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Disturbances and the sustainability of long-term site productivity in lodgepole pine forests in the central interior of British Columbia—an ecosystem modeling approach

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Abstract

The ecosystem-management model FORECAST was used to compare some ecological impacts of natural disturbance (wildfire) and timber harvesting. The scientific objective of the study was to assess whether or not two types of timber harvesting at various rotation lengths would have biogeochemical and biomass implications that are within the natural range of variation caused by wildfire. The practical objective was to identify management strategies that would sustain or improve long-term site productivity in lodgepole pine forests in the central interior of British Columbia. We defined three fire severity categories (low, medium and high), three fire return intervals (40, 80 and 120 years), two utilization levels (including stem-only harvesting [SOH] and whole-tree harvesting [WTH]), and three timber production rotation lengths (40, 80 and 120 years). Differences in simulated productivity, decomposing litter mass, total available soil nitrogen and nitrogen removals were compared for all 15 combinations of the five levels of disturbance at the three frequencies. The simulated nutritional impacts of timber harvesting were within the simulated range of impacts caused by the wildfire defined in this study. They were similar to the simulated long-interval, low-severity wildfire regimes. Simulations suggest that ecological rotation lengths for long-term site productivity for lodgepole pine forests in the study area would be 80–120 years. These rotation lengths are close to the average wildfire return intervals (100–125 years) in the study area, supporting the idea that the present harvesting strategies should sustain tree growth at this frequency of harvest and severity of harvesting impacts. Both WTH and SOH are acceptable harvesting methods for the maintenance of long-term site productivity in these lodgepole pine forests if harvest intervals are 80 years or longer. However, SOH is a more nutrient conservative harvest method, and should be used instead of WTH for rotations less than 80 years. The importance of initial site quality in assessing sustainable long-term site productivity by modeling is demonstrated.

Keywords: Natural disturbance; Timber harvesting; Long-term site productivity; Ecosystem modeling; Ecological rotation

1. Introduction

The impact of timber harvesting on long-term site productivity has been the subject of debate in many of the world forests (Nambiar et al., 1990; Nambiar and Sands, 1993; Johnson, 1994). The significant yield decline of Chinese fir (*Cunninghamia lanceolata*

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[Lamb] Hook) in Southern China (Yu, 1988; Sheng and Xue, 1992) and of radiata pine (*Pinus radiata* D. Don) in Southeastern Australia (Keeves, 1966; Squire, 1983) and New Zealand (Whyte, 1973) after several forest-harvest rotations exemplifies this concern, and the issue has gained renewed attention as interest has grown in forest certification, biodiversity and sustainability. In contrast, many forests have not shown rotation-to-rotation yield decline as a consequence of harvesting (Johnson, 1994; Evans, 1999). Empirical evaluations of this issue require evidence from at least half a rotation, and may require several rotations. This suggests the need to use ecosystem-management models for the development of harvesting policy (Dyck and Cole, 1994).

A key issue in the discussion of sustainability is the comparability in ecological impacts between timber harvesting and natural disturbance (e.g. wildfire, insects and disease). Much of the focus in this discussion has been on the characteristics that clear-cutting and natural disturbance have in common (Hammond, 1991; Keenan and Kimmins, 1993). However, the debate has frequently been frustrated by the lack of an adequate description of the range of ecological effects of both natural disturbance and forest harvesting. A variety of recent initiatives in forest policy in both the United States and Canada have emphasized natural disturbance processes and their structural consequences as models of forest management (Lertzman et al., 1997). However, implementing this approach is often limited by our incomplete understanding of natural disturbance regimes (Lertzman and Fall, 1998). Quantitative analyses of the ecological impacts of natural and human-caused disturbances are needed to evaluate their implications for long-term site productivity, but this again requires studies over spatial and time scales that are so large that progress on policy revision is slow without the assistance of ecosystem modeling.

