



## The use of soil organic matter as a criterion of the relative sustainability of forest management alternatives: a modelling approach using FORECAST

Dave M. Morris<sup>\*</sup>, J.P. (Hamish) Kimmins<sup>1</sup>, Dan R. Duckert

Ontario Ministry of Natural Resources, Centre for Northern Forest Ecosystem Research, c/o Lakehead University, 955 Oliver Road,  
Thunder Bay, Ont., Canada P7B 5E1

Accepted 22 November 1996

### Abstract

The purpose of this study was to evaluate the usefulness and sensitivity of parameters that describe various soil organic matter characteristics for the evaluation of harvesting impacts on ecosystem function, using an ecosystem-level, hybrid simulation model (FORECAST, a model developed from its predecessor FORCYTE-11). Four separate sets of forest management options were applied to both a simulated unmanaged Douglas-fir forest (with a high accumulation of forest floor, coarse woody debris, and the nutrients contained therein) and to a simulated Douglas-fir forest growing on a site depleted in organic matter and nutrients. These four options consisted of the combination of two rotation lengths (40 vs. 80 years), and two levels of biomass utilization (full-tree vs. conventional tree length harvest).

Based on the model simulations, productivity on the previously unmanaged site dropped significantly (to 59% of the value for the original, unmanaged forest) by the end of the second 40 year rotation when subjected to an intensive management option (40 year rotation, full-tree harvesting). However, a rapid drop in the active soil pool of decomposing organic matter occurred and was not rebuilt. As a result of this reduction in the size of the active soil pool, nitrogen deficiencies (N-demand greater than N-uptake) occurred in the subsequent rotations. In contrast, the initially nutritionally degraded site responded positively to an intermediate level of management (80 year rotations, stem-only harvesting), with a steady increment in the active soil organic matter pool size over the 240 year simulation period. This response indicates that sites degraded by past activities generally have the ability to recover (aggrade) if put under a less demanding management regime. Change in the mass and dynamics of active soil organic matter provides a more rapid and sensitive parameter than tree growth when attempting to assess the sustainability of management alternatives. Examples are presented which illustrate the importance of the starting state condition, as well as the management system being applied, when attempting to assess the sustainability of management alternatives. © 1997 Elsevier Science B.V.

**Keywords:** Forest sustainability; Site productivity; Soil organic matter; N-availability; Ecosystem-level modelling; FORECAST

### 1. Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is one of the world's most important and valuable softwood tree species. It has been a major

<sup>\*</sup> Corresponding author.

<sup>1</sup> Present address: University of British Columbia, Vancouver, B.C., Canada, V6T 1Z4.

component of the forests of western North America since the mid-Pleistocene (Hermann, 1985). Periodic recurrence of catastrophic wildfires created vast, almost pure, even-aged stands of Douglas-fir throughout much of its range. These stands have been the focus of attention in recent years as logging and environmental advocates struggle with the issue: **can wood extraction be conducted without causing any significant long-term change in ecosystem function?** This 'function' is defined as the constant exchange of matter and energy between the physical environment and the living community by which biomass is created, stored, and passed through the trophic web (Kimmins, 1987). Productivity of any given ecosystem is determined by the efficiency with which matter and energy enter, move through, and are stored at the various trophic levels.

There is little question that stand-replacing disturbance (natural or anthropogenic) of a mature forest ecosystem causes an alteration in ecosystem structure and function for a significant period of time. However, all ecosystems tend to recover towards their pre-disturbance condition through autogenic succession, a pervasive process that provides ecosystems with an inherent stability. Regardless of the type of ecosystem or seral stage, if the external stress is not too great and if the frequency of disturbance is low relative to the rate of autogenic recovery, the system will eventually return to its pre-disturbance condition. The time period required for a given site, managed under a given management system, to return to its pre-disturbance ecological conditions is termed its 'ecological rotation' (Kimmins, 1974). Simply put, sustainability can be achieved if the set of forest management actions are such that the timber extraction rotation is longer than the ecological rotation. **In terms of site nutrient capital and productivity, the length of the recovery period is a function of: (1) the degree of site nutrient depletion accompanying harvesting (Timmer et al., 1983; Mahendrappa et al., 1987), and (2) the rate of replacement of these nutrient losses (Wells and Jorgensen, 1979).** Several studies have reported relatively consistent trends in declining organic matter content and nutrient availability for 15–30 years after harvesting, but returning to near pre-felling values by Years 60–80 (Boyle, 1976; Aber et al., 1978; Covington, 1981; Gordon, 1983; Martin, 1985). However, this harvest-related

nutrient loss and subsequent replacement is complex, varying among species (Kimmins, 1977; Alban et al., 1978; Mahendrappa et al., 1987; Maliondo, 1988), site quality factors, age (White and Harvey, 1979; Freedman, 1981), and stand density. Unfortunately, it is much easier to evaluate the degree to which harvest-induced nutrient depletion occurs as the intensity of utilization increases than to determine how important such increased losses are in terms of reduced future productivity (Kimmins, 1977).

In managed forest ecosystems, both ecosystem processes and the outputs generated from these processes can be significantly altered in comparison with unmanaged forests. **An important and practical question in this regard is whether the productivity of a managed forest can be maintained over multiple rotations** considering the effects of management on site biogeochemistry—the capital, availability, and accumulation and loss of nutrients. This is a complex issue and it is difficult to predict how important a harvest-induced nutrient depletion is in terms of reduced future site productivity. However, we cannot wait one or two rotations to learn by experience the relative sustainability of different forest harvesting and management strategies. We must use our present, albeit incomplete, understanding of ecosystem function to make the best scientifically based evaluation we can. One way of doing this is to employ an ecologically based forest management simulation model. **The purpose of this study was to use a modelling approach to examine the usefulness of short- to medium-term trends in soil organic matter dynamics as a criterion with which to assess the long-term sustainability of a forest management system.** In addition to this central objective, other questions are addressed: (1) Does the initial (starting) state of a forest ecosystem have an influence on the evaluation of sustainability? (2) Do disruptions in ecosystem function caused by harvesting have permanent impacts on site productivity? (3) Once an ecosystem is degraded, can it recover if a less demanding forest management regime is applied? A recent review of the whole topic of the impacts of forest harvesting on long-term site productivity has been given by Dyck et al. (1994).

A calibration data set for FORCYTE-11 (Forest Nutrient Cycling and Yield Trend Evaluator) for coastal Douglas-fir (Sachs and Trofymow, 1991) was

used in FORECAST (Forestry and Environmental Change Assessment), the successor model to FORCYTE-11 (Kimmins, 1993), to simulate alternative management options, plant production and soil organic matter dynamics for ecosystems representing (1) sites that had previously supported a mature, unmanaged Douglas-fir forest, and (2) an area that had been nutritionally degraded by a period of non-sustainable forest management.

## 2. Materials and methods

### 2.1. Model approach and description

For nearly two centuries, volume–age curves, height–age curves, and yield tables have been the basis on which foresters have predicted future yields. This historical bioassay is valid for the species involved and the particular set of biotic and abiotic growth conditions that pertained over the period of growth. However, if changes in future management regimes, human impacts on the atmosphere (e.g. climate change, atmospheric chemistry), and/or changes in soil fertility significantly alter future growth conditions, the predictions of the bioassay are unlikely to be accurate (Kimmins, 1988, Kimmins, 1990).

Because of the inflexibility of this traditional growth and yield approach, a great deal of interest and research has been focused recently on mechanistic models. These process-based models consist of empirically derived relationships between a series of independent variables and the dependent variable, tree (stand) growth. Examples of such models developed for forests and other ecosystems can be found throughout the literature (e.g. Sollins et al., 1979; Running, 1984; Barclay and Hall, 1986; Parton et al., 1987; Bossel and Schäfer, 1989; Dixon et al., 1990). A detailed, process-based simulation model would be the ideal approach to simulating forest growth and yield if there were a near-complete knowledge of all significant forest ecosystem processes, and the necessary calibration data were readily available.

A third approach to yield prediction has been developed which attempts to combine the strengths of the other two approaches and thereby compensate for their individual weaknesses. The most developed

models in this ‘hybrid’ category which are suitable for the assessment of harvesting impacts on long-term site productivity include LINKAGES (Pastor and Post, 1985), FORCYTE-11 (Kimmins, 1993), and FORECAST (the successor to FORCYTE-11). These models take the yield (production) predictions from a historical-bioassay model (or from raw field data), and modify these predictions according to a simulation of the temporal variation in competition for light and in the availability of one or more nutrients. Nutrient availability is the focus of the process simulation because it is often the factor which most limits forest growth, as well as being the site factor that is most subject to change as the type and/or intensity of forest stand management changes. However, light competition is also a central component of the simulation of stand development. Moisture limitations and moisture competition are not well represented in these models, which are, therefore, restricted in their application to sites that do not have severe site moisture deficits or severe soil moisture competition.

