest floor
- on warm, dry sites the forest is completely dominated by *Betula* and *Populus* and mosses cannot grow (Bonan and Korzukhin 1989).

While the progress in modelling two-layered moss development has succeeded in more accurately describing moss dynamics based on physiology, developed models do not necessarily include all parameters influencing bog development. For example, although a living and a dead moss layer are individually modelled to form a bog complex, the interaction of the entire complex with external factors, such as annual precipitation, the fluctuation of the water table, changes in soil chemistry, the occurrence of snowfall or the presence of permafrost, may not have been adequately parameterized. The factors initiating bog development, as well as the influences controlling changes in peat production and decomposition rates, are important to consider.

The literature summary which follows is an attempt to describe first the types of bog formation associated with the boreal forest, and then to summarize interactions of external factors on the boreal forest bog, with enough detail to later include them in a model. The modelling of forest stands will later have a larger scope for decision making. Expected changes in climatic parameters or in disturbance regimes can be forecasted for the boreal forest. The modelling of bogs as a part of developing future scenarios also has an integral role in deciding future use of the boreal forest for industry or recreation, or for planning its restoration and conservation.

2.2. Bog Development

Three types of bog landscapes are identified with the boreal forest. These are raised bogs, blanket bogs and patterned bogs.

2.2.1. Raised Bogs

Raised bogs occur confined to local depressions, where microclimate conditions and poor drainage combine to produce moss growth wherever trees are inhibited. Sedges and dwarf shrubs are the dominating vascular plants. These mires originated during the Postglacial, and continuous peat accumulation has since formed a typical convex dome shape. In the boreal forest, raised bogs often occur at the southern margin, where warmer or drier conditions do not permit extensive bog growth, but rather, bogs are limited to localized areas. Size is perhaps a few hundred hectares, and depth of peat accumulation several metres, raised a few metres above the surrounding land (Gore 1983).

2.2.2. *Blanket Bogs*

Blanket bogs, in contrast to raised bogs, form over extensive, undulating terrain and are not confined to depressions. They are usually formed in response to a very humid climate, i.e. where precipitation exceeds evapotranspiration (Gore 1983). Except for the fact that blanket bogs are not typically associated with exposed water bodies, they are most similar in size and biology to the expansive formations which characterize the bogs in the boreal forest (patterned bogs).

2.2.3. *Patterned Bogs*

Patterned bogs is the term best used to describe the bog formations in the boreal forest, which typically follow drainage patterns, and are associated with surface, stagnating water tables. Patterned bogs develop a patchwork landscape over the boreal forest by interrupting large expanses of timber. The Canadian word "muskeg" and the Finnish word "aapa" are also correct ways of referring to patterned bog formation. In most biological characteristics, patterned bogs are similar to blanket bogs, and factors describing moss growth in blanket bogs can be considered interchangeably with those influencing muskeg.

2.2.4. *Background Information*

References have been reviewed from Great Britain, Scandinavia, the Netherlands, Germany, the Soviet Union, Canada and the United States. By far the greatest number of studies on contemporary ecology of bogs involves raised bogs on a local scale. More useful literature for boreal forest studies clearly involves blanket bogs, which are referenced in specific literature below. Paleoecological studies are available but factors accounting for prehistoric bog dynamics are more often theoretical extrapolations which are less useful to the present purpose.

2.2.5. *Rates of Production and Decomposition*

For vascular plants and for bryophytes typically found in raised and blanket bogs, an excellent summary of growth rates drawn from a variety of referenced studies exists in a table format in a chapter by Bradbury and Grace (1983), pp. 290-291. References may be easily pursued for more detailed data. For blanket bogs, Clymo and Reddaway (1974) provide mean growth rates plus standard deviations of 41 to 276 samples of *Sphagnum rubellum* in three bog sites. Similarly, Forrest (1971) provides a summary of such data for vascular and non-vascular species in a blanket bog (p. 469). All units are in $gm^{-2}yr^{-1}$. For specific information on height increases in bog vegetation, Van der Molen and Hoekstra (1988) provide summary tables for both bryophytes and vascular plants above the water table in cm (p. 265). References are provided (p. 264), and, again, more detailed data can be pursued. Very general summaries of bog production are also available in Clymo (1983).

In general, vascular plant production is 100-800 $gm^{-2}yr^{-1}$. Production of *Sphagnum* varies with bog microtopography but is roughly equal to 150 $gm^{-2}yr^{-1}$ on hummocks, 500 $gm^{-2}yr^{-1}$ on lawns and 800 $gm^{-2}yr^{-1}$ in hollows. Height increases may reach 12 $cmyr^{-1}$, and a maximum production rate of 1400 $gm^{-2}yr^{-1}$ is considered as a broadly defined upper growth limit (Clymo 1983).

The opposite aspect to consider is rate of decomposition. Empirical measurements of decay rates in many bogs, studied experimentally as percent annual loss in weight, exist for both bryophytes and for various organs of vascular bog plants. See especially Clymo (1983), Figures 4.22 to 4.25 and Table 4.13, pp. 202-207. Unfortunately, no general decay rates can be quoted. "The biggest single gap is the lack of reliable estimates of the actual rate of decay deep in the peat" (Clymo 1983). Also, no information, other than various paleoecological interpolations, exist for the relationship between height of peat domes and the density of the compacted peat layer in a bog.

2.3. Factors Influencing Bog Production

The current issue involves the factors accounting for the variation documented in production rates, which are listed below:

2.3.1. Water Budget

Very general summaries of bog ecosystems point out that positive water balances are essential for development, survival and stability of muskegs (Terasmae 1977). That is, unless inputs from precipitation (P) and inflows (WI) are larger than rate of evapotranspiration (Et) and runoff (R), muskeg will not develop. Where water balances were previously positive, but, subsequently $P + WI < Et + R$, existing bogs become increasingly restricted to lowland areas and local depressions. Survival of the bog then depends on intrinsic factors, such as depressed pH, water-holding capacity of peat and microclimate.

In modelling the basic water budget of a bog, the variables P, WI and R above are independent of the wetland itself. Water inputs from precipitation, P, can be derived from the climatic parameters of the Boreal Forest Stand Simulator. For most purposes when considering grid cells independently, it is my opinion that $WI = R$ is an adequate approximation which avoids the necessity of calculating inflows and runoff. However, there are references available describing models of bog hydrology with regard to channel flow, overland flow, capillary action as pipe flow, and water storage (Ingram 1983). The fourth variable in the water budget which must be modelled, both because it determines whether or not $P > Et$ and the conditions necessary for bog initiation or development are met, and because it interacts with the water table, an important factor in determining peat accumulation rates, is Et_{bog}, evapotranspiration from the bog. [In a vegetation model, depending on the size of the bog relative to the size of the simulated forest plot, Et_{bog} may be equal to or just a fraction of the total evapotranspiration, Et.]