Both timber harvesting and wildfire disturbances can vary substantially in size, intensity, severity, frequency and internal heterogeneity, greatly complicating comparisons of the effects of different disturbance types. The differences relate to differences in forest type, topography, timing of the disturbance, local management methods, and management objectives (Lertzman and Fall, 1998; Parminter, 1998). From a nutrient perspective, a major difference between timber harvesting and wildfire disturbance is the biomass of woody debris left in the ecosystem, and the quantity of nutrients removed. This is equally true for clear-cutting, shelterwood, and uneven-age partial-harvest systems. Another difference is related to the succession pathways and rate of recovery of the ecosystem nutrient inventory following disturbance. These differences and their long-term implications for ecosystem sustainability must be quantified in order to identify appropriate management strategies by which to sustain long-term site productivity of particular ecosystem types, and to achieve particular non-timber management objectives.

In lodgepole pine forests of the central interior of British Columbia, concerns have been expressed over potential impacts of intensive timber harvesting on long-term site productivity (Steen, Forest Ecologist, Ministry of Forests, Cariboo Forest Region, British Columbia, personal communication; Kimmins, 1993; Wei et al., 1997). Two harvesting methods, whole-tree harvesting (WTH) and stem-only harvesting (SOH), have been used in the study area. Differences between WTH and SOH include the amount of woody debris left after logging, and in the removal of nutrients in crown materials, and this may result in considerably more nutrient depletion with WTH than that caused by SOH. Wei et al. (1997) conducted a field investigation to quantify the difference in the mass and nutrients of woody debris remaining following harvesting (WTH and SOH) and wildfire disturbances in lodgepole pine forest in this area. This paper reports on the long-term implications of those differences for site productivity and sustainable management strategies.

There are four main approaches that could be used to evaluate the consequences of timber harvesting on site productivity over multi-rotation time scales: long-term field trials or experiments, chronosequence studies, retrospective studies, and ecosystem simulation. The strengths and weaknesses of these approaches have been reviewed by Dyck and Cole (1994). Most field studies of the effects of disturbance have been limited to time scales of a few years or decades (Dewar and McMurtrie, 1996), and several studies have reported a significant difference between short-term and long-term results (e.g. Lundmark, 1977; Dyck and Skinner, 1990). In the absence of multi-rotation experience or field trials, chronosequence studies can be helpful, but there are frequently difficulties in locating valid chronosequence study sites (Dyck and Cole, 1990), and chronosequences rarely address multiple rotation effects. Retrospective studies often suffer from incomplete knowledge of pre-disturbance conditions and inadequate descriptions of the disturbance. Of the four methods, ecosystem simulation may be the most feasible way of comparing the impact of management or natural disturbance scenarios over long time scales and large spatial scales (Korzukhin et al., 1996). While ecosystem modeling is, like the other methods, subject to a variety of shortcomings, including the difficulty of validating the predictions (Dyck and Cole, 1994); this is true of all but the long-term field trial method), it may be one of the most feasible ways of undertaking such comparisons.

The ecosystem model FORECAST, or its forerunner FORCYTE, has been used as a management evaluation tool in several types of forest ecosystems (Sachs and Sollins, 1986; Kellomäki and Seppälä, 1987; Wang et al., 1995; Wei and Kimmins, 1995; Morris et al., 1997; Wei et al., 2000; Seely et al., 2002; Welham et al., 2002). The model was specifically designed to examine the impacts of different management strategies or natural disturbance regimes on long-term site productivity. A brief description of the FORECAST model approach will be presented in the next section; details are found in (Kimmins, 1993; Seely et al., 1999; Kimmins et al., 1999).

The objectives of this study were to: (1) evaluate some differences in nitrogen budgets between clearcutting and wildfire disturbance and the implications of the differences for long-term site productivity of lodgepole pine forests in the central interior of British Columbia; (2) quantify differences in ecosystem sustainability with either SOH or WTH; and (3) identify management strategies that should maintain the potential long-term site productivity of these forests. The hypothesis underlying the study is that because stand-level ecosystem sustainability is defined by combinations of: (1) severity and scale of disturbance; (2) frequency of disturbance; and (3) ecosystem resilience, there will be several different combinations of disturbance severity and frequency that will result in non-declining patterns of ecosystem change.