FORECAST was used as the forest simulator in this study. Fig. 1 depicts a flow chart of the files and programs that are contained within this ecosystem management model. Kimmins (1993) has provided an in-depth review of the scientific foundations and programming logic used in the development of FORCYTE-11, which is conceptually and structurally similar to FORECAST. Basic empirical data (Fig. 1: TREEDATA, PLNTDATA, BRYODATA, and SOILDATA) are fed into the setup programs (TREEGROW, PLNTGROW, BRYOGROW, and SOILS), which perform all the required calculations needed to establish a set of simulation rules and values (contained in the \*TRND files) for various process rates that are used in the ECOSYSTEM program to simulate the management of the ecosystem. The SOILDATA ‘setup’ also produces an INITSTAT file, which, used in conjunction with a special run of ECOSYSTEM, results in a description of the initial values for organic matter and nutrient inventories for the start of future runs (the ECOSTATE file). The ecosystem simulation performed by ECOSYSTEM is under the control of the ECODATA file. This file is analogous to ‘scheduler’ files in other models; it prescribes the various management options and duration of the runs you wish to impose on the ecosystem. Output files are then fed into the FORTOON

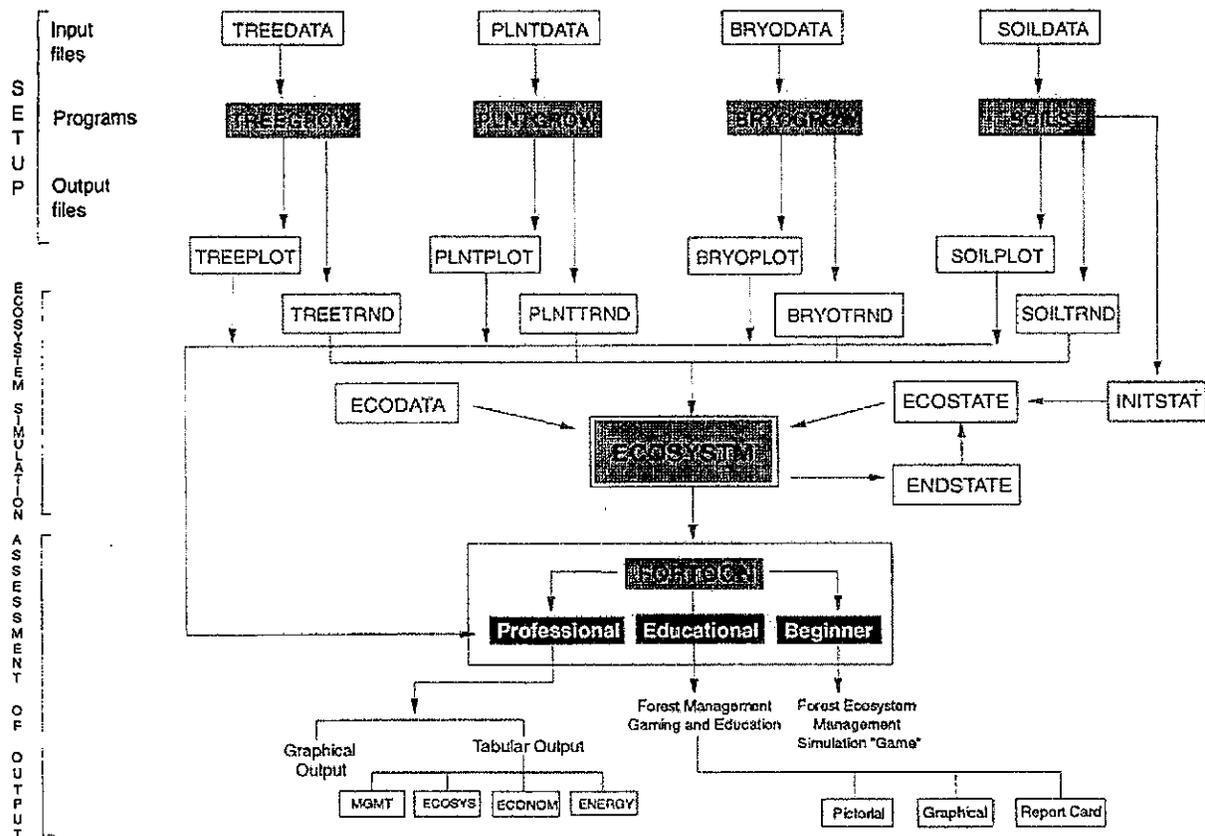


Fig. 1. Flow chart of files and programs that constitute FORECAST.

output management program for viewing and printing of the results generated from the ECOSYSTEM runs.

The data requirements for model calibration are outlined in the FORCYTE-11 User's Manual (Kimmins et al., 1990), a comparable manual for FORECAST having not yet been prepared. Because the development of indices or coefficients for the various ecosystem processes is conducted within the model itself and because the model represents, or has the capability to represent, a variety of ecosystem processes and management activities (Fig. 2), the data requirements to run the model are substantial, and much larger than in comparable 'gap' models (e.g. LINKAGES), where this development is done external to the model. Data are required on height, stand density, stem size frequencies, biomass accumulation, nutrient concentrations in the various biomass components, atmospheric nutrient inputs, foliar leaching (optional), biomass to litterfall trans-

fer rates, photosynthetic adaptations of foliage (e.g. ratio of sun to shade foliage), and a variety of other stand and soil (physical and chemical properties) information from a chronosequence of stands on sites that vary in nutritional site quality. By providing empirical data that demonstrate different process rates and different growth strategies in response to varying nutrient availability (i.e. data from sites varying in nutritional site quality), the model is able to simulate altered production and carbon allocation in response to management-induced changes in soil resource availability. For the model simulation conducted in this study, input data for Vancouver Island Douglas-fir sites were used (Sachs and Trofymow, 1991).

## 2.2. Model assumptions and validation

As with most models, FORECAST relies upon several assumptions which, if not met, will reduce

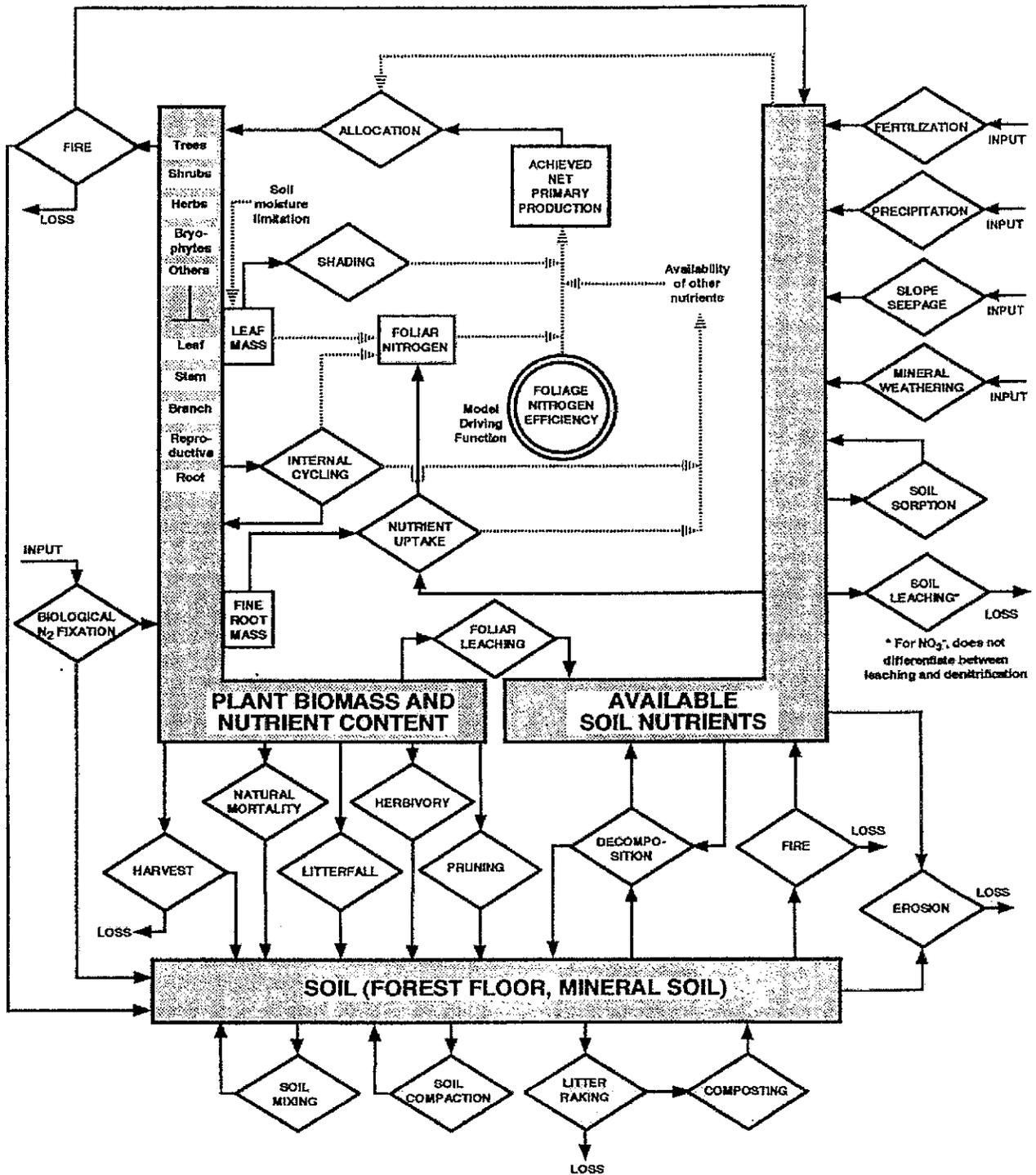


Fig. 2. Major compartments and transfer pathways represented in FORECAST.

the accuracy of the outputs. These assumptions are as follows: (1) the historical bioassay provides the best available estimate of the growth potential of the species being simulated; (2) the best method to simulate the consequences of environmental change over time for growth allocation and biomass turnover is to use data on patterns of allocation and turnover from environments with a range of values for the environmental variables of interest; (3) the initial conditions of the plant community and soil (ECOSTATE file) can be accurately defined; (4) the method used to estimate certain process rates indirectly from input data produces acceptable estimates of the rates (Kimmins, 1993).