A detailed mathematical model for explaining bog development and peat accumulation on sloped blanket bogs (Wildi 1978) contains a simple relationship between evapotranspiration rate and amount of water present in a bog, showing how the water balance is highly dependent on the height of the water table, expressed as the mass of dry (aerated) peat, m-w/wc. The equation developed shows that there is an exponential decline in evapotranspiration rate with lowering of the water table, such that:

$$Et_{bog} = E * e^{k*(m-w/wc)}, \qquad (13)$$

where $E =$ evaporation rate when water is at the peat surface, obtainable from surface water evaporation rates ($160\ cmyr^{-1}$ were assumed for Wildi's simulations)

$k =$ proportionality factor derived from regression analysis of evapotranspiration values highly correlated with amount of water on selected local raised bog sites (Neuhaeusl 1975) as well as with the most frequent water table height in the blanket bogs studied by Wildi (1978) himself. Eq. 13 gives a significantly better fit to these data than any linear model; for Wildi (1978), $k = -0.077\ cm^{-1}$

$m =$ active moss biomass (in $10gdm^{-2}$), i.e. the living layer; Wildi's initial value, $m = 6$

$w =$ amount of water (in $100gdm^{-2}$), initial value $= 4$

$wc =$ specific water holding capacity of moss $= 0.95$.

2.3.2. Climate and Landscape

The requirement of cool, moist climates for bog formation helps to explain its present association with the boreal forest zone. In the past, muskeg distribution is known to have undergone a marked expansion outside its Glacial refugia in Yukon and Alaska, about 5000-6000 B.P., in response to a cooling of climate that was accompanied by an increase in available moisture (Terasmae 1977). This period appears in pollen records from northwestern Canada as a decline in white spruce, *Picea glauca*, after a period of dominance in the early Holocene. At sites near or north of the modern treeline, this mid-Holocene white spruce pollen decline is thought to reflect the southward movement of the limit of trees in response to a cooling of summer temperatures. However, within the boreal forest, *Picea glauca* was replaced by other boreal trees associated with thick moss mats and soil organic layers, increasingly moist soils and the development of permafrost, e.g. *Picea mariana* and *Betula papyrifera*. This pollen zone boundary is frequently accompanied by stratigraphic transitions from mineral soils to peat layers (Ritchie 1987), indicating that bog development occurred synchronously with southward migration of the treeline, development of permafrost (see Section 2.3.6), and a general cooling of the climate. The present distribution of bog vegetation types in North America and Eurasia is shown in Figures 2 and 3. The relationships between the distribution of the bog types and climate can be determined by comparison with climatologic maps.

Seasonal distribution of rainfall and snow is also important to bog formation. Humidity requirements for bog development cannot be met if large amounts of rainfall occur only in very short periods of time at specific times of the year. Also, if more precipitation falls as snow rather than rain, a sudden influx of meltwater will not meet conditions for muskeg development (Terasmae 1977).

Association of bogs with particular substrates or geomorphic landscapes only becomes obvious in the extreme southern boundary of the muskeg region, the so-called transition zone (Terasmae 1977). Here, for example, raised peat bogs may be limited to landforms characterized by cooler depressions, such as the kettle depressions in a moraine landscape. Flat basins or river valleys are also prone to bog formations, as are lowlands accompanying rivers but separated from them by sand and gravel deposited during floods. Water-impermeable soil sediments such as clay deposits, especially if they are periodically saturated with slowly running or stagnant water, are often covered by bogs (Frenzel 1983).

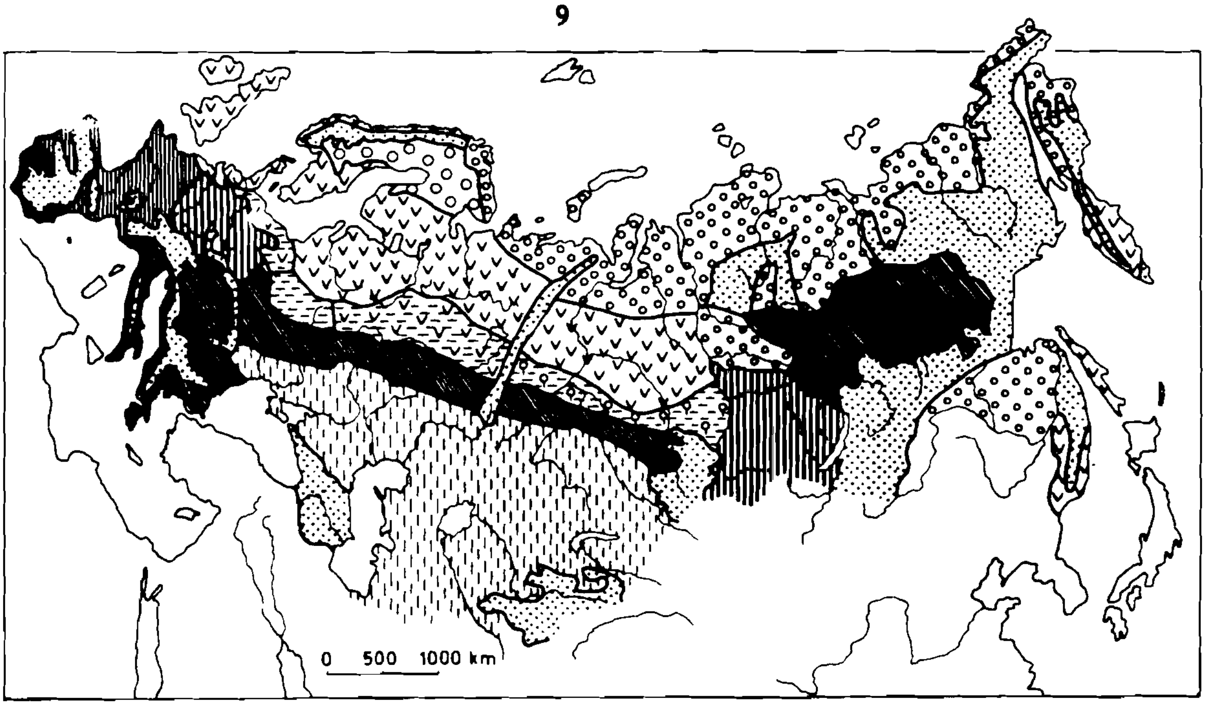
In other cases, bogs may create their own soil conditions for self-perpetuation by iron pan forming processes. Iron leached from the organic horizon may develop into a pan, which creates a perched water table, later forming an isolated bog. Enhanced iron pan formation may later lead to the spread of the bog. This soil process was described in detail for a Sytomino catena in Siberia by Karavaeva (1982).

In some cases, paludification may accompany soil changes brought about by a cooling and moistening of the climate. Climate may favour the leaching of soils, producing a deficiency in mineral nutrients. It is then possible that an acidophilic shrub vegetation expands into this area, replacing the former forest stand (Frenzel 1983). Moistness and coolness of climate then stimulates the accumulation of peat in a variety of ways.

2.3.3. Water Table

Fluctuations in local water table appear to be the most critical factor in determining rates of production and decay of bog vegetation. For raised bogs, this was discovered as early as 1932 (Granlund 1932): "So far I have exclusively discussed the importance of the water supply in the formation of raised bogs. Naturally, many other factors might be relevant, such as different peat-forming plants in different areas, temperature fluctuations, etc. However, all these factors have such a small influence that it is impossible to observe the results of their action on the main features of the growth mechanism of the raised bog."

Maximum growth in height of many species of *Sphagnum*, e.g. *S. cuspidatum*, *S. fuscum*, *S. compactum* and *S. nemoreum* occurs during a rise in the water table (Clymo 1983; also McLaren 1989). However, the exact effects on growth rate depend on the species, and whether increase in height or increase in weight are being considered. Laboratory growth experiments with twelve species of *Sphagnum* (Clymo 1973) show that for most species, shading combined with a high water table reduces growth in weight. On the other hand, five species of *Sphagnum* increase their rate of extension under wetter conditions. Clymo (1973) hypothesizes that reduced weight growth for the same species may be due to the increased liquid diffusion path for CO_2. In summary, regarding the complex behaviour of *Sphagnum* with changes in the water table, Clymo (1973) summarizes that: "No obvious pattern emerges though there is perhaps some indication that growth in length with a low water table is less reduced for the species which normally grow in drier habitats."



