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# Understanding the role of forest simulation models in sustainable forest management

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**Abstract**

Sustainable forest management (SFM) represents a new paradigm for forestry. Traditional forestry objectives aimed at sustainable yield management are being replaced with those of a sustainable ecosystem management. This paradigm shift in forest management requires an effective transfer of results from researchers to forest managers. To predict the potential impacts of future changes in global environment (such as climate, land use, fire disturbance, and forest harvesting) on the sustainability of forest ecosystems, forest resource managers will require forest simulation models. There have been two basic approaches to modeling forest vegetation growth and dynamics: empirical and mechanistic forest simulation models. This paper reviews and compares three major types of forest simulation models: (1) growth and yield models (empirical approach); (2) succession models (empirical–mechanistic hybrid approach); and (3) process models (mechanistic approach), and describes three case studies as examples. The advantages and disadvantages of the different modeling approaches are discussed. The case studies deal with predicting future forest stocks under different management options, simulating the potential effects of climate change, and effects of fire disturbance on structure and function of forest ecosystems in Canada. There is still a gap between foresters and ecologists in developing and using forest simulation models. Diversified modeling approaches integrated into a decision–support system, which will become an important tool for evaluating the sustainability of forest ecosystem in a changing environment, is emphasized. 

*Keywords:* Forest simulation models; Sustainable forest management

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## 1. Introduction

Today's forest resource managers face a number of important challenges. One of the most critical is the need to provide forest products for an increasing world population despite a shrinking natural resource base challenged by global change, desertification, environmental pollution, and other stresses. Social and political pressures require that forest management meet these challenges in an ethical and economical fashion, ensuring environmental stewardship and sustainable productivity. Sustainable forest management (SFM) represents a new paradigm for forestry in Canada [7,8], and involves management of both temporal and spatial patterns of ecosystem conditions at both stand and landscape levels [11,40]. Traditionally, forest science has focused on stand-level processes, and the prediction of forest growth and yield has been through use of the historical bioassay [21]. Many of the contemporary issues facing global change, biological conservation, and sustainable management, however, cannot be handled solely at the stand level, and do not have historical analogues for their solution [24,26]. Rather, the issues are at the landscape level, and related to the patterns of change at various spatial and temporal scales. One of the challenges is to predict the long-term and large-scale response of forests to a rapidly changing environment, and to transfer of the knowledge to forest managers, policy makers, and the decision-making public.

Forests are dynamic biological systems that are continuously changing; To obtain relevant information for decision making, it is necessary to project these changes. Forest management decisions are based on information about both current and future resource conditions. In the absence of long-term field data, forest simulation models that describe forest dynamics (i.e., growth, succession, mortality, reproduction, and associated stand changes) have been widely used in forest management to update inventory, predict future forest yield, and species composition and ecosystem structure and function under changing environmental condition. They also allow exploration of management options and silvicultural alternatives, and provide information for sound decision making [5,62,76].

In the last decade, there has been a number papers discussing application of various types of forest models (e.g., [2,21,25,34,76]). But none of them has comprehensively compared three important types of forest simulation models (e.g., growth and yield, succession, and process models) and provided specific example of case studies in assessing their role in sustainable forest management. In this paper, we discuss traditional sustained yield management compared with sustainable ecosystem management; and briefly review and compare three major types of forest simulation models that have been widely used for forest management. Application of the models is presented in three case studies that deal with predicting future forest stocks under different management options, simulating the potential effects of climate change, and the effects of fire disturbance on the structure and function of forest ecosystems in Canada.

## 2. From sustained yield management to sustainable ecosystem management: A paradigm shift in forestry

### *2.1. Sustained yield management (SYM) as a traditional paradigm*

Sustained yield management has guided Canadian forestry for many years now. The objectives of SYM are focused on the sustained timber production. Current forest policies are focused on Annual Allowable Cuts (AACs), which are embed in timber harvesting, processing, and regeneration policies. The AACs are the primary mechanism whereby sustained flows of timber are ensured by SYM policies [29]. This approach was historically based on the assumption that if stands suitable for timber production are sustained, then nontimber resources will also be sustained. The AACs have been shown to have great potential for providing incentives for firms to invest private funds in past forest management [29,61]. The major limitation of SYM is that it accounts for only one physical output (volume yield) from the forest, but fails to account for how society may value that output, or its effects on community stability [79]. Moreover, forestry based on sustained yield can be performed at a very low yield level. For instance, a mature natural forest ecosystem could be defined as operation on a sustained yield (equaling zero) level [16]. Ecologically sound management of forests for timber production should be in harmony with wildlife, water, fish, and other resource values. To include these values in forest management requires a switch from the traditional sustained yield ideal to sustainable ecosystem management.

### *2.2. Sustainable forest management (SFM) as a new paradigm in forestry*

Ecosystem management is at the core of SFM. The concept of *ecosystem* can be traced back to Arthur Tansley's [73] effort to provide a more precise and holistic term for the set of biological and physical factors that affect an organism and that form its environment. The most common use of *ecosystem* by ecologists is in a localized sense, referring to a distinct and coherent ecological community of organisms and the physical environment with which they interact. A generally accepted definition of ecosystem management is still being developed, despite widespread use of the term. Christensen et al. [9] describe ecosystem management as ". . . management driven by explicit goals, excluded by policies, protocols, and practices, and made adaptable by monitoring and research based on our best understanding of the ecological interactions and processes necessary to sustain ecosystem composition, structure, and function. . . ." Ecosystem management is holistic, incorporating all important elements of the ecosystem, both biological and physical, and their interrelations. Christensen et al. [9] included the following elements in ecosystem management: (1) long-term sustainability as a fundamental value, (2) clear, operational goals, (3) sound ecological models and understanding, (4) understanding complexity and interconnectedness, (5) recognition of dynamic character of an ecosystem,

(6) attention to context and scale, (7) acknowledgement of humans as an ecosystem component, and (8) commitment to adaptability and accountability.

Sustainability is a major element, and is at the core of ecosystem management. The ecosystem's composition, structure, function, goods, and services are the ecological basis for ecosystem management. Healthy ecosystems perform diverse functions that provide both goods and services to humanity. Here, goods refer to items with monetary value in the market place, whereas although services are valued, they are rarely bought or sold. Ecosystem functions relate variously to the habitat, biological, or system properties, or processes of ecosystems. Ecosystem goods and services are the benefits that human populations derive, directly or indirectly, from ecosystem functions.