One of the most difficult aspects of model simulation is the validation of a model's long-term predictions. FORCYTE-11 has been evaluated by Sachs and Trofymow (1991), who utilized 20 year thinning and fertilizer data from Shawnigan Lake. In some of the treatments, the model underestimated biomass accumulation and mortality, but model rankings of the simulated treatments did not differ significantly from the treatment rankings produced by the field experiment. For many of the treatments, the fit between model prediction and field data was good. It should be recognized that this was only a short-term (20 year) validation. It is not reasonable to expect ecosystem models to predict the long-term future condition of the ecosystem with high accuracy, or to provide exact predictions of future harvests. However, if they are to be useful in the design of sustainable forest management systems, they should be capable of an accurate ranking of the alternative management options. Until long-term validations, which are currently being initiated, are completed, it is premature to make statements about the validity of the long-term predictions of this model.

### 2.3. Establishing 'starting-state' forests

The first step in the study was to generate two contrasting initial forest states. A comparison of the simulated ecosystem function starting from these two different ecosystem conditions should suggest those site parameters that are useful indicators of the response of forests to the stresses imposed by timber harvesting. The first of the initial ecosystem conditions (a site that had carried a mature, unmanaged

Douglas-fir forest for a long time) was developed by running the ECOSYSTEM program for four successive 200 year periods, with a stand-replacing 'windthrow' event (i.e. all the trees were knocked over but left on site) at the end of each of the first three periods. A stems-only harvest was conducted at the end of the last 200 year period. The state of the ecosystem at the end of this 800 year simulation was used as the starting state (the ECOSTATE I file) for the 'mature, unmanaged forest stand' condition, and was characterized by very large accumulations of forest floor and logging slash, and the nutrients contained therein. The second ecosystem condition (a site that had been degraded by mismanagement) was established by simulating six successive 40 year rotations, with full-tree harvesting (90–95% of all above-ground tree biomass removed at harvest). These short rotations and the high levels of nutrient removals accompanying the simulated high level of biomass utilization resulted in low levels of forest floor mass and associated nutrients. The condition at the end of the 240 year period was used as the ECOSTATE II file in the next phase of the study.

To compare the consequences of these two starting state conditions (ECOSTATE I and ECOSTATE II) for subsequent tree growth, forests were grown from each starting state condition for a period of 200 years. Examination of the differences between the structural and functional characteristics of these two 200-year-old forests provided an evaluation of the sensitivity of future forest development and productivity to the initial (starting) state

### 2.4. Management scenarios

Two separate sets of forest management options were defined in the ECODATA file and were combined with the ECOSTATE I and ECOSTATE II files to produce four separate model runs. FORECAST offers the possibility of simulating a wide range of forest management practices. This experiment was kept very simple because unless the model is used as a factorial experiment, interpretation of the results becomes extremely difficult. Only rotation length (40 vs. 80 years) and level of biomass utilization (stem-only harvest vs. full-tree harvest) were varied. We focused on these two management variables (rotation length and utilization level) because

they have the potential to have a major effect on site nutrient balance and on nutrient-determined biomass production.

The total length of the modelling runs was 240 years. For Management Option A (intensive management), six 40 year rotations were conducted using the full-tree harvesting method. In this method, 95% of the stemwood and bark, and 90% of the live branches and foliage were removed from the site during harvest. All below-ground material was left on site and was added to the active soil pool of organic matter. For Management Option B (an intermediate level of management), three 80 year rotations were conducted using conventional tree length harvesting. In this method, 90% of the stemwood and bark were removed from the site during harvest. All live branches and foliage, as well as the below-ground biomass, remained on the site. Examination of changes in various site parameters provided an assessment of the relative sustainability of various ecosystem characteristics under these two management scenarios, as well as the effect the initial site conditions had on this evaluation of sustainability.

### 3. Results and discussion

#### 3.1. Comparison of 'starting-state' forests

Table 1 summarizes several structural and functional characteristics of simulated 200-year-old forests grown on both a previously unmanaged site (ECOSTATE I) and a degraded site (ECOSTATE II). Data are presented for three points in time (0 years—initial state, 40 years, and 200 years—end state) during stand development. The end state values generated for the forest grown on the unmanaged site appear to be realistic compared with actual values. For example, Zobel et al. (1976) reported a range of 734–1773 t ha<sup>-1</sup> of above-ground biomass for mature Douglas-fir forests growing on a wide range of sites. The model-generated value was 786.2 t ha<sup>-1</sup>. Youngberg (1966) reported forest floor biomass values of 22–85 t ha<sup>-1</sup> in Douglas-fir stands. Our model-generated value for the active soil pool size of 119 t ha<sup>-1</sup> is greater than Youngberg's range. This higher value, however, is probably due to the fact that fire was not included when establishing the

ECOSTATE I file (simulated 100% windthrow every 200 years and a stems-only harvest at the end of the 800 year simulation). Fire, which removes organic matter accumulation, was a prominent feature of the forests studied by Youngberg.

The data presented in Table 1 illustrate major differences in biomass production between the forests generated on the two contrasting site conditions. For example, above-ground biomass accumulation (standing crop) at 200 years was 786.2 t ha<sup>-1</sup> for the previously unmanaged site as compared with 609.2 t ha<sup>-1</sup> for the degraded site. These data reflect the traditional use of above-ground biomass production and accumulation as an index of the impact of intensive forest management on site productivity. However, simple differences in biomass production do not provide any insight into why these differences occur or what processes are being effected.

In terms of soil organic matter parameters, there appears to be little difference after 200 years between simulations based on the two different initial site conditions. For example, active soil pool sizes were 119 t ha<sup>-1</sup> for the unmanaged site as compared with 101.0 t ha<sup>-1</sup> for the degraded site (Table 1). However, it is the ability of this active pool to meet the demands of the growing forest that is of greater interest; this requires a comparison of the temporal patterns of N-release and N-demand by the trees.

The active soil pool for the unmanaged site exhibited a sharp decline in the total pool size from 340.1 t ha<sup>-1</sup> at Year 0 to 51.0 t ha<sup>-1</sup> at Year 40 before recovering to 119 t ha<sup>-1</sup> by Year 200 (Table 1, Fig. 3(a)). The N-release from the pool, after dropping rapidly from 123.2 kg N ha<sup>-1</sup> year<sup>-1</sup> to just over 40 kg N ha<sup>-1</sup> year<sup>-1</sup>, begins to rebound by Year 40 and remains equivalent to that of the fresh litter N-inputs (Fig. 3(a)), a rate that was capable, except for two brief periods, of meeting the nutrient demands of the growing forest throughout the 200 year simulation period (Fig. 3(b) (N-demand equals N-uptake)). This is not the case for the degraded site.

During early stand establishment on the degraded site, the active soil pool size drops from 75.8 t ha<sup>-1</sup> (largely a result of logging residue) to 14.1 t ha<sup>-1</sup>. Except for a brief pulse of nitrogen released in the first 5 years (assart flush), the annual N-release only rises slightly from 16.5 kg N ha<sup>-1</sup> year<sup>-1</sup> to 18.6 kg N ha<sup>-1</sup> year<sup>-1</sup> by Year 40 (Table 1, Fig.

4(a)). Because of differences in the composition of the forest floors in the two different site conditions, the N-release represents a smaller percentage of the active N-pool in the first 40 years on the degraded site than for the unmanaged site (Table 1: degraded site, 8.5%; unmanaged site, 12.8%). It is not until crown closure and the increase of litterfall inputs, occurring at approximately Year 20 (Fig. 4(b)), that the size of the active soil pool begins to increase (Fig. 4(a)). The annual release of nitrogen from this pool also increases and eventually reaches equilibrium with total demand at Year 70 (comparing Fig. 4(a) (N-release from active soil pool) with Fig. 4(b)

(total N-demand)). The low initial values of N-release result in an inability of the site to supply sufficient nutrient (N) during the forest's rapid period of growth, which occurs between Year 20 and Year 70 (Fig. 4(b) (total demand greater than total uptake)). Nitrogen availability is commonly cited as the primary factor that limits productivity of forest ecosystems (Binkley and Hart, 1989). It is this shift in active soil pool components and corresponding N-release which should be monitored as previously unmanaged forested sites undergo intensive management.