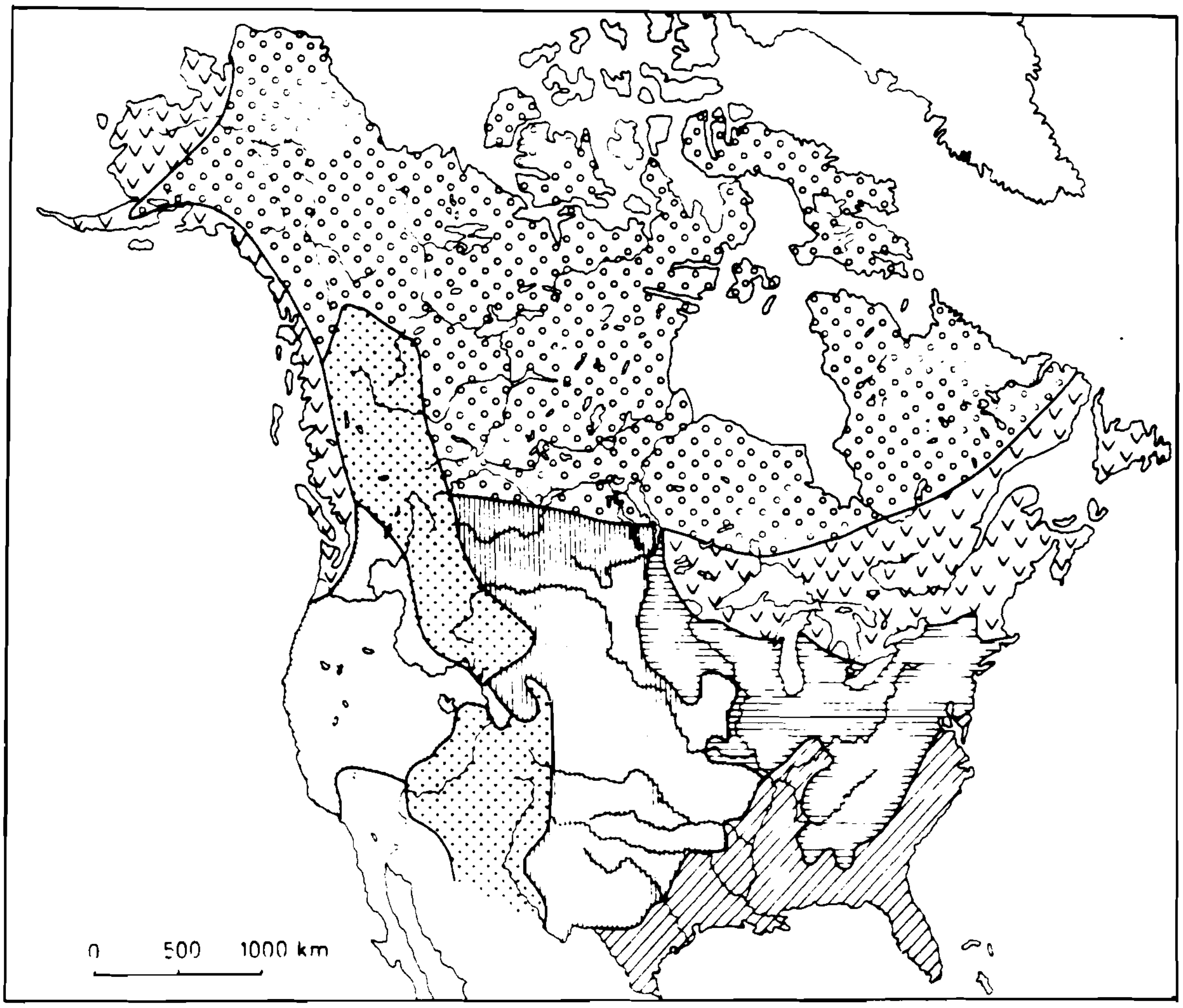
BOG REGIONS:

○ ○	Region characterized by patterned bogs; classified by Frenzel (1983) as aapa bogs typical of the Finnish boreal forest.
° ° °	Bogs associated with the boreal forest region, but occurring together with permafrost. This region also includes some wetlands classified as fens, a broader term including a wider range of pH and species. An attempt to describe the modelling of more general wetland types is not made in this paper.
V V	A region more generally characterized by blanket bogs, patterned bogs and raised bogs.
V - V	An area in which typical bogs become relatively rare; wetland areas of other types do occur, however, with or without scrub or woodland vegetation.
- - -	Typical bogs again rare; wetlands occur only with herb and moss vegetation.
♀ - ♀	Wetlands widely distributed, but most outside the classification range of the bog types discussed in this report.
▥	Bogs very rare; various other wetland types occur.

WETLAND REGIONS WITHOUT BOGS:

‖‖‖	Wetlands limited to forest swamps, overgrown by coniferous and deciduous trees.
▨	Fens and other wetland vegetation rich in herbs; tree cover very sparse.
| |	Fens characterized by strongly humified peat; this humification increases steadily to the south.
⁘	Mountainous regions where various wetland types occur relative to local topography.

Figure 2. Provinces of wetland types in northern Eurasia (Kats 1958; as published in Frenzel 1983).



BOG REGIONS:

◦◦ Bogs associated with the boreal forest region, but occurring together with permafrost. This region also includes some wetlands classified as fens, a broader term including a wider range of pH and species. An attempt to describe the modelling of more general wetland types is not made in this paper.

V V A region more generally characterized by blanket bogs, patterned bogs and raised bogs.

▥ Bogs very rare; various other wetland types occur.

WETLAND REGIONS WITHOUT BOGS:

▤ Wetlands limited to forest swamps, densely overgrown by deciduous trees.

▨ Forest swamps rich in relics of Tertiary times; some treeless fens occur. This region includes mangrove vegetation often found close to the sea-shore and in brackish water.

⁙ Mountainous regions where various wetland types occur relative to local topography.

Figure 3. Provinces of wetland types in North America (Kats 1958, 1959; as published in Frenzel 1983).

To give an example of the adaptations of *Sphagnum* to conditions of flooding and drought, Van der Molen and Hoekstra (1988, pp. 252, 262) created an historical humidity index by analysis of the *Sphagnum* species present in peat cores, and by rhizopod analysis. High humidity index corresponded to communities belonging to dry habitats. These authors concluded, after paleoecological analysis of a core into a raised bog in the Netherlands, that peat accumulation rate was well correlated with this humidity index, with drier circumstances resulting from a lowering of the water table leading to higher mean peat accumulation rates. Drier (hummock) communities were dominated by the faster-growing *Sphagnum imbricatum*, and wetter communities were always slower-growing and dominated by *S. cuspidatum*.