### *2.3. Contrasts between sustained yield management and sustainable ecosystem management*

Sustainable ecosystem management and sustained yield management are fundamentally different (Table 1). Sustained yield management (SYM) is a single resource, and is based on the concept of equilibrium—that is, the balance between harvest and growth can be sustained in perpetuity. However, sustainable forest management (SFM) produces multiple resources, and is based on a holistic approach—that is, sustaining the production of goods and services, and balancing ecosystem capabilities with social and economic needs. Further explanation of differences are as described by the Society of American Foresters [68]:

1. First, the major distinction between the two paradigms is determined by their objectives and constraints. SYM seeks to sustain flow of specific products to meet human needs, constrained to minimize adverse effects. The harvest of any one resource is constrained by its growth. On the other hand, SFM seeks to maintain ecological and desired forest conditions within which the sustained yield of products meet human needs. Maintaining the forest as an ecosystem is the operational constraint.
2. Second, there is the nature of multiplicity. For many years, arguments about sustained yield management concentrated on how to achieve multiplicity. One view debates that sustained yield management can be adjacent rather than simultaneous. This kind of multiple-use sustained yield is a matter of policy. Sustainable ecosystem management, on the other hand, is rooted not in policy but in a fundamentally different perception of the forest landscape.
3. Third, there is the interaction of the system. SYM contains no necessary condition of connectedness. The elements of resources can be considered as independent. In SFM, each element of a resource per-

Table 1
A simplified comparison of sustained yield management (SYM) and sustainable forest management (SFM)

| | Sustained yield management (SYM) | Sustainable forest management (SFM) |
|---|---|---|
| Paradigm | Traditional | New and emerging |
| Objective | Sustained flow of specific products to meet human needs, constrained to minimize adverse effects | Maintains ecological and desired forest condition within which the sustained yield of products to meet human needs are achieved |
| Constraint | Periodic harvest of each resource must be less than or equal to its periodic growth | Maintains the forest as ecosystem, and balances ecosystem capabilities with social and economic needs |
| Character | Market-oriented, emphasizes production efficiency within environmental constraints | Ecosystem-oriented, retains complexity and processes, provides framework for the whole system |
| Strategy | Resembles the agricultural model | Reflects natural disturbance patterns and the dynamics processes of ecosystems |
| Unit of management | Stands and aggregations of stands within an ownership | Landscape and aggregation of landscapes across ownership |
| Time unit | Multi-rotations with rotation length determined by landowner objectives | Multi-rotations with length reflecting natural disturbance, although intensive management will cause some to be short |
| Current status | In transition. New knowledge is bringing new values. Remains a valid strategy for portion of the landscape | Evolving, accepted for management on US federal lands |

Modified from [68].

ceived by humans can be linked to all the other elements in the ecosystem, including the flow of energy, and the cycling of carbon, water, and nutrients. Change in any one of these resources (such as harvesting) will affect all the others.

4. Finally, SYM is market oriented, an exercise in rationing determined by the economics of consumption. SFM is ecosystem oriented, an exercise in husbandry determined by the production of goods and services from the ecosystem.

## 3. Forest simulation models

There are three approaches to assess the effects of a changing environment on forest dynamics [5]: (1) our knowledge of the past, (2) present

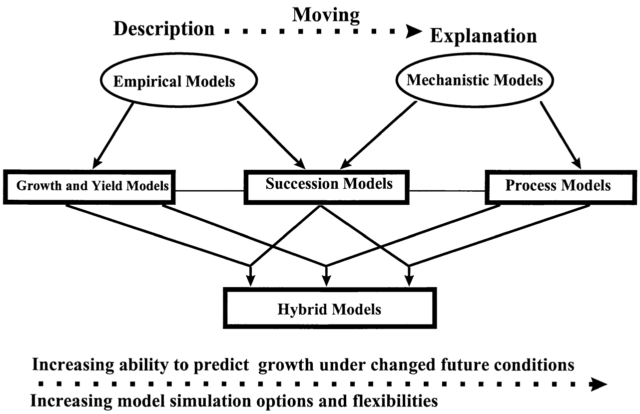


Fig. 1. The categories and features of forest simulation models used in forest management.

measurements, and (3) our ability to project into the future. Our knowledge of the past and present measurements are of great potential importance, but have been of limited use. Long-term monitoring of the forest has proven difficult due to cost and long-term commitment from individuals and institutions. Because the response of temporal and spatial patterns of forest structure and function to changing environment is complicated, current experimental techniques are not directly applicable. In contrast, models provide a means of formalizing a set of hypotheses that link pattern and process. Over the years, a number of forest simulation models have been developed to assess forest growth and yield [14,36,37,66,71,74,76,80], forest succession and vegetation dynamics [4–6,19,41,54,62,69,70], net primary productivity, carbon storage in vegetation and soil, nutrient cycling, or water and energy balance with the atmosphere [1,12,27,34,42,43,49,51,55,56]. Although the design and output variables of these models may vary, they fall into three main categories (Fig. 1): forest growth and yield models (empirical approach), forest succession models (hybrid approach), and forest process models (mechanistic approach). Depending on the extent to which an understanding of process is incorporated, forest simulation models can be classified as either empirical or mechanistic. Because there is a continuum across the range, the term hybrid is used for models that provide some explanation of processes influencing tree growth.

### *3.1. Forest growth and yield models*

The origin of modern forest simulation systems lies in the development of a yield table by mensurationists in Germany in the late 18th century, published approximately 200 years ago [78]. Extensive collection of forest biomass data and estimates of existing timber volumes led to the development of growth and yield models as powerful prediction tools for forest management since the last century. Most of these growth and yield models used a site index to determine the potential or maximum growth rate [10,76]. Besides a site index, a number of growth and yield models have used competition indices to measure the competition effects of adjacent trees, and incorporated these into predictive models to estimate individual tree growth [19,30,35,37].

Based on empirical records of how forests have grown on a site in the past, this historical bioassay approach is the simplest and most believable method of predicting future forest growth on that site if the future growing conditions and management regimes are expected to be similar [24,76]. The major strength of empirical approaches is to describe the best relationship between the measured data and the growth-determined variables using a selected mathematical function or curve. The empirical approach are most important during the descriptive stage, and may be an appropriated method for predicting future short-term forest growth and yield (for time scales over which growth conditions are not expected to change significantly), because their representation of ecosystem processes is implicit rather than explicit. However, they are only appropriate if environmental condition remain stable [2]. Past performance is not always a reliable predictor of future development. A good metaphor to illustrate this was given by J.P. Kimmins (pers. commun., 1996), who "likened the use of empirical relationships for predicting future tree growth to driving a car using only the rear view mirror—perhaps acceptable for short periods in the prairies, but not sustainable in mountainous terrain." Most forest growth and yield models cannot be used to analyze the consequence of climatic changes, as climate is ignored as a determinant of forest growth [12,21,34,47,64].