Cole and Gessel (1963) stated that many of the

Table 1

Comparison of the structural and functional characteristics of simulated 200-year-old Douglas-fir forests grown on both a previously unmanaged (ECOSTATE I) and a degraded (ECOSTATE II) site using FORECAST

Ecosystem characteristics	Unmanaged state			Degraded state		
	0 years	40 years	200 years	0 years	40 years	200 years
Stand density (stems ha <sup>-1</sup> )	1200	1020	420	1200	1176	612
<i>Stand biomass (tonnes ha<sup>-1</sup>)</i>						
Stemwood	0	349.9	644.9	0	139.4	480.8
Bark	0	41.9	85.6	0	15.8	83.1
Live branch	0	37.0	38.2	0	18.6	27.4
Dead branch	0	18.8	0.4	0	2.6	0.3
Foliage	0	17.1	17.1	0	6.9	17.3
Large root	0	74.7	138.3	0	28.4	105.1
Medium root	0	12.8	13.1	0	7.4	12.0
Small root	0	4.9	3.1	0	3.8	3.0
<b>Total tree biomass</b>	<b>0</b>	<b>557.1</b>	<b>940.7</b>	<b>0</b>	<b>237.9</b>	<b>730.2</b>
Litterfall (t ha <sup>-1</sup> year <sup>-1</sup> )	0	11.4	9.9	0	7.9	9.8
<i>Forest nutrition (kg N ha<sup>-1</sup> year<sup>-1</sup>)</i>						
Total demand	0	48.6	77.2	0	42.8	77.9
Total uptake	0	48.6	77.2	0	27.3	77.9
Loss to litterfall	0	46.1	64.9	0	23.1	65.9
Loss to foliar leaching	0	1.8	5.1	0	0.2	5.2
Loss to tree mortality	0	0.2	5.7	0	0.2	4.6
<i>Soil organic matter</i>						
Active pool (t ha <sup>-1</sup> ) <sup>a</sup>	340.1	51.0	119.0	75.8	23.2	101.0
Total N—active (kg ha <sup>-1</sup> )	961.6	326.9	480.8	330.1	220.1	440.1
N release—active (kg ha <sup>-1</sup> year <sup>-1</sup> )	123.2	41.9	69.0	16.5	18.6	68.7
Stable pool (t ha <sup>-1</sup> ) <sup>b</sup>	10.5	9.4	7.8	6.5	6.4	3.2
Total N—stable (kg ha <sup>-1</sup> )	106.4	97.9	89.4	88.8	87.1	110.5
N release—stable (kg ha <sup>-1</sup> year <sup>-1</sup> )	2.2	1.5	1.4	1.7	1.4	1.9

<sup>a</sup> Active pool includes fresh litter and litter undergoing decomposition.

<sup>b</sup> Stable pool includes both the passive and slow pools of stable organic matter. In the model, these are collectively defined as 'humus'.

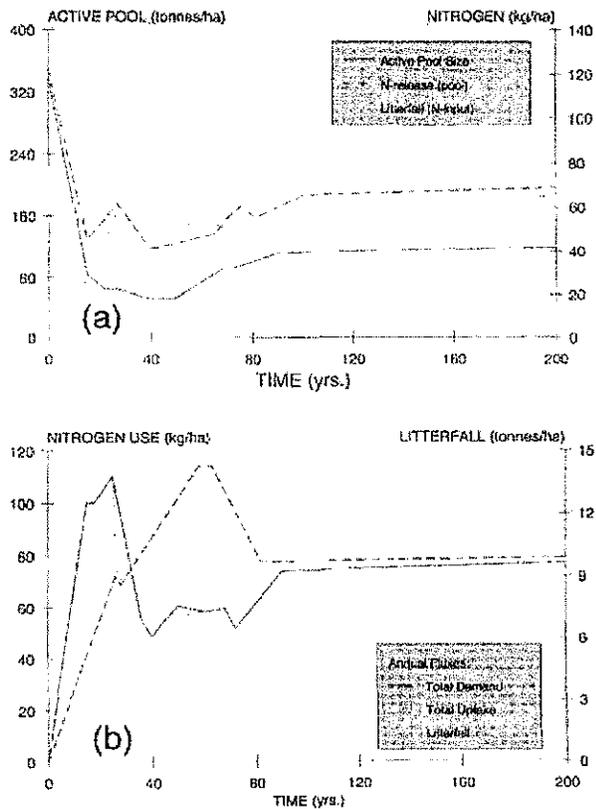


Fig. 3. (a) Depiction of changes in the active soil pool size, N-release from the pool, and N-inputs from fresh litterfall for a simulated 200-year-old Douglas-fir forest grown on a previously unmanaged (ECOSTATE I) site. There was no management imposed in this simulation. (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) and litterfall inputs (includes fine root turnover) for a simulated 200-year-old Douglas-fir forest grown on a previously unmanaged (ECOSTATE I) site. There was no management imposed in this simulation. Note: in this case, N-demand is equal to N-uptake for the majority of the 200 year simulation period.

major problems of forest tree nutrition and soil fertility are related to the amount and nature of the organic debris reaching the forest floor and its rate of decomposition. In attempts to examine soil organic matter dynamics in agricultural and grassland ecosystems, other models (e.g. CENTURY—Parton et al., 1987; PHOENIX—McGill et al., 1981) have partitioned the soil organic matter pool into five distinct fractions (active, metabolic, structural, slow, and passive fractions) and define the decay functions and transfer rates between these fractions. This modelling approach requires accurate estimates of (1) the

size of the fractions (pools), (2) coefficients which are fed into the decay functions, and (3) the magnitude of the transfer rates between the various fractions. Unfortunately, very few data exist to generate this information for forest ecosystems (e.g. data on all these pools for all the different litter types in a forest). As a result, FORECAST takes the approach of applying age-specific litter decomposition rates to simulated amounts of fresh litter and nine age-classes of decomposing residues for each litter type (e.g. leaves, twigs, bark, etc.). The combination of all of this material represents the active soil pool. The

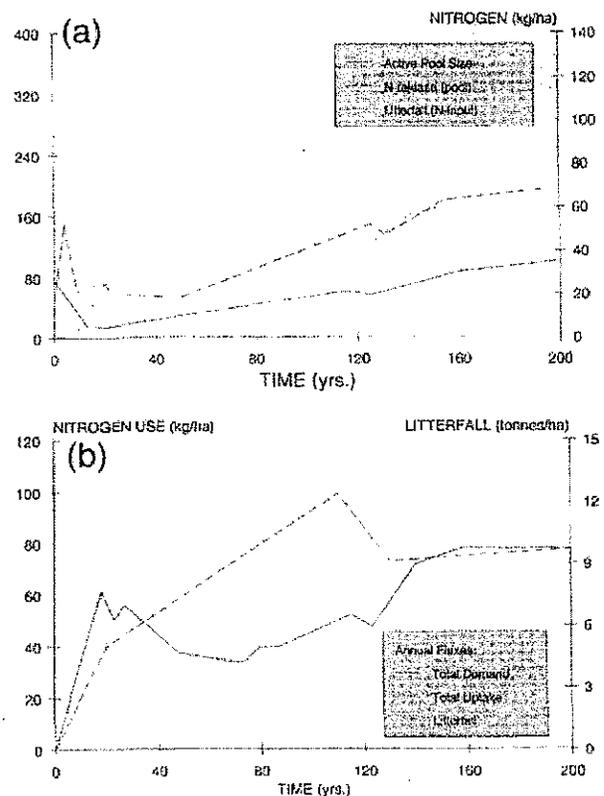


Fig. 4. (a) Depiction of changes in the active soil pool size, N-release from the pool, and N-inputs from fresh litterfall for a simulated 200-year-old Douglas-fir forest grown on a degraded (ECOSTATE II) site. There was no management imposed on this simulation. (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) and litterfall inputs (includes fine root turnover) for a simulated 200-year-old Douglas-fir forest grown on a degraded (ECOSTATE II) site. There was no management imposed in this simulation. Note: in this case, a period of nutritional stress is identified where N-demand was greater than N-uptake.

relatively stable end-product of the decomposition of these litter types is collectively called 'humus' (stable soil pool). Nutrient immobilization and mineralization for a particular litter cohort is simulated as the difference in nutrient content between different time steps of a decomposing litter cohort. In relating our approach to that used in the CENTURY model, our active soil pool would be broadly analogous to the combination of the active, metabolic, and structural fractions, whereas our stable soil pool would be

representative of a composite of the slow and passive fractions.

As anticipated, although some changes are evident in the stable soil pool size over time, these changes represent very little in terms of total nutrient (N) supply (of the order of  $1.7 \text{ kg N ha}^{-1} \text{ year}^{-1}$ ), and are similar for both sites (Table 1). The stable pool size predicted by the model is relatively small. This pool size is a function of the input calibration data (from Sachs and Trofymow (1991)) that we

Table 2

Comparison of biomass pools and process rates at the end of six successive 40 year rotations of Douglas-fir grown on two contrasting site conditions: a previously unmanaged site (ECOSTATE I) and a degraded site (ECOSTATE II), subjected to an intensive forest management option<sup>a</sup>