In conclusion, the relationship between peat accumulation and water table fluctuations can only be generalized, and varies considerably for different bog communities, and also within the microtopography of a single bog. For example, many studies show that, contrary to the results of Van der Molen and Hoekstra (1988), hollows have faster peat accumulation rates than hummocks (Barber 1981; Clymo 1983). Very early studies show that reduction in net photosynthesis occurs when *Sphagnum* grows in dry conditions (Clymo 1973). The *Sphagnum* communities on hollows and hummocks clearly vary considerably. The communities are well summarized for North America in Kenkel (1988) and for Europe in Van der Molen and Hoekstra (1988). The laboratory experiments of Clymo (1973) failed to show why there exists a distinction in the communities on hummocks and hollows, since certain field conditions, for example rare extremes in climate, were impossible to duplicate in the greenhouse. Field transplants of *Sphagnum* have illustrated that generally greater growth occurs in wetter habitats, but that each species grows better than competitors in the specific habitat which it normally occupies (Clymo 1970). It is impossible to derive reliable growth rate-water table relationships even about individual species of *Sphagnum*, however. Field experiments cannot be carried out easily; the experiments of Clymo (1973) are for simulated conditions and are based on two replicates only; presumably, repeating the experiment might yield very different results.

More universal models have been developed for raised bogs, which associate the amount of precipitation received in a bog, and the height of the peat dome, which could be used to predict increases in peat dome convexity (hence, accumulation rates). Granlund (1932) and Wickman (1951) define maximum height above the water table,

$$J^2 = k (P - b) , \tag{14}$$

where P = mean annual precipitation,
b = an evapotranspiration constant, given as 480 mm/yr
k is proportional to various bog size classes.

For bogs with diameters of 1000 m, Wickman (1951) found that the relationship above produced a coefficient of correlation of 0.998. If bogs of such a size class are to be modelled, it is my belief that a relationship between peat accumulation rates and moss height, together with the above strongly correlated relationship between changes in water table and forced changes in bog height, could effectively link climate change to peat accumulation.

A final consideration of water table is its effect on tree growth. Limiting the growth of trees is an important feature of bogs. One of the most useful models which considers the survival of trees with relation to the height of the water table is briefly presented here. Phipps (1979) created a computer program SWAMP, which considered the effects of flooding on trees in the southern wetlands forest of the United States. His equation,

$$H = 1 - 0.05511 (T - W) \tag{15}$$

where H = growth multiplier for a given species for one year
T = water table depth (cm)
and W = optimum water table depth for the given species,

was part of a subroutine WATER, which gauged the growth of trees according to the height of the water table. The equation was empirically derived for a forest reserve in Arkansas, but presumably the same approach could be used to model the response of boreal forest trees growing on bogs, given studies of their optimum water table depth.

2.3.4. Cation Concentration

In the laboratory experiments of Clymo (1973), pH and Ca^{2+} were also used as variables, with experimental ranges larger than those normally experienced by most species of *Sphagnum*, in contrast to the experimental heights of the water table which were well within natural ranges. However, the effects of these two variables on moss growth were smaller than those created with fluctuation in water table. Nevertheless, high pH associated with high Ca^{2+} concentration caused some death of individuals. In the field, this combination of conditions also inhibits the occurrence of *Sphagnum*.

Wildi (1978) suggested that the sum of alkali cations in a bog, especially the concentration of Ca^{2+}, may be a limiting factor. He modelled the nutrient component of a bog by generalizing a cation with molecular weight of 25 and a valence of 1, creating a charge density close to that of Ca^{2+}, and assumed that peat exchanges these cations with a specific cation capacity of 150 mmol/100 g valence. Base saturation as a percent is:

$$\begin{aligned} b &= 100 * 10 * 1000 * x / 150 / 25 / m \ , \\ &= 267\ x / m \end{aligned} \qquad (16)$$

where x = mass of dissolved nutrients in gdm^{-2}, given an initial value of 1 in Wildi's simulations

m = peat biomass, as in (Eq. 13) above.

Field observations then suggest that nutrient concentration in bog water, c, depends directly on base saturation. Regression analysis of base saturation and nutrient concentration in Wildi's (1978) field data revealed that:

$$c = 10^{0.42*(1.65-\ln(100/b-1))} \qquad (17)$$

Finally, many growth experiments with *Sphagnum* show that the biomass of bog plants (hence, rate of peat accumulation) increases with increasing nutrient concentration. Clymo (1973) showed that there is a positive correlation between growth and supply of inorganic ions for most species. However, *Sphagnum* plants tend to die off faster with increasing nutrient concentration. This puts an upper limit on the cation concentrations in which bogs will develop. The Ca^{2+} limit corresponds, for generalized modelling purposes, to a pH of 4.5 (Rudolph 1963).

The Michaelis-Menten equation for plant growth was also used by Wildi (1978) in his sloped bog models, and has general application to modelling the influence of soil nutrient concentrations on bog development. The equation is:

$$V_c = V_{max} \frac{c}{KS + c} \ , \qquad (18)$$

where V_c = growth rate at nutrient concentration, c and

KS = Michaelis constant, about 2.5 ppm for bog plants (Clymo 1973).

Bog plants contribute to some peat accumulation, and the growth of ericads often provides a support for *Sphagnum* growth. Therefore, increase in height of peat mosses is closely correlated with growth rates of bog plants. This is the finding of Clymo and Reddaway (1974), working with *Calluna vulgaris*, and of McLaren (1989), working with *Chamaedaphne calyculata*. If this relationship is considered useful, Wildi (1978) provides a differential equation modelling the growth of bog plants, using the Michaelis constant.

2.3.5. *Weight of Snowfall*

Past studies of production in blanket bogs point to a further factor controlling peat growth rates (Clymo and Reddaway 1974; Forrest 1971). Apparently, a major stress on the surface moss layers is weight of snow. Thirty centimetres of snow may produce a stress of about 3 gcm^{-2}. Such compression limits the growth and erectness of ericad stems, e.g. *Calluna vulgaris*. *Sphagnum* growth rate is known to be positively correlated with the above-ground biomass of *Calluna* (Clymo and Reddaway 1974). Other factors influencing compression of heath stems possibly include high winds and mean snow depth (Forrest 1971).

Furthermore, snowfall has been shown through field studies of boreal forest muskeg to be extremely important in determining seasonal flow of heat through peat layers, and depth of freezing (Brown 1977). The importance of the thermal conductivity of peat to bog growth and permafrost is discussed in Section 2.3.6 below.

2.3.6. *Occurrence of Permafrost*

Present literature is weak regarding the relationship between permafrost and muskeg, as it developed shortly after deglaciation of the boreal forest region (Terasmae 1977). It is assumed that bogs are abundant in the permafrost zone, because an impervious layer in the soil often keeps the water table high. In such conditions, surface water may be present in abundance even when annual precipitation is low.

On the other hand, peat provides thermal insulation which helps to maintain the permafrost. More precisely, during summer, surface layers of peat become drier through evaporation. Thermal conductivity of dry peat is low, and warming of the underlying soil is impeded. Secondly, when peat freezes, its thermal conductivity increases considerably. Hence, less resistance is offered to the winter cooling of the underlying soil than to its warming in summer. When conditions, dependent on thickness and compactness of the peat layer, rates of evapotranspiration, and conductivity of the peat, are such that the underlying soil remains below 0°C throughout the year, permafrost results (Brown 1977). There is a further positive feedback relationship. As permafrost spreads, and depth to soil thaw decreases, there is an accompanying decrease in the decomposition rate of peat. Therefore, the peat layer becomes thicker, and further promotes the development of permafrost (G. Bonan, 1989 personal communication).