### *3.2. Forest succession models (Gap models)*

The forest succession (or gap) model, which incorporates explicit representation of key ecological processes (establishment, tree growth, competition, death, nutrient cycling), has been developed to capture the transient response of vegetation or a simple biome to changing climate (e.g., [62,63]). The first such model was the JABOWA model [4], developed for forests in New England. Over the past 20 years, succession models have been developed for a wide variety of forest ecosystems [5,63]. A number of different forest gap models have been used to simulate time-dependent changes in species composition and abundance under a changing climate (e.g., [5,6,41,53,54,69,70]). Several obstacles stand in the way of the extensive use of currently available dynamic vegetation models in forest management and global change studies. For example, The gap-level models are incapable of investigating the consequences of the processes operating on a scale larger than a gap size, and hence, the interactions among the dynamics of these gap-sized sites were neglected. It is also impractical to use gap-level models to predict shifts in vegetation beyond those at the local scale because of the large number of points that would have to be simulated. Dynamic models require much more information on the silvical characteristics of species than is easily available or even known for some areas of the globe [69]. These ecosystem models resulted in predictions for regional scale or ecosystem, but have not yet been applied at the global scale [65,67]. In fact, most succession models are still limited to research and education tools. They may be realistic and general, but may not be sufficiently precise for forest management decisions [76]. Also, the absence of below-ground biomass components in most succession models make them of little use in addressing questions concerning the use of forests to mitigate the atmospheric increase in $CO_2$ [31,54]. Succession models need to become more process based to address questions about the response of forest growth to changes in climate and $CO_2$ concentration. Incorporating decomposition dynamics into a succession model [45,46] was a valuable addition.

### *3.3. Process models*

The term "process model" refers here to simulating the structure and function of the forest ecosystem by mathematical representations of the underlying biological processes controlling the behavior of an ecosystem [15]. The International Biological Program of the late 1960s and early 1970s [58], with its emphasis on understanding and quantitatively describing the key features and dynamics of forested ecosystem structure and function, provided a major boost to the developing field of ecosystem process modeling.

Early process models were unable to address time scales that are relevant to traditional forest management issues (i.e., tree crop rotation) and to the analysis of sustainability issues (multiple tree crop rotations). With increased understanding of the ecosystem, processes and computing power process models have become increasingly accurate and useful as representations of ecological systems. In addition, process models have the potential to be far more flexible than an empirical relationship, and can be used to explain the cause–effect. However, they require more field data than empirical models for complex calibration and validation procedures. A valuable summary of process modeling of forest growth response to environmental pressure and global change can be found in Dixon et al. [12], and a special issue of Ecological Modelling (1995, 83:1–293). Unfortunately, process models have not yet been studied much in forest management because they are less able to predict forest yield at a particular site than a conventional growth and yield model developed from historical data from that site [1].

## 4. Applications of forest simulation models: Three case studies in Canada

A number of forest simulation models are constructed for many reasons and for a variety of users including resource managers, ecologists, economists, financial advisers, and students. These users may apply forest simulation models for (1) predicting tree volume, (2) optimizing appropriate silvicultural input for maximizing yield, (3) understanding forest succession, (4) assessing effects of environmental stress such as air pollution, acid rainfall, and climate change, (5) evaluating sustainability of forest ecosystems, (6) testing various hypotheses about tree structure and function, and (7) teaching and education. These diverse objectives involve dynamic processes that range in a time scale from minutes to centuries, and are applicable at spatial scales that range from the leaf to the ecosystem [1,13]. Comprehensive reviews of model applications in forest management are given by Botkin [5], Vanclay [76], Shugart and Smith [65], Kimmins [24], Landsberg and Gower [26], Newton [38], and Battaglia and Sands [1]. Three case studies in Canada are provided below (Table 2).

### *4.1. Case I: Red pine (*Pinus resinosa*) density management diagram (DMD) for Ontario*

One of most useful growth and yield modeling tools to assist forest managers in enhancing the volume production of a stands is the Density Management Diagram (DMD). The DMD initially developed by Japanese scientist in early 1960s is based on the $-3/2$ power rule (or law) of self-thinning, and is an age-independent, average-stand mortality model that predicts the development of fully stocked natural stands. An overview of historical development and applications of DMD in forest management planning was given by Newton [38]. Smith and Woods [66] recently developed red pine (*Pinus resinosa*) Density Management Diagram (DMD) for Ontario (Fig. 2). One example is provided below to illustrate sawlog production for red pine (Fig. 2). Site index (SI) for each stand is estimated to be 20 cm. All estimates of stand density, volume production, and the timing of thinnings and rotation harvests are given in Table 3 with an initial density of 1,200 sph (stems per hectare). To ensure that sawlogs reach a target $DBH_q$ (quadratic diameter at breast height) of 30 cm, the forest manager then drafts a line downward from the intersection of 30 cm $DBH_q$ isoline and the initiation line of mortality. Moreover, a line from the location of the CT is plotted, which runs parallel to the 18-m height isoline. This represents an age of 48 years (43 years breast-height age from site index curves, plus 5 years to breast height), and 575 sph are removed by thinning treatment. This results in an approximate extracted volume of 75 $m^3$ $ha^{-1}$ (or a basal area of 12 $m^2$ $ha^{-1}$). Consequently, the residual stand then has a density of 625 sph, and self-thinning will not start until individuals had attained a $DBH_q$ of 30 cm. The final harvest volume of sawlogs is calculated at 469 $m^3$ $ha^{-1}$ (or a basal area of 44 $m^2$ $ha^{-1}$), and the total volume removed from the stand is estimated to be 544 $m^3$ $ha^{-1}$.

### *4.2. Case II: Simulating effects of climate change on species composition of boreal ecosystems using FORSKA 2.0*

FORSKA 2.0 is a forest succession model originally designed to simulated landscape-level processes in Scandinavian boreal forests [28,53]. Stand