Ecosystem characteristics (at end of each rotation)	Unmanaged site						Degraded site					
	40 yrs	80 yrs	120 yrs	160 yrs	200 yrs	240 yrs	40 yrs	80 yrs	120 yrs	160 yrs	200 yrs	240 yrs
Stand density (stems $\text{ha}^{-1}$ )	1007	1139	1151	1163	1176	1176	1176	1176	1176	1176	1176	1176
<i>Stand biomass (t <math>\text{ha}^{-1}</math>)</i>												
Stemwood	350	202	164	154	150	147	138	138	138	138	138	138
Bark	42	24	19	17	17	16	16	16	16	16	16	16
Live branch	37	25	22	20	20	20	19	19	19	19	19	19
Dead branch	19	11	10	8	8	8	7	7	7	7	7	7
Foliage	17	10	8	7	7	7	7	7	7	7	7	7
Large root	74	42	34	32	31	30	29	29	29	29	29	29
Medium root	13	9	8	8	8	8	7	7	7	7	7	7
Small root	5	5	4	4	4	4	4	4	4	4	4	4
Total tree biomass	557	328	269	250	245	240	227	227	227	227	227	227
Litterfall (t $\text{ha}^{-1} \text{ year}^{-1}$ )	12	10	9	8	8	8	8	8	8	8	8	8
<i>Forest nutrition (kg N <math>\text{ha}^{-1} \text{ year}^{-1}</math>)</i>												
Total demand	49	53	45	45	44	44	42	42	42	42	42	42
Total uptake	49	35	32	30	29	29	28	28	28	28	28	28
Loss to litterfall	47	32	27	26	24	24	24	24	24	24	24	24
Loss to foliar leaching	2	0.5	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Loss to tree mortality	0.2	2	1	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2
<i>Soil organic matter</i>												
Active pool (t $\text{ha}^{-1}$ ) <sup>a</sup>	48	31	27	24	24	24	23	23	23	23	23	23
Total N—active (kg $\text{ha}^{-1}$ )	346	288	250	240	231	231	220	220	220	220	220	220
N release—active (kg $\text{ha}^{-1} \text{ year}^{-1}$ )	38	21	18	18	18	18	19	19	19	19	19	19
Stable pool (t $\text{ha}^{-1}$ ) <sup>b</sup>	10	9	9	8	8	7	6	6	6	6	6	6
Total N—stable (kg $\text{ha}^{-1}$ )	99	99	97	97	94	92	88	88	88	88	88	88
N release—stable (kg $\text{ha}^{-1} \text{ year}^{-1}$ )	1.6	1.4	1.4	1.5	1.4	1.4	1.3	1.3	1.3	1.3	1.3	1.3

<sup>a</sup> The intensive management option consisted of six 40 year rotations after which each stand was harvested using the full-tree harvesting method.

need which determine how much mass from the active soil pool remains to be transferred to ‘humus’ at the end of the decomposition period. Many western soils do have larger mineral soil organic matter pools than those used for model calibration. It is possible, therefore, that a larger stable pool and larger N-release from this pool may have increased the resistance of the ecosystems to declines in productivity during the model simulation. It should be remembered, however, that this stable soil pool in FORECAST combines the slow and passive fractions described by Parton et al. (1987). The constituents of these fractions are complex, highly charged, organic molecules, which are tightly bound to clay particles or within soil microaggregates. As a result, estimates of turnover rates for these pools have been reported as 25 years and 1000 years, respectively (Paustian et al., 1992). Composite soil estimates of turnover rates of 900–1000 years have also been documented (Paul et al., 1964).

### 3.2. Impacts of Management Option A (intensively managed)

Table 2 summarizes some of the structural and functional characteristics of forests at the end of six successive 40 year rotations with full-tree harvesting, starting with either the previously unmanaged or the degraded initial site condition.

There was a decline in total biomass production over the six rotations on the previously unmanaged site (Fig. 5(a)). However, the total biomass production in the first rotation period (Table 2:  $557 \text{ t ha}^{-1}$ ) was identical to the production at Year 40 of the unmanaged forest (Table 1:  $557.1 \text{ t ha}^{-1}$ ). It is in the second rotation period (Years 41–80) that the productivity dropped significantly to 58.9% of the unmanaged forest. Total biomass production during the first rotation, therefore, provided no indication that the prescribed management option might not be sustainable. This is explained by Fig. 5(b), which depicts the total N-demand vs. the total N-uptake. During the first 40 year rotation, the decomposition and release of nitrogen from the large active soil pool was sufficient to match the demand of the growing forest (total N-demand equals total N-uptake) for the majority of the rotation period. The active soil pool of the previously unmanaged forested site contained sufficient reserves of available nutri-

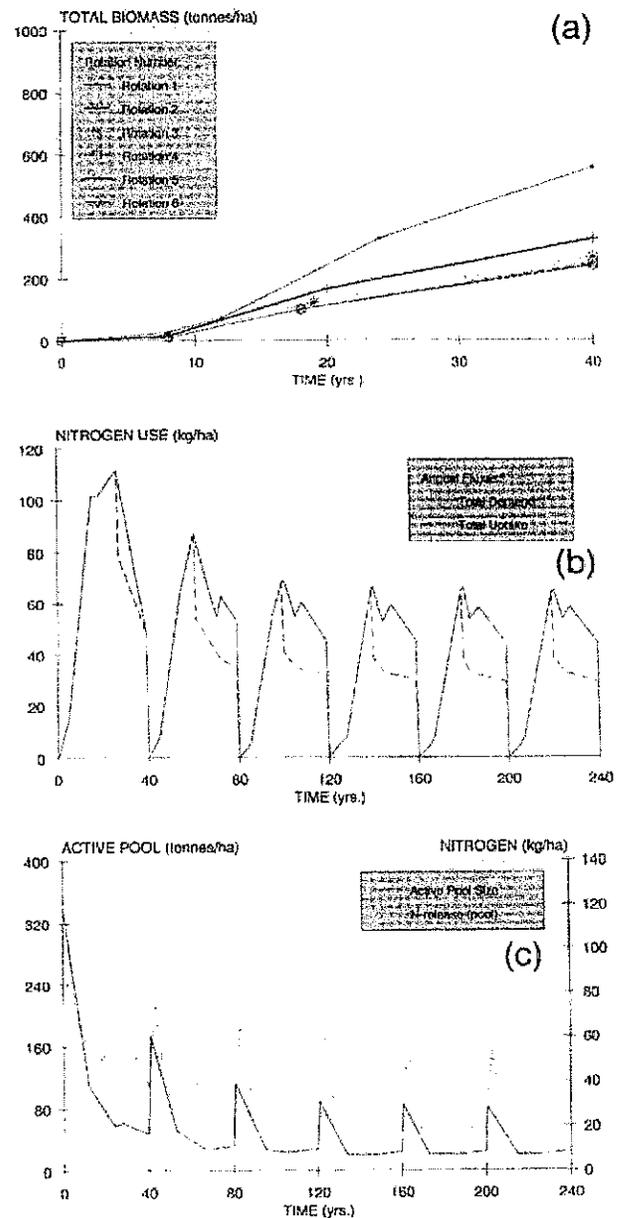


Fig. 5. (a) Comparison of total biomass production for six successive rotations of Douglas-fir grown on a previously unmanaged (ECOSTATE I) site, subjected to an intensive management option (six 40 year rotations, full-tree harvesting). (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) for a previously unmanaged (ECOSTATE I) site, subjected to intensive management options (six 40 year rotations, full-tree harvesting). Note: in this case, a period of nutritional stress is identified where N-demand was greater than N-uptake. (c) Depiction of changes in the active soil pool size and N-release for a previously unmanaged (ECOSTATE I) site, subjected to intensive management options (six 40 year rotations, full-tree harvesting).

ents to satisfy the growth demands of the developing forest. However, the size of this pool became progressively smaller at the start of each successive rotation (Fig. 5(c)), resulting in a total N-demand greater than total N-uptake (Fig. 5(b)), and culminating in successive reductions in productivity (Table 2, Fig. 5(a)). By the fourth rotation, where biomass production has dropped to  $250 \text{ t ha}^{-1}$  (Table 2), the ecosystem appears to be approaching a new equilibrium level that is nearly equivalent to that of the degraded site at approximately  $230 \text{ t ha}^{-1}$  (comparing Fig. 5(a) with Fig. 6(a)). Both the total N-demand and the total N-uptake curves for the previously unmanaged site begin to resemble, in terms of shape and magnitude, those generated for the degraded site (comparing Fig. 5(b) with Fig. 6(b)).

Total biomass production for the degraded site was  $227 \text{ t ha}^{-1}$  for all six rotations (Table 2, Fig. 6(a)), a level that could apparently be sustained. The pattern of N-demand vs. N-uptake, depicted in Fig. 6(b), is extremely similar for all rotations. This pattern shows N-demand equal to N-uptake until about the fifteenth year into each rotation period. This equality is largely a function of the assart flush occurring at the beginning of each rotation (Fig. 6(c)). After the fifteenth year, an N-deficit appears, and it continues to increase until the end of each rotation (Fig. 6(b)).