In the early Holocene, there is indication that permafrost aggradation occurred widespread, in response to the accumulation of peat (see Section 2.3.2), for example in poorly drained sites along the MacKenzie River valley (Ritchie 1987). This relationship between bog development and permafrost indicates that permafrost should be more resistant to thawing given future temperature increases in areas dominated by bog vegetation than in exposed areas.

2.3.7. *Anthropogenic Influence*

The work of many paleoecologists suggests that paludification may be closely related to patterns of human agriculture. Particularly the spread of blanket bogs in the United Kingdom and Western Europe is tied to the period of forest clearance by man. Frenzel (1983) lists 15 bogs in Ireland and Scotland where the beginning of the formation of blanket bogs is known to coincide with the onset of agriculture, land clearance and the devastation of natural forests. Iversen (1964) cites a location in Denmark where replacement of a dense oak forest with a *Calluna* bog occurs with a marked charcoal layer in the stratigraphy. Work in a raised bog in Ontario revealed a similar charcoal layer immediately below a level of accelerated peat growth (McLaren 1989). Both examples suggest forest removal by fire can stimulate bog growth. In the Hunsruck Mountains, West Germany, overgrazing of beech forests is similarly known to have led to the spread of acidophilic ericaceous (bog) plants. Likely, land clearing changes the rates of runoff and transpiration, increases soil wetness, and leads to the accumulation of peat (Frenzel 1983).

These observations of anthropogenic influence may be less useful to simulating boreal forest bog growth. However, it may be important to consider that sudden forest clearance (which can easily occur in the boreal forest given fires, pest epidemics, etc.) can lead to the spread of bogs. This spread can be a direct result of soil moisture changes, or an indirect result of soil erosion following loss of forest cover on adjacent sloped ground. The downwash of fine silt onto previous permeable river soils could increase the incidence of flooding and result in the spread of a patterned bog landscape (Frenzel 1983). Finally, it is worth mentioning that the work of the beaver in changing drainage patterns and soil moisture conditions, which also can ultimately lead to bog formation, is not to be underestimated.

2.4. Modelling Bog Decomposition

A final consideration in the modelling of bog development is, of course, peat decay rates. Recall that models are at present very simple and based on empirical data. Peat decay rates are not modelled with external factors, with the exception of the water table relationship of Antonovsky *et al.* (1987). In this document, a theoretical model is described in ample detail. Further relationships concerning peat decay are described below.

Because the thickness of a blanket of peat remains fairly constant over time, decay rates must vary to some extent with production rates. Many models describe the function as:

$$dM/dt = -aM \quad \text{(or)} \quad \ln(M_t/M_0) = -at, \tag{19}$$

where a = decay rate and M = total peat biomass of active and dead moss layers (Clymo 1983). With the assumption that decay rate is a function of the amount of total moss available, the amount of net peat accumulation becomes

$$x = p/a*(1-e^{-at}), \tag{20}$$

where p = production rate and is balanced with the rate of decay. That is, the ratio p/a becomes the steady state total peat biomass. Clymo and Reddaway (1974) estimate for North Pennine blanket bogs that about 5% of the total *Sphagnum* biomass is decomposed annually (i.e. a = 0.05).

There are other indications that decay models can become more complex. Recall that Rudolph (1963) has found that *Sphagnum* plants die off more quickly with increasing nutrient concentration. Wildi's (1978) model allows soil aeration and the increased availability of alkali substances to accelerate the decomposition of the active layer of moss. This more accurate model is as follows:

$$dm/dt = a * b^k * (m-w/wc), \tag{21}$$

where
a = decay rate (as in Eq. 19)
b = percent base saturation (as in Eq. 16)
k = proportionality factor for decomposition = 0.2
m = peat biomass of the active layer }
w = mass of water in active layer } as in Eq. 13
wc = water holding capacity for peat }

In Eq. 21, the expression in parentheses is a factor that incorporates the proportion of aerated (water-free) peat. The parameters a and k are empirically derived.

For bog plants, decay rate also changes constantly (Wildi 1978). The relationship is this time with nutrient concentration as c above (Eq. 14), where:

$$\text{decay rate} = d_i * e^{kc} \tag{22}$$

d_i = initial death rate, conservatively estimated to be 0.25 at zero nutrient concentration (Wildi 1978)
k = proportionality factor for death rate = 0.462 ppm^{-1}.

Decay rate of vascular plants increases exponentially as cation concentration, c, increases linearly.

Lastly, there is data available showing a decrease in decomposition rate of peat for an increase in the height of the permanently frozen soil layer (G. Bonan, 1989 personal communication), another factor linking bog development to the occurrence of permafrost in northern boreal forest areas.

3. FOREST FIRE DYNAMICS

3.1. Introduction

Contrary to the situation for the modelling of bogs, many adequate mathematical models exist which describe the behaviour of fire in many forest ecosystems. However, there is also great variety in the usefulness of these models and the literature in developing a subroutine for fire behaviour in the Boreal Forest Stand Simulator. First, although fire occurs in many ecosystems, concentration must be on models and equations developed specifically for boreal forest litter. Also, not all existing models are linked to climatic parameters, even though climatic controls on fire occurrence are very important. Soil organics and climate will be carefully considered in this section. Furthermore, models specifically developed for a small regional scale will be described, and attention will be given to the effects of fire in relation to injury to trees and to the survival and regeneration of post-fire species.

3.2. Fire Occurrence and Climate

The relationship between fire models and climate has been indeed very simple in the past. In the only boreal forest model to consider fire subroutines, Bonan (1988a) simulates fire occurrence by using an inverse of documented recurrence intervals in North America. The model does consider regional patterns which influence recurrence time, such as increasing recurrence intervals eastward over North America (with more moist conditions) and increasing intervals toward the treeline (related to air mass movements). A model written for high-altitude Australian *Eucalyptus* forests (Noble *et al.* 1980) is even more simplified. Climatic records from the area provide only an average recurrence interval, whose inverse is used to plot a constant random probability of a wildfire occurring any given year. However, one feature of this model is that prescribed burns are modelled as a probability function of time since a previous fire. This may be useful to forest models, as prescribed fires are becoming a regular interval management practice for many ecosystems. In summary, though, both the Bonan and the Noble models use only a fire probability function to randomly call fires into the forest plot.

The Canadian Fire Weather Index (FWI) (Van Wagner 1987) is a set of models written in the form of a FORTRAN program, which is used by the Canadian government in predicting the probability of fire occurrence in the boreal forest. Although the model makes no attempt to describe post-fire vegetational changes or succession, it is most useful in coupling climate with fire regime.

Two advantages exist in the FWI model. First, soil moisture parameters, the fuel loading and drought codes, were developed for a generalized jackpine/lodgepole pine forest, which is appropriate for all of the North American boreal forest, and can also likely be transferred to Pinus forests of Siberia and China. Second, fire occurrence probability is based on the FWI, which is realistically dependent on climatic data.

The structure of the index system is such that the forest floor is divided into three fuel moisture complexes:

(1) FFMC or Fine Fuel Moisture Code, a numerical rating of the moisture content of litter and other fine fuels,
(2) DMC or Duff Moisture Code, including loosely compacted organic layers of moderate depth and medium-sized woody material, and
(3) DC or Drought Code, for deep, compact organic layers.