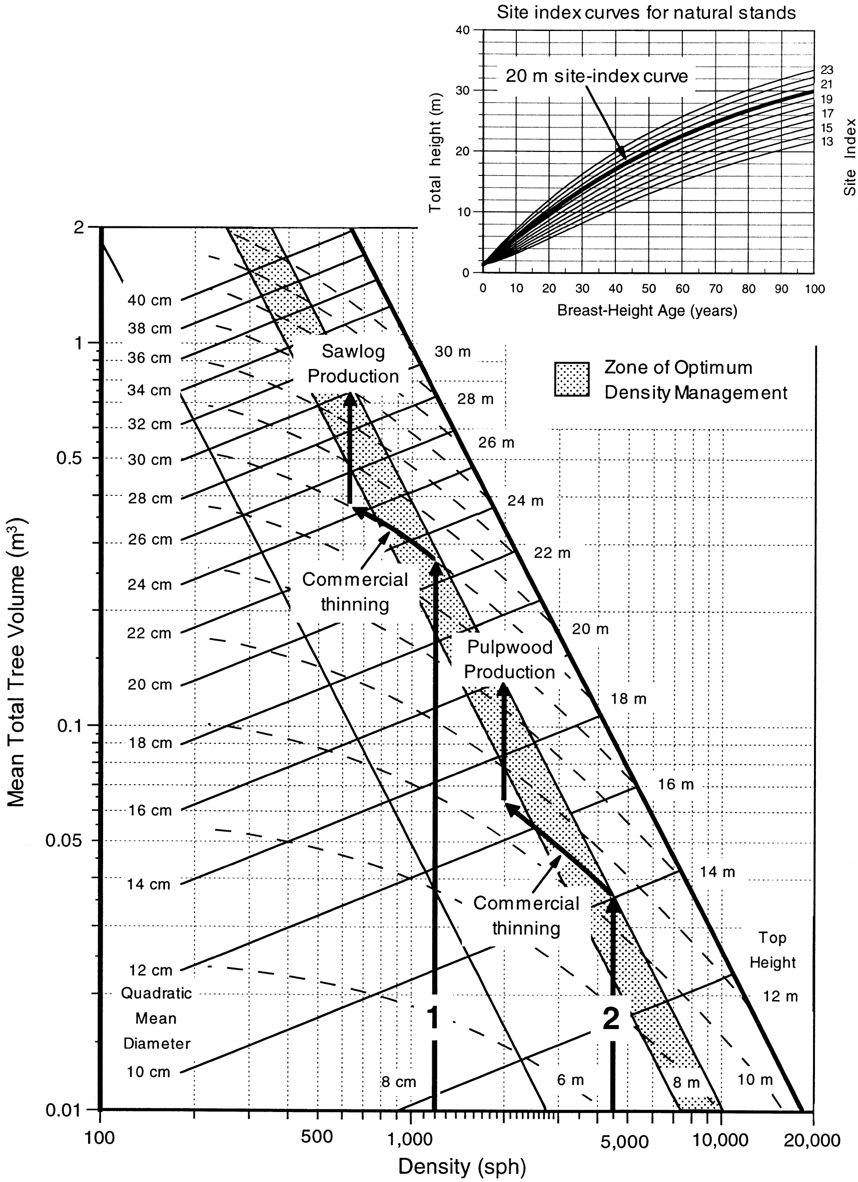


Fig. 2. Stand development trajectories for red pine (*Pinus resinosa*) pulpwood and sawlog production (reprinted with permission from [66]).

Table 2
Comparison of three types of forest simulation models

| | Growth and Yield Models | Succession Models | Process Models |
|---|---|---|---|
| Purpose | management for timber production | Ecological studies of forest dynamics and education | Ecological studies of forest structure and function, and education |
| Forest types | mainly managed forests or plantations | mainly nature forests | nature or managed forests |
| Model complexity | low | intermediate to high | intermediate to high |
| Simulation time | short (10–20 years) | intermediate to long (50–1,000 years) | intermediate to long (50–1,000 years) |
| Attributes | description | explanation | explanation |
| History | about 200 years | about 25 years | about 15–20 years |
| Data requirement | site-specific tree and environmental data | site-specific environmental data and species-specific tree data | climate data, soil data, specific-species tree data |
| Measure of environmental factors | site index | multiplication of effects of single factors | temperature, light, water, nutrients, and disturbance |
| Simulation area | large (hundred or more hectares) | small (a gap size, usually 0.01–0.1 ha) | small to large (hundred or more hectares) |
| Number of species simulated | one to several commercial (timber) species | a few (or even more than 100) ecologically important species | single species or mixed stand |
| Modeling spatial relations among trees | vertical: function of tree size; horizontal: distance dependent or independent | vertical: light extinction function: horizontal: generally distance independent | vertical: function of tree process; horizontal: distance independent |
| Model testing | calibration and validation | calibration | calibration and validation |
| Examples | DMD[a] | FORSKA2.0[b] | CENTURY4.0[c] |

[a] DMD: Density Management Diagram [66].
[b] FORSKA2.0: a forest succession model [28,54].
[c] CENTURY4.0: a process-based plant-soil model [32,42].

growth dynamics are simulated in arrays of 0.1 ha patches, interrupted at random intervals by patch-replacing disturbances. The representation of growth processes allow physiological parameters affecting photosynthesis to be specified, including the shape of light response curve and the ratio of intercellular to ambient $CO_2$ concentrations. FORSKA 2.0 also contains a simple soil–water balance "bucket" model that calculates average daily actual evapotranspiration using the Priestley-Taylor [57] equation balanced

Table 3
Estimates for two thinning treatments for red pine stands.

| | Sawlog production with commercial thinning |
|---|---|
| Initial density (sph) | 1,200 |
| Number trees cut at thinning | 575 |
| Total age at thinning (years) | 48 (43 + 5)[a] for CT (based on height of 18 m on SI 20 curve) |
| Pulpwood volume at thinning ($m^3$ $ha^{-1}$) (pre-CT vol. − post-CT vol.) | 75 [(1,200 sph × 0.26 $m^3$ $tree^{-1}$) − (625 sph × 0.38 $m^3$ $tree^{-1}$)] |
| Basal Area (BA) removed at thinning ($m^2$ $ha^{-1}$) (pre-CT BA − post-CT BA) | 12 [(1,200 sph × $(21\ cm)^2$ × 0.00007854) − (625 sph × $(24.5\ cm)^2$ × 0.00007854] |
| Sawlog volume at rotation age ($m^3$ $ha^{-1}$) | 469 (625 sph × 0.75 $m^3$ $tree^{-1}$) |
| Basal area removed at sawlog rotation ($m^2$ $ha^{-1}$) | 44 [625 sph × $(30\ cm)^2$ × 0.00007854] |
| Sawlog rotation age (years) | 71 (66 + 5)[a] (based on height of 24 m on SI 20 curve) |
| Total volume harvested ($m^3$ $ha^{-1}$) | 544 (75 + 469) (CT thinnings + small sawlogs) |

Modified from [66], with permission.

[a] Age, assumes red pine (*Pinus resinosa*) will reach breast height (1.3 m) after 5 years. CT = commercial thinning; n/a = not applicable.

against mean daily precipitation and soil–water storage. Soil moisture is then used as an environmental factor to limit sapling survival and tree growth rates, instead of imposing a maximum temperature limitation to growth, as is used in the original succession models (e.g. [4,62]. It has recently been used to investigate the potential impacts of future climate change scenarios on unmanaged boreal forest ecosystems in central Canada [54–56].

Fig. 3 shows that under the GISS (Goddard Institute for Space Studies) 2 × $CO_2$ climate scenario, significant shifts in species composition are predicted for all three forest sites, with pine and hardwoods contributing less to total biomass in the north (Thompson), but more in the south (Prince Albert). In contrast, spruces and "other conifers" become more abundant in the north (Thompson), but less in the south (Prince Albert). Hardwood biomass is only mildly affected under GISS 2 × $CO_2$ climate scenario, while spruces gain at all three locations, particularly in the south. Total biomass was increased by about 13% in Thompson, 9% in Flin Flon, and 17% in Prince Albert.