Although productivity on the previously unmanaged site was unaffected in the first rotation, Fig. 5(c) shows a marked decline in the active soil pool size from the initial condition to the end of the rotation. However, litterfall inputs to the pool are minor before crown closure (approximately Year 20), allowing for only a minor recovery of pool size before harvesting (Fig. 5(c)). The active pool size and the annual release of nitrogen become comparable with those of the degraded site by the fourth rotation (Table 2, comparing Fig. 5(c) with Fig. 6(c)). Decomposition and N-release in the subsequent rotations is based primarily on the more stable plant residues, with only small pulses (assart flush) of decomposition of more labile residues corresponding to each harvesting operation (Fig. 5(c) and Fig. 6(c)). The assart flush continues only until the fresh, highly labile material is decomposed or converted into soil organic matter (Kimmins, 1987). This decomposition trend appears to be following the two-

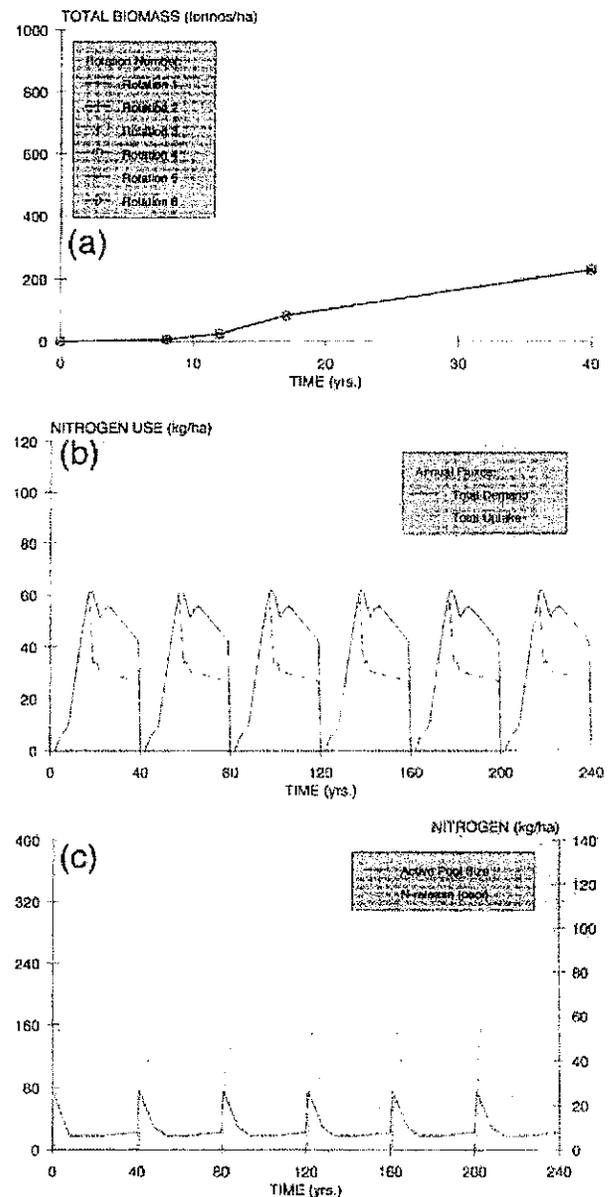


Fig. 6. (a) Comparison of total biomass production for six successive rotations of Douglas-fir grown on a degraded (ECOSTATE II) site, subjected to an intensive management option (six 40-year rotations, full-tree harvesting). (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) for a degraded (ECOSTATE II) site, subjected to intensive management options (six 40-year rotations, full-tree harvesting). Note: in this case, a period of nutritional stress is identified where N-demand was greater than N-uptake. (c) Depiction of changes in the active soil pool size and N-release for a degraded (ECOSTATE II) site, subjected to intensive management options (six 40-year rotations, full-tree harvesting).

compartment exponential decay model based on first-order kinetics described by Jenkinson (1977) and others (Van Veen and Paul, 1981; Voroney et al., 1989).

There is no indication that any increase in N-release from the stable soil pool occurs to compensate for the depletion in the active soil pool (Table 2). Therefore it is this significant change in active soil pool size which should be viewed as a sensitive

parameter of a change in ecosystem function and, ultimately, in ecosystem stability. Table 2 does show a long-term decline in the size of the stable soil pool from a maximum of  $10 \text{ t ha}^{-1}$  to  $7 \text{ t ha}^{-1}$ . This pool plays a role in soil structure, cation exchange capacity, pH, moisture retention, and other physical and chemical soil properties. Therefore, a long-term decline in the stable soil pool could have implications related to soil genesis.

Table 3

Comparison of biomass pools and process rates at the end of three successive 80 year rotations of Douglas-fir grown on two contrasting site conditions: a previously unmanaged site (ECOSTATE I) and a degraded site (ECOSTATE II), subjected to an intermediate level of forest management<sup>a</sup>

Ecosystem characteristics (at end of each rotation)	Unmanaged site			Degraded site		
	80 years	160 years	240 years	80 years	160 years	240 years
Stand density (stems $\text{ha}^{-1}$ )	875	935	947	1080	972	1008
<i>Stand biomass (t <math>\text{ha}^{-1}</math>)</i>						
<b>Stemwood</b>	<b>563.5</b>	<b>518.4</b>	<b>490.2</b>	<b>265.4</b>	<b>348.3</b>	<b>414.7</b>
Bark	61.6	56.6	53.6	30.1	39.2	45.6
Live branch	40.3	36.2	34.5	21.6	26.2	30.2
Dead branch	5.4	7.2	7.8	7.6	8.6	8.9
Foliage	14.1	12.7	12.5	8.2	10.7	11.5
Large root	122.6	111.6	104.2	58.4	76.4	89.9
Medium root	15.3	15.2	14.9	11.5	13.3	14.3
Small root	3.6	4.4	5.1	4.8	5.5	5.8
<b>Total tree biomass</b>	<b>826.4</b>	<b>762.3</b>	<b>722.8</b>	<b>407.6</b>	<b>528.2</b>	<b>620.9</b>
Litterfall (t $\text{ha}^{-1} \text{ year}^{-1}$ )	9.7	11.1	12.1	10.6	12.1	12.5
<i>Forest nutrition (kg N <math>\text{ha}^{-1} \text{ year}^{-1}</math>)</i>						
Total demand	65.1	55.2	56.3	39.7	51.9	55.2
Total uptake	65.1	55.2	56.3	39.7	51.9	55.2
Loss to litterfall	48.9	45.4	47.5	33.0	41.8	45.8
Loss to foliar leaching	2.7	1.5	1.4	0.2	0.7	1.0
Loss to tree mortality	5.7	4.8	3.0	0.8	2.1	2.8
<i>Soil organic matter</i>						
Active pool (t $\text{ha}^{-1}$ )	98.6	91.8	88.4	41.7	67.0	76.3
Total N—active (kg $\text{ha}^{-1}$ )	403.9	442.3	461.6	306.5	418.7	456.0
N release—active (kg $\text{ha}^{-1} \text{ year}^{-1}$ )	55.4	56.7	54.2	29.1	38.8	44.6
Stable pool (t $\text{ha}^{-1}$ )	12.1	12.4	12.8	9.7	11.1	11.9
Total N—stable (kg $\text{ha}^{-1}$ )	137.6	150.5	161.9	130.9	152.0	161.7
N release—stable (kg $\text{ha}^{-1} \text{ year}^{-1}$ )	2.1	2.2	2.4	1.8	2.2	2.3

<sup>a</sup> The intermediate-level management option consisted of three 80 year rotations after which each stand was harvested using the conventional harvesting method.

### 3.3. Impacts of Management Option B (an intermediate level of management)

Table 3 summarizes some of the structural and functional characteristics of forests at the end of three successive 80 year rotations with conventional (stem-only) harvesting, starting with either the unmanaged or degraded initial site condition. Based on the change in active soil pool size and the ratio of total N-demand to total N-uptake, this management option also caused some impacts on ecosystem function. For example, the active soil pool size for the previously unmanaged site condition is reduced to a pre-harvest value of approximately  $90 \text{ t ha}^{-1}$  after the 240 year simulation period (Table 3). The pool size does increase to over  $300 \text{ t ha}^{-1}$  (pool plus harvesting residues) immediately after the final harvest. Fig. 7(a) indicates that, although the total N-uptake was nearly equal to total N-demand throughout the first rotation, nitrogen deficits occurred for brief periods during each of the next two rotations (Fig. 7(a)). These deficit periods, however, were not as severe, in terms of duration and magnitude, as those which occurred when the previously unmanaged site was exposed to the intensive management option (Fig. 5(b)). Further to this, even in the third rotation the total N-uptake rebounds after Year 40 and becomes equivalent once again to the total N-demand by Year 65 (Fig. 7(a)). This recovery is largely due to an increase in litterfall inputs causing a rise in the active pool size, and a subsequent increase in N-release from the active soil pool (Fig. 7(b)). The changes in these parameters resulted in a 13% drop in total biomass production from the first to the last rotation period (Fig. 7(c), Table 3: from  $826.4$  to  $722.8 \text{ t ha}^{-1}$ ). These production values are still comparable with the production at Year 80 of the unmanaged forest ( $827.8 \text{ t ha}^{-1}$ ).