Weather observations are begun on the third snow-free day, and the following values are initialized: FFMC=85(%), DMC=6, DC=15. Measurements of ambient temperature (T), relative humidity (H), previous day's rainfall (R) and windspeed (W) are taken at noon or interpolated from climatic data. In the case of vegetation models, monthly means, variances and ranges of T, H and R may be used to interpret daily climate. Windspeed can probably be considered a random parameter in the climate models. T,H,R and W together with the previous day's FFMC are used to calculate daily FFMC. Similarly, T,H and R are used to calculate DMC and T and R are used to calculate DC. Windspeed and FFMC are then combined to form an Initial Spread Index (ISI) for forest fires, and DMC and DC are combined to form a fuel Build-Up Index (BUI). ISI and BUI calculate FWI. All equations in the Danger Rating System are based on empirically derived equations for the physical drying of pine forest litter. The publication provides a FORTRAN program which is designed to output FWI given user input weather observations, but could be modified to provide a dataset of daily FWI measurements for monthly climate simulations.

The only drawbacks of the model according to Van Wagner (1987) are that fire weather may not be uniform throughout the boreal forest region. However, the scales of the codes in the model could easily be modified regionally. Also, while weather observations represent a single time of day, length of day also influences the drying of the forest floor, and daylength varies with latitude and time of year. DMC and DC derivations include a daylength factor that changes monthly, but is valid only for one latitude. Discrepancies for the 20° latitude variation of the Canadian boreal forest were judged small, however.

The following derivations come from the FWI model:

(1) Fire occurrence is best related to FFMC
(2) Fire spread is best related to ISI
(3) FWI combines many factors, and may be correlated with many aspects of fire activity
(4) BUI is a fair indicator of fire activity.

It is my intention to use the FWI model to improve probability prediction of fire occurrence. Increasing values of FFMC indicate an increasing likelihood of fire occurrence. Total or mean FFMC values for every day in a month could be scaled to some multiplication factor which improves fire prediction in the other vegetation models described, in which occurrence is based only on inverse recurrence intervals. Alternatively, the sequence of days in which continuously high FFMC, or extreme FWI, occurs may be considered a better factor to correlate with probability of fire occurrence. In this case, a counter could be set up to assess maximum intervals of FFMC or FWI above set critical values.

The contribution of the Canadian Fire Weather Index, then, is in predicting fire occurrence based on weather conditions. It is my conclusion that it has many advantages over similar models produced by other nations. For example, the Fire Danger Index (FDI) used in Soviet Forestry is very simplified, and deals only with estimating critical values of FDI for various successional stages of a number of forest types. FDI is simply the sum of air temperatures taken at 1300 hours multiplied by absolute humidity measured at 1300 hours, for all days since the last day in which 3 mm or more of rain fell, and is measured in mbar*degrees (Antonovsky *et al.* 1989). Other factors influencing the moisture content of litter and fuels are not considered.

There is a further important advancement, however, provided by recent Soviet literature (Antonovsky and Ter-Mikhaelian 1987; Antonovsky *et al.* 1989), in coupling fire occurrence with climate data. These models do not consider prediction of fire occurrence in great detail -- in fact, the reccurrence time for fires is adjusted until the model properly duplicates the distribution of natural fires in the study region, and is not theoretically derived -- however, they provide excellent regressions of fire spread probability with climatic parameters. In the first model (Antonovsky and Ter-Mikhaelian 1987), the probability of a single landscape unit burning is considered a function of stand age and the probability of an ignition source. But the major contribution of this paper is that it describes the possibility of modelling interactions between adjacent landscape units over large, non-homogeneous forest. The probability of adjacent stands burning once one stand is ignited in this case becomes a function of stand age. In the second paper (Antonovsky *et al.* 1989), four forest types on the Kas-Eniseyskaya Plain, East Siberia, are carefully studied so that, while many small fires occur because of random modelling based on reccurrence intervals, the occurrence and spread of large fires are modelled according to climate, successional stage, wind direction and the possibility of obstacles such as rivers, highways, etc. That is, this is the only literature available which considers the probability of large, irregularly-occurring fires as distinct from the probability of occurrence of small fires. By using a different set of parameters to model the spread of fires in this way, the natural bimodal distribution of fire frequency (many small fires, a few very large fires) was much better simulated.

Antonovsky *et al.* (1989) begin modelling the spread of fires to adjacent cells by considering eight successional seres of the East Siberian boreal forest. These are defined by age as shown in Table 1. Then, the influence of seven climatic parameters on the fire spread probability, P_k, is tested for each sere, k, using stepwise regression of the climatic parameters with real data concerning probability of fire spread, calculated as the ratio of days with FDI (as above) higher than critical values to the total length of the fire season. It turns out that mean temperature during the fire season, May 1 to September 30, TR (deg. C), maximum period between successive days of rainfall more than 3 mm, MP (days), and total precipitation for the fire season, PR (mm), are the significant variables, which define P_k with very high regression coefficients for Eq. 23 using FDI data (Table 1). In their paper, Antonovsky *et al.* (1989) model fire frequency using probability distributions for the variables TR, MP and PR. The authors actually use this model to predict changes to fire spread given climatic change, illustrating the close coupling of climate as a fire spread parameter in this model.

$$P_k = a_{1(k)}\,TR + a_{2(k)}\,MP + a_{3(k)}\,PR + a_{4(k)} \tag{23}$$

Table 1. Successional stages for East Siberian boreal forest, with regression coefficients and multiple regression coefficients for Eq. 23, describing forest fire spread from adjacent cells (Antonovsky *et al.* 1989).

No.	Age of Sere (years)	Regression Coefficients				Multiple Regression Coefficient
		$a_{1(k)}$	$a_{2(k)}$	$a_{3(k)}$	$a_{4(k)}$	
1	0-1					
2	2-15	.0511	.00363	-.0007	-.0973	0.824
3	16-40	.0491	.00561	-.0006	-.2217	0.858
4	41-80	.0509	.00625	-.0006	-.2954	0.850
5	81-120	.0326	.00677	-.0002	-.3780	0.780
6	121-160	.0232	.00660	-.0002	-.2705	0.794
7	161-180	.0109	.00681	n/a	-.2354	0.798
8	> 180	.0068	.00493	n/a	-.1660	0.764

One criticism of the above model is that, unlike the FWI model (Van Wagner 1987), and unlike the fire spread models discussed in Section 3.4 below (Alexander *et al.* 1984), Antonovsky *et al.* (1989) do not consider detailed modelling of the forest litter layer (i.e.

three fuel depths, fine fuels, duff and deep organic layers), nor parameters relating to the moisture conditions of the fuel. However, fuel load and drought determine fire intensity, which in turn controls fire spread. Use of climatic data alone in parameterizing fire spread may under average circumstances produce a realistic distribution of the frequency of large fires (Antonovsky *et al.* 1989), but it is possible that a summer characterized by many rainy periods but also one long period of drought, may have a high value for MP, the second significant variable in the regression Eq. 23, but that in such a case, deeper fuels may not dry to an extent which produces a high probability of fire spread. High multiple regression coefficients between observed and predicted values of P_k (Table 1) may partly be artifacts of the choice of the empirical data used to represent observed P_k, as the FDI index is also based only on climate data including temperature and number of days between rainfall events. Further modelling of fire intensity and other physical features of forest fires (e.g. rate of spread, temperature) is discussed in more detail below (Section 3.4).