### *4.3. Case III: Simulating effects of climate change and fire disturbances on carbon dynamics of boreal forests using CENTURY 4.0*

CENTURY, as developed by Parton et al. [42,43], is a general process model of plant–soil ecosystems that simulates the dynamics of C and N of

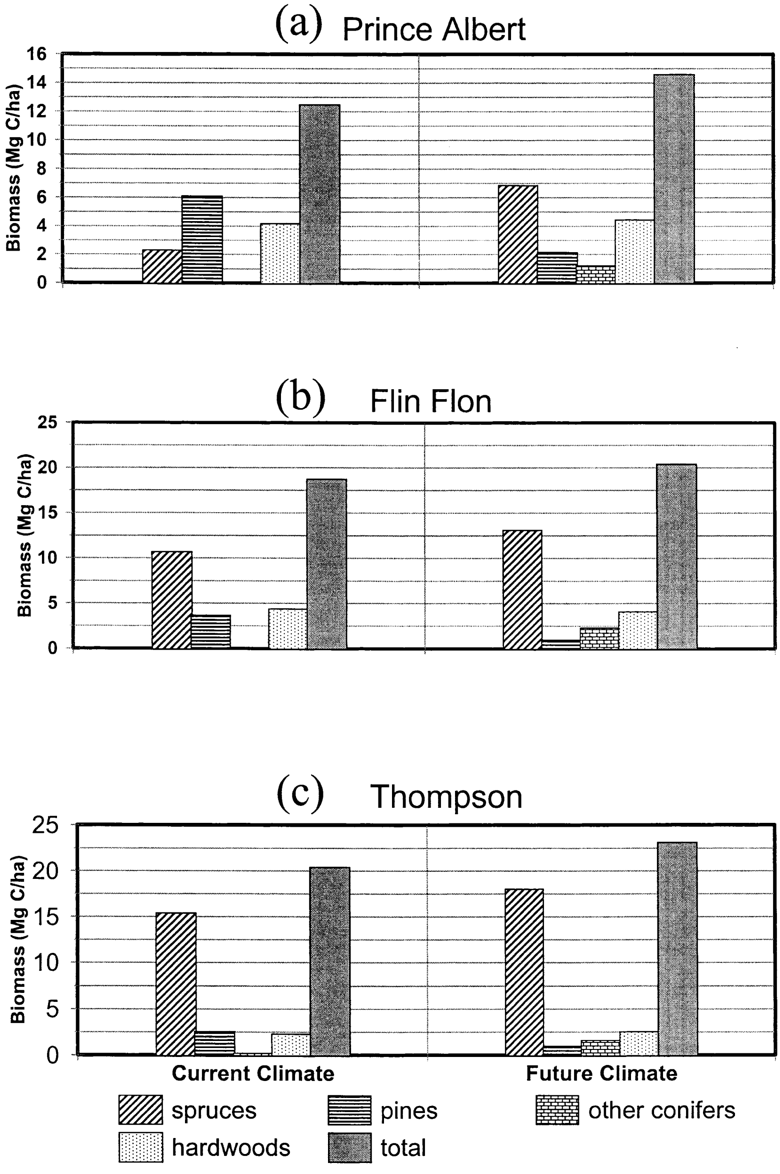


Fig. 3. Comparison of boreal forest species composition and biomass, simulated by FORSKA 2.0, under (1) current climate, and (2) future climate at (a) Prince Alberta, Saskatchewan (53°13′N, 105°41′W) (b) Flin Flon, Manitoba (54°46′N, 101°51′W), (c) Thompson, Manitoba (55°48′N, 97°42′W). Current climate is produced using data from the 1884–1992 replayed to create a synthetic 1800-year time series. The data presented for current climate are spatial average biomass (Mg C $ha^{-1}$) averaged over the last 200 of the first 800 years of simulation. The data presented for future climate are spatial average biomass (Mg C $ha^{-1}$) for the last 200 of the each 1800 years of simulation. Future climate is based on the Goddard Institute for Space Studies (GISS) general circulation model (GCM) under $2\times CO_2$ scenario [18,56].

various plant–soil systems including grassland, agriculture land, savannas, and forests. It incorporates representations of key processes relating to carbon assimilation, turnover, and decomposition, based on a set of existing submodels. It also permits simulation of many management measures, including grazing, cropping, fertilization, irrigation, and control of wildfire. The model has been previously described by Parton et al. [42,43] and Metherell et al. [33]. The latest version, CENTURY 4.0, that operates on a monthly time step, also includes a water balance submodel that calculates monthly evaporation, transpiration, water content of soil layers, snow water content, and water flow between saturated soil layers. Major input variables for the model include (1) monthly mean maximum and minimum air temperature, (2) monthly precipitation, (3) soil texture, (4) atmospheric and soil N inputs, (5) plant lignin content, and (6) initial soil C and nutrient levels.

Earlier versions of CENTURY have been used widely to simulate plant productivity, biomass and soil C and N dynamics in agroecosystems [32,48], grasslands [17,43,44,81], tropical forests [59,75,77], as well as in savanna and tundra environments [33]. More recently, CENTURY 4.0 has been validated for the boreal forest ecosystems in central Canada using field data of above-ground biomass and soil organic matter [49,51,55]. The potential impacts of climate change and fire disturbance on carbon dynamics of the boreal forest in the area of the Boreal Forest Transect Case Study in central Canada were reported by Peng and Apps [49,50] and Peng et al. [51]. Under a GISS $2 \times CO_2$ climate scenario the total biomass was slightly increased, and litter and soil carbon storage were greatly decreased due to the increase in soil decomposition (Fig. 4). A increase in fir frequency (from a 150- to a 50-year fire interval) decreased total biomass (Fig. 5).

## 5. Discussion

### *5.1. Gaps between foresters, forest managers, and ecologists*

There is still a gap between forest ecology and applied forestry in developing and using forest simulation models. Foresters and forest managers prefer empirical or statistical based approaches. "Forest textbooks and journals have contained useful information for forest modelers for more than a hundred years, but most of this information remains undiscovered by those who develop ecological models . . ." [60]. It has become fashionable among ecologists to favour mechanistic approaches than empirical ones [1,2,12,25]. This increased interest in aspects of ecosystem dynamics led to the development of process-based models that perhaps were epitomized by the International Biological Program [58]. The strength of the process models is the weakness of the growth and yield models, and vice versa. The link between foresters and ecologists coupled with combining empirical and mechanistic approaches into a hybrid approach will certainly advance