The degraded site appears to respond positively to this intermediate level of management, with a steady increment in active soil pool size over the three rotations (Table 3). The prolonged deficit between N-demand and N-uptake apparent during the first rotation, although not eliminated, is reduced by the third rotation (Fig. 8(a)). This increase in N-availability is a direct result of leaving the branches and foliage on site at the time of harvest. It has been reported that after clearcutting, slash in Douglas-fir

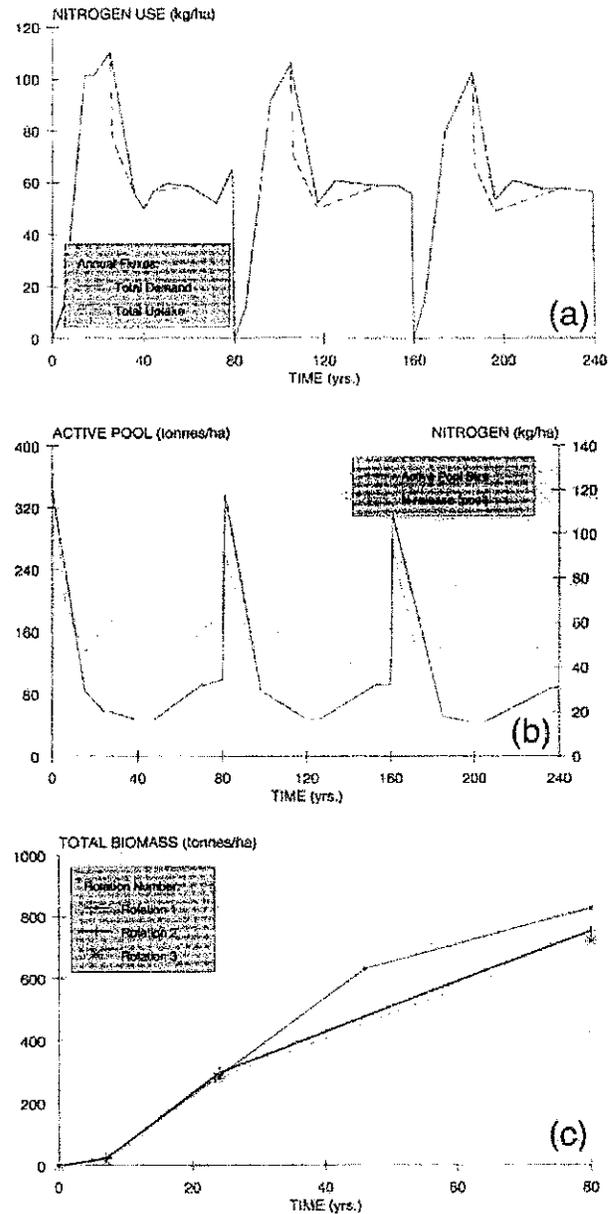
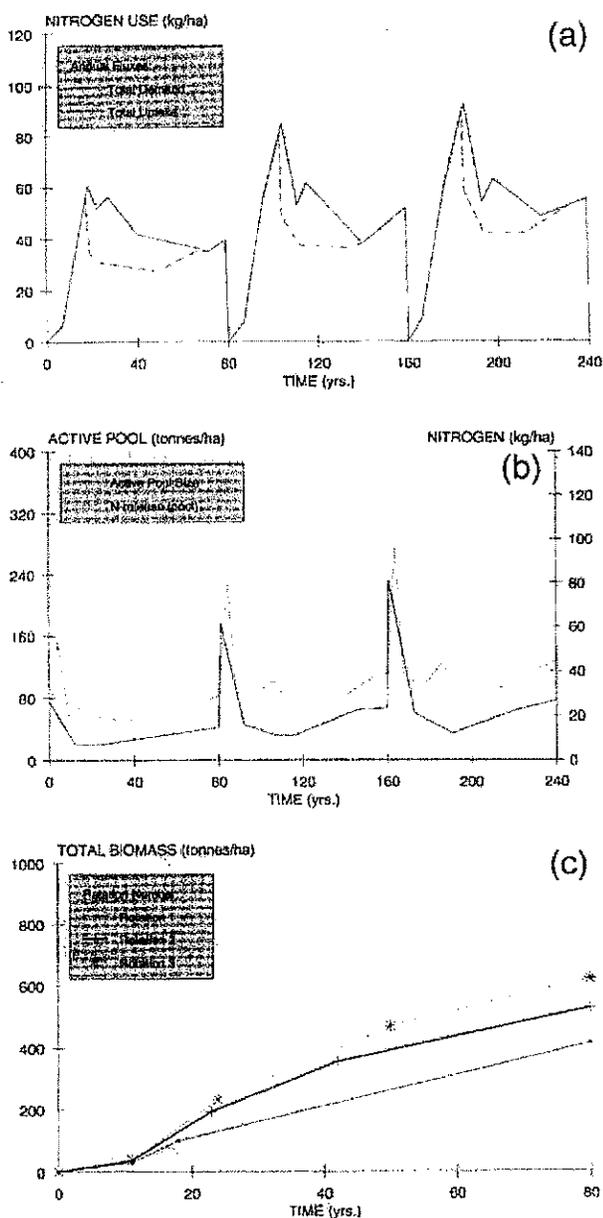


Fig. 7. (a) Comparison of total biomass production for three successive rotations of Douglas-fir grown on a previously unmanaged (ECOSTATE I) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting). (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) for a previously unmanaged (ECOSTATE I) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting). Note: in this case, a period of nutritional stress is identified where N-demand was greater than N-uptake. (c) Depiction of changes in the active soil pool size and N-release for a previously unmanaged (ECOSTATE I) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting).

forests can weigh up to  $516 \text{ t ha}^{-1}$  (Dell and Ward, 1971). In our simulation, the active soil pool (including harvesting residues) increased immediately after the second harvest to over  $230 \text{ t ha}^{-1}$  (Fig. 8(b)), and by the end of the third rotation, the values for a majority of the structural and functional characteristics of the forest on the degraded site were beginning to resemble those of the forest on the previously unmanaged site at the same time interval (Table 3).



This aggradation of site parameters resulted in an increase in biomass accumulation from the first to last rotation (Fig. 8(c)). We expect that a new equilibrium point would be reached and maintained somewhere between the values currently depicted for the two site conditions if the intermediate-level of management (e.g. 80 year rotations, stem-only harvest) were continued in perpetuity on both sites. Based on the model simulations, this equilibrium point should generate a total biomass production value nearly double that generated for the intensive management option, when using Year 40 as a reference age (i.e. between  $400$  and  $375 \text{ t ha}^{-1}$ , as shown in Fig. 7(c) and Fig. 8(c), vs. between  $240$  and  $227 \text{ t ha}^{-1}$ , as shown in Table 2).

#### 3.4. The influence of initial site condition on evaluating sustainability

There is an ever-increasing need to clearly demonstrate to the international community that marketed forest products have been produced under a sustainable forest management regime. This requires answers to the questions: How can sustainability be determined? What criteria should be used in its evaluation? It has been suggested that sustainability should be judged by comparing the attributes of a managed forest with those of the pre-management condition. If one applies this approach to the simulations presented in this paper, one finds that sustainability is defined as much or more by the choice of starting conditions as by the choice of management method. For example, when the intensive management option was applied to the previously unmanaged site (ECOSTATE I), biomass accumulation fell

Fig. 8. (a) Comparison of total biomass production for three successive rotations of Douglas-fir grown on a degraded (ECOSTATE II) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting). (b) Depiction of nitrogen availability (illustrated by comparing N-demand with N-uptake) for a degraded (ECOSTATE II) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting). Note: in this case, a period of nutritional stress is identified where N-demand was greater than N-uptake. (c) Depiction of changes in the active soil pool size and N-release for a degraded (ECOSTATE II) site, subjected to an intermediate level of forest management (three 80 year rotations, stem-only harvesting).

from nearly  $560 \text{ t ha}^{-1}$  to approximately  $240 \text{ t ha}^{-1}$  (Fig. 5(a)). Clearly, this management regime would not be considered sustainable. However, when the same management option was applied to the degraded site (ECOSTATE II), biomass accumulation was sustained at a constant level throughout the simulation period (Fig. 6(a)). In contrast, when the intermediate-level management option was applied to the two starting states, biomass accumulation fell marginally on the previously unmanaged site (Table 3,  $-13\%$ ); whereas many of the site attributes, including biomass accumulation, of the degraded site began to increase (Fig. 8c, Table 3).

We rarely have sufficient information to characterize the starting state condition of mature, unmanaged forests when they are put under management. The starting state of a previously unmanaged site which has been subjected to repeated, high-intensity fires may more closely resemble the conditions (e.g. organic matter and nutrient reserves) generated in our degraded site. This same site with a history of insect outbreaks or windthrow would be expected to have large inventories of soil organic matter and available nutrients. Owing to the complex interactions of site, topography, climate and biota, together with variable histories of past disturbances, it is nearly impossible to determine starting state conditions accurately without a thorough, pre-management site description and dendrochronology. Currently, in most, if not all, jurisdictions in Canada, as well as elsewhere, the human resources, expertise, and financial resources are not available to conduct this type or intensity of pre-cut inspection. In many cases, a modelling exercise, such as was conducted to establish the ECOSTATE files in this study, may represent one of the best ways of establishing the starting 'benchmark' ecosystem conditions against which indications of sustainability will be assessed.

We believe that the important influence of initial ecosystem conditions on the effect of harvesting practices on ecosystem sustainability may be one of the reasons why the literature is so inconclusive regarding the issue of harvesting impacts. Unless one knows the starting conditions, one cannot predict whether a particular practice will degrade, enhance, or cause no change in ecosystem productivity. This poses a serious problem for the process of 'green' certification of sustainable forest management.

#### 4. Conclusions

Total biomass production in the first rotation of management in a previously unmanaged forest provided little indication that the prescribed management options may not be sustainable. On the other hand, there was a marked decline in the active soil pool size over this first rotation. This change in active pool size appears to represent a more sensitive parameter with which to assess the sustainability of forest management alternatives than the traditional bioassay of height and volume growth.

Based on the change (or lack of change) in active pool size, as well as the ratio of total N-demand to total N-uptake, the model simulations indicated that forest harvesting can be conducted on a sustainable basis with respect to stemwood production. However, the evaluation of this sustainability is highly dependent on the starting state forest condition.

The modelling exercise indicated that the nutritionally degraded site responded positively to an intermediate level of forest management, demonstrating that past activities do not appear to have a permanent negative impact on future ecosystem function: ecosystems are resilient and will recover if the appropriate processes are allowed to operate.