3.3. Modelling Ignition Probability

Improvement in predicting fire occurrence comes from modelling the probability of an ignition source, in addition to using parameters which define probability of a fire given an ignition source. Probabilities of ignition sources are discussed in Cunningham and Martell (1973). This article acknowledges the fact that in the Sioux Lookout area of Ontario (west of Lake Superior), approximately 65% of fires are people-caused, with the remainder ignited by lightening. Although ease of ignition is best modelled by FFMC in the Fire Weather Index model (Van Wagner 1987), random probability of lightening strike is insufficient in modelling fire occurrence. Although complete deterministic prediction of fire occurrence would be unrealistic to attempt to model, the mean probability that a person can cause a fire could be multiplied by the number of people present in a forest, to give a better prediction of total ignition sources.

Cunningham and Martell's (1973) model consults historical records which vary with land use type, that determine different frequencies, f, of man-caused fires for various FFMC intervals, on weekdays (when bush workers are in the forest) and on weekends (when there are many more people in a forest). The probability of one person igniting a fire on a given day is multiplied by the potential ignition sources to give a Poisson approximation of the probability of man-caused fire occurrence, which is viewed as a Binomial process. The probability approximates f, such that the probability of m fires occurring on any given day is, according to the Poisson distribution, $Pr(FFMC)=f^{*}e^{-f}/m!$ for m=0,1,2... For given values of FFMC, this model very closely predicted the number of days on which no fires occurred, 1, 2 and 3 or more fires occurred in one summer in the Sioux Lookout area. It is felt that if a vegetation model were to include anthropogenic effects, values of f can be found from a standard historical records for any region. Then, if FFMC were modelled daily, annual totals of the number of days of people-caused fire occurrence could easily be calculated. These totals could be used in creating a far better estimate of the probability of fire occurrence.

3.4. Forest Fire Activity

Modelling forest fire activity includes consideration of such parameters as fire intensity, temperature and rate of spread, as well as description of fuel consumption, damage to forest floor, and mortality of trees. Forest fire activity depends both on the climatic conditions at the time of the fire (described by the FWI), and on the conditions of the fuel load. Early models do not couple fire activity with climate, but rather only with the fuel load.

Simple modelling of fuel load conditions was undertaken by Bonan (1988a). The damage to trees was described only as mortality, according to three fire intensity classes, which themselves were defined by percentage of fuel load consumed. Mortality of trees occurred without regard to fire tolerance of individual species, but according to simple size and tolerance classifications as follows:

(1) gentle fires	-fuel load < 30% -trees with DBH<12.7 cm killed
(2) intense fires	-fuel load < 60% -fire tolerant trees killed if DBH<17.4 cm -moderately tolerant trees killed if DBH<25.4 cm -no fire intolerant trees survive
(3) lethal fires	-fuel load > 60% -no trees survive.

Besides tree kills, Bonan (1988a) does not consider any further damage to trees, but depth of burn is modelled such that it reduces the organic layer in the forest floor, as:

$$\%RED = (WS - W) / (WS - WD) + (0.15 + 1.5H) \tag{24}$$

where W = water content of organic moss layer
WS = water content when saturated
WD = water content when dry
H = thickness of moss organic layer.

This equation (24) causes complete consumption of the forest floor when it is completely dry. Reduction occurs otherwise as a linear function of depth and moisture.

A better coupling of physical fire parameters with climate and fuel occurs with the work of Alexander *et al.* (1984) using the Canadian Fire Weather Index (Van Wagner 1987). Use of FWI climate variables in predicting forest fire damage is handled by the Forest Fire Behaviour Prediction System. Inputs to this model include:

(1) ISI and FFMC
(2) Fuel Types, of which 14 are coded by Alexander *et al.* (1984), ranging from 7 types of coniferous stands, aspen forest and mixed forest to slash and open grassland
(3) Topography (e.g. slope, which must be input by site).

From these inputs, fire activity can be modelled by the following:

(1) Rate of Spread (ROS): 28 equations are provided, which model ROS under the 14 fuel types, and for various stand height classes. An equation gives variation in ROS with slope. Crown fire thresholds are given for ROS in each of the fuel types. This threshold might have use in vegetation modelling in improving the prediction of damage to the crown (hence, tree mortality) once a fire has occurred.
(2) Fire Size Calculations: are based on windspeed, ROS, and a standardized elliptical shape of fire spread. Calculating size of fire may have use together with the spatial models of Antonovsky and Ter-Mikhaelian (1987) and Antonovsky *et al.* (1989). Alone, the equations found in Alexander *et al.* (1984) do not consider barriers to fire spread or climate conditions in distinct adjacent cells.

The most detailed modelling of the effects of fire on the condition of trees occurs in the Australian high-altitude *Eucalyptus* forest BRIND model (Noble *et al.* 1980). Fire intensity of the fire was modelled using a Fire Danger Index (FDI), which varied with climate and fuel load based on empirical data for wildfires, and which had a set mean and standard deviation for prescribed burns. FDI was then used to calculate rate of spread (ROS) and flame height (FLHT), parameters which determined a detailed description of damage to the stand. If ROS was less than 1.0 m/hr, the fire is not considered real. Effects of burns were as follows for this ecosystem (described in excerpts from the FORTRAN program):

(1) limits on seed availability

```
       X=SEEDS(J)  [J=species]
       IF(SWITCH(J,3) .AND. FIRE)X=X*FIRSTM  [SWITCH(J,3)=1: species in
       which germination is enhanced after a fire; FIRSTM=seed pool multiplication
       factor for this species=3.0]
       IF(SWITCH(J,1) .AND. .NOT. FIRE)X=X*FRTRIG
       [SWITCH(J,1)=1: species requiring fire for germination;
       FRTRIG=mult. factor=0.001]
       TSEEDS=X+TSEEDS
```

(2) number of sites available for germination

```
       NSITES=4
       IF(FIRE)NSITES=200
       IF(.NOT. FIRE .AND. RANDOM(10) .LT. 0.1)NSITES=30
       NSITES=INT(NSITES*RANDOM(10))+1
```

(3) *tree kills, empirically by species*

```
       DO 120 J=1,NSPEC
       IF(NTREES(J) .EQ. 0) GO TO 120
       IX=IGET(J)  [IGET is a fn defined to call species]
90     HT=137.+B2(J)*DBH(IX)-B3(J)*DBH(IX)**2
       [B2,B3=derived height/diameter indices]
       PSCH=AMIN1(6.0,(SCHT-FORM(J)*HT)/(HT*(1.0-FORM(J))))
       [PSCH=proportion of canopy scorch; SCHT=scorch height=6.0*FLHT;
       FORM=ratio of bole to total height]
       SMORT=FA(J)-FB(J)*EXP(-FC(J)*PSCH)
       [FA,FB,etc.=empirically derived fire effects parameters;
       SMORT=probability of mortality]
       FARDAM(IX)=FARDAM(IX)+FD(J)*EXP(FE(J)*PSCH)
       [FARDAM=fire damage factor]
       IF(RANDOM(9) .LT. SMORT)DBH(IX)=-DBH(IX)
       [negative DBH indicates to SUBROUTINE KILL that tree has been
       killed by fire]
       KOUNT=KOUNT+1
       IF(DBH(IX) .LT. 0.)KILLK=KILLK+1
       IX=INEXT(IX)
       IF (IX .NE. 0) GO TO 90
120    CONTINUE
```