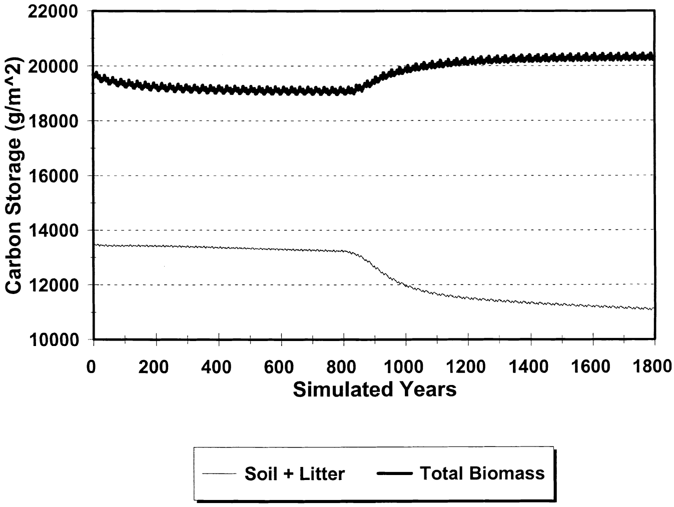


Fig. 4. Total (above- and belowground ) biomass, litter, and soil carbon density simulated by CENTURY 4.0 at Thompson, Manitoba (55°48′N, 97°52′W), using an average monthly climate record from the period 1958–1990. A simulated change in climate derived from the GISS general circulation model [18] was applied beginning at year 801, continuing until 900, followed by 800 year of a stable $2\times CO_2$ climate scenario.

our understanding of the effects of future changing environment on sustainable forest management [25,60].

It should be noted that different application purposes require different types of models and different modeling approaches. For example, foresters, forest managers, and planners need forest simulation models that have more complex description, such as planning tools for the development of forest management policy and for assessing the long-term effects forest practice and environmental pollution. Forest scientists, ecologists, teachers, and students require forest simulation models that have a more mechanistic explanation, for example, methods for studying forest succession dynamics, structure, and function, and models for predicting the responses of future forests to changes in climate and atmospheric $CO_2$. Undoubtedly, there will not be a single supermodel satisfying all of these diverse demands simultaneously. Only diverse forest modeling approaches meet the demands of informative forest management decision under the uncertainly of the future environment [2,5,76].

### 5.2. Modeling ecosystem sustainability

There are two concepts embedded in the term sustainability [8]: sustainability of timber yield and sustainability of the ecosystem. Sustainability of timber yield refers to sustaining the production level of timber from the forest area. This implies maintenance of a forest but not necessarily the

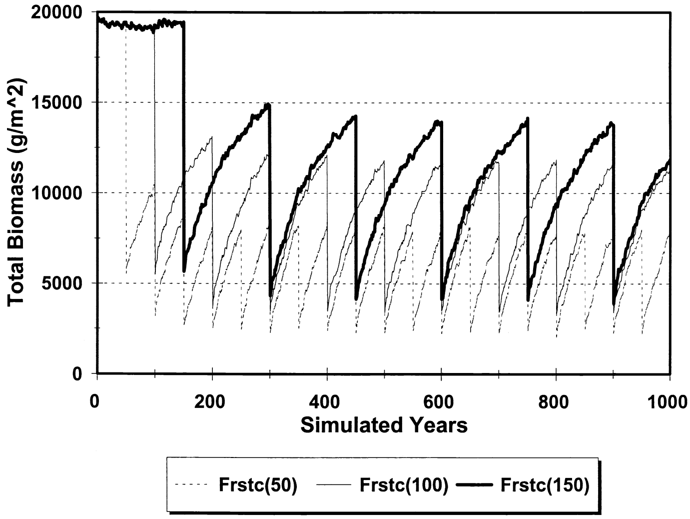


Fig. 5. Sensitivity analysis of total biomass, simulated by CENTURY 4.0 using an average monthly climate record for 1958–1990, to changes in fire disturbance regimes at Flin Flon, Manitoba (54°46′N, 101°51′W). Frstc(50), Frstc(100), and Frstc(150) represent simulations with fire return intervals of 50, 100, and 150 years, respectively.

original forest; sustainability of an ecosystem refers to sustaining the integrity of the natural forest in terms of its structure, function, composition (i.e., species composition and biological diversity) and ecological processes, along with the environmental service it provides.

One of the challenges and important issues regarding sustainable forest management is the question of sustainability, not only of timber harvesting, but of an entire ecosystem's structure and function [9]. Most traditional growth and yield models, which excluded the soil processes and the role of ecosystem disturbance in determining ecosystem function, may be able to predict the continuity of timber harvest and the nature of future forest stands, but tell us little about the effects of timber harvesting on ecosystem structure and function. For example, the DMD [66] allows forest managers to formulate reasonable consequences to various density manipulations by management objective, and provides a useful decision–support tool in stand-level management planning. However, with the increase of ability of DMDs to address multiple resource management objective simultaneously (e.g., [72]), the new generation of DMDs will play an increasingly important role in SFM [38,39]. Forest succession models have been widely used by researchers and resource managers during the past 3 decades [4,5]. They have several limitations that restrict their applications in investigation of the long-term forest ecosystem sustainability. For example, an inadequate representation of the details and determinants of production ecology, and the limiting role of soil and ecosystem disturbance processes [23] are major limitations. Although FORSKA2 [53,55,56] addresses one of these limitations by incorporating the fire disturbance in the simulating forest species dynamics, it is still the lack of the soil process that is significantly altered in a way that impairs ecosystem function. Models such as FORCYTE [21] and LINKAGE [45] offer some insight into nutrient cycling and long-term productivity changes, but are still limited to the individual tree level. New general models, such as FORECAST [22], TREEDYN3 [3], and 3-PG [27], which integrate empirical growth models with process-based ecosystem models, may provide more insight into sustainable forest management under changing environmental conditions. The greatest contributions of process models such as CENTURY 4.0 in SFM are specifically developed for the purposes of investigating the response of ecosystem function (e.g., ecosystem productivity, carbon, and nitrogen dynamics) to the long-term consequences of changes in climate and atmospheric $CO_2$ [49,50], and the effects of fire disturbances and harvesting regimes [20,52]. However, the CENTURY 4.0 is essentially a research tool, and has not been used to address the questions of multiple resources, which is indeed of interest to practical forest managers.

## 6. Conclusions

Traditional forestry objectives aimed at sustainable yield management are being replaced with those of sustainable ecosystem management. This paradigm shift in forest management requires an effective transfer of results from researchers to forest managers. Forest simulation models have proven to be useful tools for forest management. In the absence of long-term field data, results from forest simulation models are useful for assessing the effects of forest practices, climatic change, fire disturbance, and harvesting on future forest growth and dynamics. Empirical or mechanistic modeling approaches have their advantages and disadvantages. The strength of process models is the weakness of growth and yield models, and vice versa. Combining the two overcomes the shortcomings of both component approaches to some extent. A change in the questions being asked in sustainable forestry has increased the potential use of mechanistic process models. Undoubtedly, there will not be a single supermodel that will satisfy all of the diverse demands and purposes simultaneously. Only diversified modeling approaches, integrated into a decision–support system, will be useful for sustainable forest management.