It needs to be recognized that a computer model of an ecosystem is just an abstract representation of that system, and simply serves as a framework for us to formulate and pose questions. The model responses presented here should be viewed with caution and used principally to direct the development of future research projects to address critical questions. Ecosystem models are not capable of providing quantitative long-term predictions of forest productivity. However, if well designed and calibrated, they should be capable of providing believable (and explainable) temporal patterns and trends, and capable of correctly ranking the outcomes, for various ecosystem-level variables, of the alternative management choices we are making.

#### References

- Aber, J.D., Botkin, D.B. and Melillo, J.M., 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. *Can. J. For. Res.*, 8: 306–315.

- Alban, D.H., Perala, D.A. and Schlaegel, B.E., 1978. Biomass and nutrient distribution in aspen, pine, and spruce stands on the same soil type in Minnesota. *Can. J. For. Res.*, 8: 290–299.
- Barclay, H.J. and Hall, T.H., 1986. SHAWN: a model of Douglas-fir ecosystem response to nitrogen fertilization and thinning, a preliminary approach. *Can. For. Serv., Pac. For. Cent., Victoria, B.C., Inf. Rep. BC-X-280*.
- Binkley, D. and Hart, S.C., 1989. The components of nitrogen availability in forest soils. *Adv. Soil Sci.*, 10: 57–112.
- Bossel, H. and Schäfer, H., 1989. Eco-physiological dynamic simulation model of tree growth, carbon and nitrogen dynamics. In: L.C. Wensel and G.S. Biging (Editors), *Forest Simulation Systems. Proc. IUFRO Conf., Berkeley, CA, 2–5 November 1988. Univ. California, Div. Agric. Berkeley, Nat. Resour. Bull. 1927*, pp. 23–30.
- Boyle, J.R., 1976. A system for evaluating potential impacts of whole tree harvesting on site quality. *Tappi*, 59: 79–81.
- Cole, D.W. and Gessel, S.P., 1963. Movement of elements through a forest soil as influenced by tree removal and fertilizer additions. In: C.T. Youngberg (Editor), *Forest Soil Relationships in North America. Oregon State Univ. Press, Corvallis*, pp. 95–104.
- Covington, W.W., 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. *Ecology*, 62: 41–48.
- Dell, J.D. and Ward, F.R., 1971. Logging residues on Douglas-fir region clearcuts—weights and volumes. *US For. Serv. Res. Pap. PNW-115*.
- Dixon, R.K., Meldahl, R.S., Ruark, G.A. and Warren, W.G., 1990. *Process Modelling of Forest Growth Responses to Environmental Stress. Timber Press, Portland, OR*.
- Dyck, W.J., Cole, D.W. and Comerford, W.B., 1994. *Impacts of Forest Harvesting on Long-term Site Productivity. Chapman and Hall, London*.
- Freedman, B., 1981. Intensive forest harvest: a review of nutrient budget considerations. *Can. For. Serv., Maritimes For. Res. Cent., Fredericton, N.B., Inf. Rep. M-X-121*.
- Gordon, A.G., 1983. Nutrient cycling dynamics in differing spruce and mixedwood ecosystems in Ontario and the effects of nutrient removals through harvesting. In: R.W. Wein, R.R. Riewe and I.R. Methven (Editors), *Proceedings of Resources and Dynamics of the Boreal Zone, 23–26 August 1982, Thunder Bay, Ont. Assoc. Can. Univ. for North. Studies, Ottawa, Ont.*, pp. 97–118.
- Hermann, R.K., 1985. The genus *Pseudostuga*: ancestral history and past distribution. *Oreg. State Univ. For. Res. Lab. Spec. Publ. 2b*.
- Jenkinson, D.S., 1977. Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from <sup>14</sup>C-labelled ryegrass decomposing under field conditions. *J. Soil. Sci.*, 28: 424–434.
- Kimmins, J.P., 1974. Sustained yield, timber mining, and the concept of ecological rotation: a British Columbian view. *For. Chron.*, 50: 27–31.
- Kimmins, J.P., 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. *For. Ecol. Manage.*, 1: 169–183.
- Kimmins, J.P., 1987. *Forest Ecology. McMillan, New York*.
- Kimmins, J.P., 1988. Community organization: methods of study and prediction of the productivity and yield of forest ecosystems. *Can. J. Bot.*, 66: 2654–2672.
- Kimmins, J.P., 1990. Modelling the sustainability of forest production and yield for a changing and uncertain future. *For. Chron.*, 66: 271–280.
- Kimmins, J.P., 1993. Scientific foundations for the simulation of ecosystem function and management in FORCYTE-11. *For. Can., Northwest Reg., North. For. Cent., Edmonton, Alta., Inf. Rep. NOR-X-328*.
- Kimmins, J.P., Scoullar, K.A. and Apps, M.J., 1990. FORCYTE-11 user's manual for the benchmark version. *For. Can., Northwest Reg., North. For. Cent., Edmonton, Alta.*
- Mahendrapa, M.K., Maliondo, S.M. and van Raalte, G.D., 1987. Potential acidification of sites due to intensive harvesting in New Brunswick. In: Z. Stiasny (Editor), *Sixth Canadian Bioenergy R and D Seminar. Elsevier Applied Science, Barking, UK*, pp. 100–114.
- Maliondo, S.M., 1988. Possible effects of intensive harvesting on continuous productivity of forest lands. *For. Can., Fredericton, N.B., Inf. Rep. M-X-171*.
- Martin, W.L., 1985. Post-clearcutting forest floor nitrogen dynamics and regeneration response in Coastal Western Hemlock wet subzone. Ph.D. thesis, University of British Columbia, 350 pp.
- McGill, W.B., Hunt, H.W., Woodmansee, R.G. and Reus, J.O., 1981. Phoenix, a model of the dynamics of carbon and nitrogen in grassland soils. *Ecol. Bull. (Stockholm)*, 33: 49–115.
- Parton, W.J., Schimel, D.S., Cole, C.V. and Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.*, 51: 1173–1179.
- Pastor, J. and Post, W.M., 1985. Development of a linked forest productivity soil process model. *Oak Ridge Nat. Lab. Rep. ORNL/TM-9519, Environ. Sci. Div. Publ. 2455*.
- Paul, E.A., Campbell, C.A., Rennie, D.A., and McCallum, K.J., 1964. Investigations of the dynamics of soil humus utilizing carbon dating techniques. In: 8th Int. Congr. of Soil Sci., Bucharest, Romania, Vol. III. Publishing those of the Academy of the Socialist Republic of Romania, Romania.
- Paustian, K., Parton, W.J. and Persson, J., 1992. Modeling soil organic matter in organic-amended and nitrogen-fertilized long-term plots. *Soil Sci. Soc. Am. J.*, 56: 476–488.
- Running, S.W., 1984. Documentation and preliminary validation of H2OTRANS and DAYTRANS, two models for predicting transpiration and water stress in western coniferous forests. *US For. Serv. Res. Pap. RM-252*.
- Sachs, D. and Trofymow, J.A., 1991. Testing the performance of FORCYTE-11 against results from the Shownigan Lake thinning and fertilization trials on Douglas-fir. *For. Can. Pacific and Yukon Reg., Info. Rep. BC-X-324*.
- Sollins, P., Brown, A.T. and Swartzman, G.L., 1979. CONIFER: a model of carbon and water flow through a conifer forest. Revised Documentation. *Coniferous Forest Biome Bull. 15. US/IBP. University of Washington, Seattle*.
- Timmer, V.R., Savinsky, H.M. and Marek, G.T., 1983. Impact of

- intensive harvesting on nutrient budgets of boreal forest stands. In: R.W. Wein, R.R. Riewe and I.R. Methven (Editors), *Proc. of Resources and Dynamics of the Boreal Zone*, 23–26 August 1982, Thunder Bay, Ont. Assoc. Can. Univ. for North. Studies, Ottawa, Ont., pp. 131–147.
- Van Veen, J.A. and Paul, E.A., 1981. Organic C dynamics in grassland soils. I. Background information and computer simulation. *Can. J. Soil Sci.*, 61: 185–201.
- Voroney, R.P., Paul, E.A. and Anderson, D.W., 1989. Decomposition of wheat straw and stabilization of microbial products. *Can. J. Soil Sci.*, 69: 63–77.
- Wells, C.G. and Jorgensen, J.R., 1979. Effect of intensive harvesting on nutrient supply and sustained productivity. In: A.L. Leaf (Editor), *Impact of Intensive Harvesting on Forest Nutrient Cycling: Symp. Proc.*, Syracuse, NY, 13–16 August 1979. State University of New York, College of Environmental Science and Forestry, Syracuse, NY, pp. 212–230.
- White, E.H. and Harvey, A.E., 1979. Modification of intensive management practices to protect forest nutrient cycles. In: A.L. Leaf (Editor), *Impact of Intensive Harvesting on Forest Nutrient Cycling: Symp. Proc.*, Syracuse, NY, 13–16 August 1979. State University of New York, College of Environmental Science and Forestry, Syracuse, NY, pp. 264–278.
- Youngberg, C.T., 1966. Forest floors in Douglas-fir forests: dry weight and chemical properties. *Soil Sci. Soc. Am. Proc.*, 30: 406–409.
- Zobel, D.B., McKee, W.A., Hawk, G.M. and Dyrness, C.T., 1976. Relationship of environment to composition, structure, and diversity of forest communities of the central western Cascades of Oregon. *Ecol. Monogr.*, 46: 135–156.