(4) *damage to trees*

```
       AMORT=FARDAM(IX)*AGEMX(I)  [AMORT=mortality rate]
       IF (RANDOM(9) .LE. AMORT) GO TO 120
       FARDAM(IX)=FARDAM(IX)*RECOV+RECOV2  [RECOV,RECOV2=recovery
       factors, reducing the state of fire damage in damaged trees in each post-
       fire/non-fire year=0.93,0.07 resp.]
120    NTREES(I)=NTREES(I)-1
```

Kercher and Axelrod (1984) developed another detailed model for the mixed-conifer forest of the Sierra Nevada, California. Although it is perhaps more useful as it follows closely the logic of the Australian model (Noble *et al.* 1980) but describes a conifer forest, this model still has two disadvantages for application to a boreal forest model. First, the fire subroutine is only called once annually, and occurrence of a fire is based on random probability. Second, fuel loading and drought codes determining fire intensity are not based on a boreal forest litter. Among the useful contributions of this model, however, separate subroutines calculate:

(1) probability of death (PD) to trees as a function of crown scorch height (HS) [Subroutine INJURY]

$$HS=(C1*FI^{7/6})/(((C2*FI)+(C3*WIND^{3}))^{0.5})*(TKILL-T)) \qquad (25)$$

where FI = fire intensity
T = ambient temperature
WIND = windspeed
TKILL = 60°C
C1,2,3 = empirically derived constants

(2) reduction in fuel loadings (U) [Subroutine BRNOFF]

$$U(kg)=(94.1*(141.8-100*MOIS))/(17.74+100*MOIS) \qquad (26)$$

where MOIS = fractional moisture content of litter and duff.

Eq. 25 is the best description of the effect of crown damage on tree mortality. Eq. 26 is probably a more useful description of damage to the forest floor when combined with the effect of fire on the moss organic layer, described in the Bonan (1988a) model (Eq. 24).

Finally, there is one published model that considers post-fire changes in the boreal forest according to the succession patterns of individual species (Marsden 1983). This reference is cited as an example of the possibility of developing a very detailed model which considers the life history and behaviour of boreal forest species, although this particular model describes a different ecosystem. Changes in species composition and age class of a mountain stand, based on various fire probabilities, are described. The changes are derived from studying historical and modern records, under two different fire control regimes, and based on life history information concerning mortality probabilities for specific tree species.

4. CONCLUSIONS

To conclude this survey of literature, I would like to present a sequence of equations and subroutines, drawn from the examples presented above, which sufficiently and concisely describe bog and fire disturbance in the boreal forest. The intention is to adapt these equations for use in the Boreal Forest Stand Simulator. Although, earlier in this paper, I have described the interrelationships between the components characterizing the boreal forest, modelling in FORTRAN requires that bogs and fires be considered separately.

I shall first consider bog formation. Bog development is the important initial step in the disturbance subroutine which stimulates the accumulation of organic matter. In the regions of the boreal forest, bogs are apparently not limited to specific topographic features, as raised bogs are, but are most often associated with a shallow water table or with permafrost (Figures 2 and 3). Therefore, consideration of topography is not important to bog initiation, while for blanket bogs, the position of the water table and soil moisture are critical stimulating factors. Bog disturbance can develop both stochastically and deterministically. Random calling of a bog subroutine can be set to a recurrence interval which approximates cycles of disturbance by flooding through soil processes or the action of beavers. At the same time, the series of years for which precipitation inputs exceed losses by evaporation might be recorded, such that a critical sequence of these years determines calling of the bog initiation subroutine. A second deterministic method of initiating bog development might also be included, beginning bog growth whenever a significant development of permafrost occurs.

The lifespan of the boreal bog can be made to depend on rates of accumulation and decomposition of peat discussed below. During the lifespan of the bog, water table height can be modelled according to Eq. 13 or a derivation of Eq. 14. Death of trees following bog disturbance can then be modelled as a function of water table, according to a scheme like that described by Eq. 15, and consideration of the life history characteristics of individual trees (i.e. whether they grow well given a thick moss layer, whether they are flood tolerant or tolerate high levels of soil moisture). Rates of accumulation and decay of peat-forming mosses can be set to average levels among those referenced in Section 2.2.5. However, variation in these figures can be modelled, closely tied to physical parameters existing in the Stand Simulator, by a selection of equations discussed in Section 2. The work of Bonan and Korzukhin (1989) on moss physiology (Eqs. 6-12) is an important starting point for considering variation in moss production. Effect of water table on controlling rates of moss production may need to wait for additional study of bog landscapes. However, Eq. 21 concisely describes decomposition of moss with relation to soil moisture. Depth of soil thaw can be used to model variation in both production and decay of peat, using the work of Bonan (1988a) in his model. Additional important relationships may be modelled between peat accumulation and a record of the amount of snow cover, the growth rate of bog ericads (Eqs. 18 and 22), and the nutrient concentration of bog water (Eq. 17). Hydrarchic succession completing the bog disturbance cycle can be set such that flood tolerant trees re-invade once the water table falls to a critical level, or once decomposition rates exceed rates of moss production (i.e. decay rate, a, becomes 0 in simplified Eq. 19).

The second disturbance cycle to consider is forest fire. In future forest models, initiation of a fire subroutine should not be random to any extent. Enough information exists in the Canadian Fire Weather Index linking probability of fire occurrence to seasonal climate (Section 3.2), and the way in which the relationship can be modelled is described in this section. The initiation of disturbance by fire is then a function of the probability of fire occurrence and the probability of fire ignition. Cunningham and Martell's (1973) model described in Section 3.3 can be used as a basis for modelling sources of ignition deterministically. Then, in a larger model, extent of fire spread, controlling the area of disturbance, can be modelled using P_k, the probability of fire spread, according to Eq. 23 (Antonovsky *et al.* 1989). However, this relationship should be improved such that it includes more detail in the soil organic layer. After such an improvement, P_k should be combined with the probability of fire occurrence based on the FWI variables (Van Wagner 1987), since this latter model does not contain a spatial consideration. Disturbance by fire in a simulated forest plot of finite size is actually dependent on the the probability of an ignition source for the surrounding region, plus the sum of the probability of fire occurrence within the forest plot and the probability of fire spread from surrounding areas into the plot.

Once a fire disturbance event is initiated, effect of fire on organic layers and on trees can be modelled following the work of the authors listed in Section 3.4. Influence of fire on moss layers is already described for the boreal forest in Eq. 24. Influence of fires on fuel is described adequately in Alexander *et al.* (1984). Release of nutrients following a fire, an important result of the consumption of organic material and fuels, can be modelled by a relationship between the standard amount of elements found in fuels and the extent of consumption. Finally, effect of fire on trees can be derived from subroutines developed for the boreal forest species, following the logic of Noble *et al.* (1980), Kercher and Axelrod (1984), and Marsden (1983). Invasion of trees following fire can follow the life history characteristics of individual species (i.e. their tolerance to fire or their adaptedness to invading cleared areas).

Developing the bog and fire subroutines in the ways described above is an important part of future forest modelling in the Boreal Stand Simulator. Disturbance is unarguably an integral part of boreal forest dynamics. The most important features of these two disturbance regimes and their effect on organic matter and on trees have been adequately described, while allowing the possibility for concise integration into the general forest model. It is the aim that this integration should parallel the important relationship of disturbance with the boreal forest ecosystem and its governing physical climate.

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