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## References

[1] Battaglia M, Sands PJ. Process-based forest productivity models and their application in forest management. Forest Ecol Manage 1998;102:13–32.
[2] Bossel H. Modelling forest dynamics: moving from description to explanation. Forest Ecol Manage 1991;42:129–42.
[3] Bossel H. TREEDYN3 forest simulation model. Ecol Model 1996;90:187–227.
[4] Botkin DB, Jamak JF, Wallis JR. Some ecological consequences of a computer model of forest growth. J Ecol 1992;60:849–73.
[5] Botkin DB. Forest Dynamics: An Ecological Model. New York: Oxford University Press, 1993.
[6] Bugmann HM, Solomon AM. The use of a European forest model in North America: a study of ecosystem response to climate gradients. J Biogeogr 1995;22:477–84.
[7] CCFM (Canadian Council of Forest Minister). Sustainable forests: A Canadian commitment. Quebec, Canada: Author, 1992. p. 35.
[8] CCFM (Canadian Council of Forest Minister). Criteria and indicators of sustainable forest management in Canada, Technical Report. Ottawa, Canada: Author, 1997. p. 137.
[9] Christensen NL, et al. The report of the ecological society of America committee on the scientific basis for ecosystem management. Ecol Appl 1996;6:665–91.
[10] Clutter JL, Fortson JC, Pienaar LV, Brister GH, Bailey RL. Timber management: A Quantitative Approach. New York: John Wiley & Sons, Inc., 1983.
[11] Cocklin CR. Methodological problems in evaluating sustainability. Environ Conserv 1989;16:343–351.
[12] Dixon RK, Meldahl RS, Ruarke GA, Warren WG. Process Modeling of Forest Growth Responses to Environmental Stress. Portland, OR: Timber Press, 1990.
[13] Ehleringer JR, Field CB. Scaling Physiological Processes: Leaf to Globe. San Diego, CA: Academic Press, Inc., 1993. p. 388.
[14] Ek AR, Monserud RA. FOREST: A Computer Model for Simulating the Growth and Reproduction of Mixed Species Forest Stands. University of Wisconsin, Res. Papers R2635, 1974. p. 13.
[15] Godfrey K. Compartmental Models and Their Application. New York: Academic Press, 1983.
[16] Hägglund B. Sustained yield forest management: the view from Sweden. Forest Chron 1990;66:29–31.
[17] Hall DO, Ojima DS, Parton WJ, Scurlock MO. Response of temperature and tropical grassland to $CO_2$ and climate change. J Biogeogr 1995;22:537–47.
[18] Hanson J, Fung I, Lacis A, Rind D, Russell G, Lebedeff S, Reudy R, Stone P. Global climate changes as forecast by the GISS-3-D model. J Geophys Res 198;93:9341–64.
[19] Hix DM, Lorimer CG. Growth-competition relationship in young hardwood stands on two contrasting sites in southwestern Wisconsin. Forest Sci 1990;36:1032–49.
[20] Jiang H, Apps MJ, Peng CH, Zhang Y. Modelling the effects of fire disturbances on the carbon dynamics of boreal forests in central Canada. Global Change Biol (submitted).
[21] Kimmins JP. Modeling the sustainability of forest production and yield for a changing and uncertain future. Forest Chron 1990;66:271–80.
[22] Kimmins JP, Scoullar KA. Incorporation of nutrient cycling in the design of sustainable,

stand-level, forest management systems using the ecosystem managment model FORECAST and its output format FORTOON. In: Nilsson LO, editor. Nutrient Uptake and Cycling in Forest Ecosystems. Ecosyst. Res. Rep. No. 13, UNR 15405, 1995.
[23] Kimmins JP. Importance of soil and role of ecosystem disturbance for sustained productivity of cool temperate and boreal forests. Soil Sci Soc Am J 1996;60:1643–54.
[24] Kimmins JP. Forest Ecology: A Foundation for Sustainable Management, 2nd ed. Englewood Cliffs, NJ: Prentice Hall, 1997. pp. 475–95.
[25] Korzukhin MD, Ter-Mikaelian MT, Wagner RG. Process versus empirical models: which approach for forest ecosystem management? Can J Forest Res 1996;26:879–87.
[26] Landsberg JJ, Gower ST. Applications of Physiological Ecology to Forest Management. San Diego, CA: Academic Press, 1997. pp. 249–76.
[27] Landsberg JJ, Waring RH. A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecol Manage 1997;95:209–28.
[28] Leemans R, Prentice IC. FORSKA2: A General Forest Succession Model, vol. 2. Uppsala, Sweden: Meddelanden från Våxtbiologiska Institution, 1989. p. 60.
[29] Luckert MK. Towards a tenure policy framework for sustainable forest management in Canada. Forest Chron 1997;73:211–15.
[30] Mäkinen H. Possibilities of competition indices to describe competitive differences between Scots pine families. Silva Fennica 1997;31:43–52.
[31] McGuire AD, Joyce LA. Response of Net Primary Production to Change in $CO_2$ and Climate. Fort Collins, CO: Rock Mountain Forest and Range Experiment Station, General Technical Report; RM-GTR-271, 1995. pp. 9–45.
[32] Metherell AK. Simulation of Soil Organic Matter Dynamics and Nutrient Cycling in Agroecosystems. Ph.D. Dissertation, Colorado State University, CO, 1992.
[33] Metherell AK, Harding LA, Cole CV, Parton WJ. CENTURY Soil Organic Matter Model Environment. Fort Collins, CO: Technical Documentation, Agroecosystem version 4.0. Great Plains System Research Unit, Technical Report No. 4. USDA-ARS, 1993.
[34] Mohren GMJ, Bartelink HH, Jansen JJ. Contrasts between bilogically-based process models and management-oriented growth and yield models. Forest Ecol Manage 1994;69:1–331(Special issue).
[35] Monserud RA. Methodology for Simulating Wisconsin Northern Hardwood Stand Dynamics. Ph.D. Dissertation, University of Wisconsin, Madison, 1975.
[36] Monserud RA, Sterba H. A basal area increment model for individual trees growing in even- and uneven-aged forest stands in Austria. Forest Ecol Manage 1996;80:57–80.
[37] Newnham RM. The Development of a Stand Model for Douglas Fir. Ph.D. Dissertation, The University of British Columbia, Vancouver, Canada, 1964.
[38] Newton PF. Stand density management diagrams: review of their development and utility in stand-level management planning. Forest Ecol Manage 1997;98:251–65.
[39] O'Hara KL, Valappil NI. Masam—a flexible stand density management model for meeting diverse structural objectives in multiaged stands. Forest Ecol Manage 1999;118:57–71.
[40] Oliver CD, McCarter JB. Development in decision support for landscape management. Proceedings of GIS'95, vol. I. The Ninth Annual Symposium on Geographic Information System. Vancouver, 1995. pp. 26–34.
[41] Overpeck JT, Bartlein PJ, Webb T III. Potential magnitude of future vegetation change in Eastern North America: comparisons with the past. Science 1990;254:692–95.
[42] Parton WJ, Schimel DS, Cole CV, Ojima DS. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci Soc Am J 1987;51:1173–79.
[43] Parton WJ, Scurlock JMO, Ojima DS, Gilmanov TG, Scholes RJ, Schimel DS, Kirchner T, Menaut JC, Seastedt T, Garcia Moya E, Kamnalrut A, Kinyamario JI. Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem Cycles 1993;7:785–809.
[44] Parton WJ, Scurlock JMO, Ojima DS, Schimel DS, Hall DO, SCOPEGRAM GROUP

MRMBERS. Impacts of climate change on grassland production and soil carbon worldwide. Global Change Biol 1995;1:13–22.
[45] Pastor J, Post WM. Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles. Biogeochem 1986;2:3–27.
[46] Pastor J, Post WM. Response of northern forests to $CO_2$-induced climate change. Nature 1988;334:55–58.
[47] Pastor J, Post WM. Linear regressions do not predict the transient responses of eastern north American forests to $CO_2$-induced climate change. Climatic Change 1993;23:111–19.
[48] Paustian K, Parton WJ, Persson J. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. Soil Sci Soc Am J 1992;56:476–88.
[49] Peng CH, Apps MJ. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in the Central of Canada: II sensitivity to climate change. Global Biogeochem Cycles 1998;12:393–402.
[50] Peng CH, Apps MJ. Modeling the response of net primary productivity (NPP) of Boreal Forest ecosystems to changes in climate and fire disturbnace regimes. Ecol Model 1999;122:175–93.
[51] Peng CH, Apps MJ, Price DT, Nalder IA, Halliwell D. Simulating carbon dynamics along the Boreal Forest Transect Case Study (BFTCS) in the Central of Canada: I model testing. Global Biogeochem Cycles 1998;12:381–92.
[52] Peng CH, Apps MJ, Jiang H, ZhangY. Simulating the effects of harvesting regiomes on carbon and nitrogen dynamics of boreal forests in central Canada using a process model. Forest Sci (submitted).
[53] Prentice IC, Sykes MT, Cramer W. A simulation model for transitient effects of climate chnage on forest landscapes. Ecol Model 1993;65:51–70.
[54] Price DT, Apps MJ. Boreal forest responses to climate-change scenarios along an ecoclimatic transect in central Canada. Climatic Change 1996;34:179–90.
[55] Price DT, Peng CH, Apps MJ, Halliwell D. Simulating effects of climate change on boreal ecosystem carbon pools in Central Canada. J Biogeogr 1999;26:1237–1248.
[56] Price DT, Halliwell D, Apps MJ, Peng CH. Sensitivity to climate variability in a path model applied to the boreal zone of central Canada. J Biogeogr 1999;26:1101–1114.
[57] Priestley CHB, Taylor RJ. On the assessment of surface heat flux and evaporation using large-scale parameters. Monthly Weather Rev 1972;100:81–92.
[58] Reichle DE, editor. Dynamics Properties of Forest Ecosystem. International Biological Programme 23. Cambridge, MA: Cambridge University Press, 1981. p. 683.
[59] Sanford RL, Parton WJ, Ojima DS, Lodge DJ. Hurricane effects on soil organic matter dynamics and forest production in the Luquillo Experimental Forest, Puerta Rico: results of simulation modeling. Biotropica 1991;23:364–72.
[60] Schenk HJ. Modeling the effects of temperature on growth and persistence of tree species: a critical review of the tree population models. Ecol Model 1996;92:1–32.
[61] Schweitzer DLR, Sassaman RW, Schallau CH. Allowable cut effect: some physical and economic implications. J Forest 1972;70:415–18.
[62] Shugart HH. A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models. New York: Springer-Verlag, 1984. pp. 198–212.
[63] Shugart HH, West DC. Forest succession models. Bioscience 1980; 31:308–13.
[64] Shugart HH, Smith TM, Post WM. The application of individual-based simulation models for assessing the effects of global change. Annu Rev Ecol Systemat 1982;23:15–38.
[65] Shugart HH, Smith TM. A review of forest path models and their application to global change research. Climatic Change 1992;34:131–53.
[66] Smith DJ, Woods ME. Red pine and white pine density management diagrams for Ontario. North Bay, Ontario: SCSS Technical Report, No. 48, 1997. p. 31.
[67] Smith M, Leemans R, Shugart HH. The Application of Path Models of Vegetation Dynamics to Global Vegetation Issues. GCTE Workshop Summary. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1994.

[68] Society of American Foresters. Task force report on sustaining long-term forest health and productivity. Bethesda, MD: Author, 1993. p. 36.
[69] Solomon AM. Transient response of forests to $CO_2$-induced climate change: simulation modeling experiments in eastern North America. Oecologia 1986;68:567–79.
[70] Solomon AM, Bartlein PJ. Past and future climate change: response by mixed deciduous-coniferous forest ecosystems in northern Michigan. Can J Forest Res 1992;22:1727–38.
[71] Stage AR. Prognosis model for stand development. USDA Forest Serv Res Pap INT-137, 1973. p. 32.
[72] Sturtevant BR, Bissonette JA, Long JN. Temporal and spatial dynamics of boreal forest structure in western Newfoundland: silvicultural implications for marten habit management. Forest Ecol Manage 1996;87:13–25.
[73] Tansley AG. The use and abuse of vegetational concepts and terms. Ecology 1935;16:284–307.
[74] Teck R Moeur M, Eav B. Forecasting ecosystems with the forest vegetation simulator. J Forest 1996;94:7–10.
[75] Townsend AR, Vitousek PM, Trumbore SE. Soil organic matter dynamics along gradients in temperature and land use on the Island of Hawaii. Ecology 1995;76:721–33.
[76] Vanclay JK. Modelling Forest Growth and Yield: Applications to Mixed Tropical Forests. UK: CAB International, 1995. pp. 223–50.
[77] Vitousek PM, Turner DR, Parton WJ, Sanford RL. Litter decomposition on the Mauna Loa environmental matrix, Hawaii: patterns. mechanisms, and models. Ecology 1994;75:418–29.
[78] Vuokila Y. Functions of variables density yield tables of pine based on temporary sample plots. Commun Inst Forest Fenn 1965;60:1–86.
[79] Walker JL. Traditional sustained yield management: problem and alternatives. Forest Chron 1990;66:20–24.
[80] Wykoff WR, Crookston NL, Stage AR. User's Guide to the Stand Prognosis Model. USDA Forest Gen Tech Rep INT-133, 1982.
[81] Xiao X, Ojima DS, Parton WJ, Chen Z, Chen D. Sensitivity of Inner Mongolia grassland to climate change. J Biogeogr 1995;22:643–48.