2. Study area and methods

2.1. Study area

Lodgepole pine (*Pinus contorta* ssp. *latifolia* Engelm. ex S. Wats.) plays an important role in the forest industry and environment in British Columbia. It is abundant in the montane spruce (MS), sub-boreal pine spruce (SBPS) and sub-boreal spruce (SBS) biogeoclimatic zones in central British Columbia (Pojar, 1985) where it dominates forests that have been subject to high frequencies of wildfire in the past. This study was conducted in the SBPS zone west of Williams Lake in the central interior of British Columbia. The area is a gently rolling plateau of 1100–1500 m in elevation in the rain shadow of the Coast Mountains. It is subject to cold air drainage and pooling from the ice and snow fields in these mountains, and to cold, dry continental air from the Canadian boreal region during the winter; the summer is warm and relatively dry. Most of the zone is under snow for 4–5 months, from November to March. In summers, frequent thunderstorms create the potential for wildfire when fuels are dry. The mean annual temperature is less than 2 °C and annual precipitation is 400–700 mm. Soils are well-drained Brunisols and Luvisols of sandy or sandy loam texture. Soil parent material is primarily glaciofluvial or morainal.

Wildfire is one of the most important factors involved in the establishment and development of lodgepole pine forests in Northern America (Lotan et al., 1985). Fires, stand development, mortality influences, and fuel accumulation interact in a complex manner (Gara et al., 1985), especially because fires vary greatly in frequency, intensity, size, and other characteristics. A particular fire regime greatly affects forest succession, longevity of the species, stocking, and species composition; and fire also influences the incidence of insects and diseases. Fires in lodgepole pine forests can be low intensity, creeping, surface fires, but high intensity crown fires during severe weather burn vast areas (Lotan et al., 1985).

Lodgepole pine forms a self-replacing “climax” community over large areas in the central interior of British Columbia, where frequent, large-scale disturbance is a characteristic feature. Stand-replacing wildfire has historically been the major allogenic disturbance in the study area, with a fire return interval of approximately 100–125 years (Pojar, 1985; Parminter, Ministry of Forests, Victoria, BC, personal communication). Biogenic disturbance agents such as insects and disease are also common. The mountain pine beetle periodically kills lodgepole pine forests over large areas, and is often a prelude to fire. Dwarf mistletoe reduces the vigor of lodgepole pine, but has historically been kept in check by wildfire (Gara et al., 1985).

2.2. Brief description of the FORECAST model

Four approaches have been used in the prediction of future timber production and yield: historical bioassay, environmental correlation, process simulation models and hybrid simulation models. The advantages and disadvantage of each approach have been reviewed by Kimmins (1988) and Kimmins et al. (1999).

The historical bioassay involves the use of empirical growth data to develop yield tables and predictive growth equations. This is a valid method under the biotic and abiotic growth conditions that prevailed in the past, but it is unable to predict growth accurately under significantly different future conditions; it is inflexible. A key advantage of process-based models and the environmental correlation method is their flexibility in the face of anticipated future changes in ecosystem conditions (Korzukhin et al., 1996). However, these two approaches have generally failed to include sufficient complexity to account for all the major factors that determine growth. Where they have incorporated adequate complexity, they have generally been too complex for practical application in forestry. The hybrid simulation approach (combination of the historical bioassay with some process simulation) can give it sufficient flexibility to produce credible yield predictions under a variety of altered growth conditions, while calibration and application are simple enough for this type of model to be of value for forest managers.

The ecosystem-management simulation model FORECAST uses the hybrid simulation approach. Fig. 1 presents a flow chart of the major compartments and transfers. A detailed description of the model can be found in Kimmins et al. (1999). The model employs empirical data, from sites of different nutritional quality, which describe tree and plant biomass accumulation over time and plant tissue nutrient concentrations. These data form the basis from which the rates of key processes are estimated, such as canopy function (photosynthesis), carbon allocation responses to changing resource availability (nutrients), competition-related mortality (largely competition for light), and rates of nutrient cycling. FORECAST, which accounts explicitly for changes in nutritional site quality over time caused by various simulated autogenic successional processes and types (allogenic and biogenic) of disturbance, was designed for the evaluation of forest-management strategies in forests where potential net primary production is limited by nutrient availability, and in which nutrient availability is altered by management or natural disturbance events.

The driving function of the FORECAST model is foliage nitrogen efficiency (FNE): kilograms of total new plant biomass produced per kilogram of foliage nitrogen. This is similar to the nitrogen productivity concept of Ingestad et al. (1981) and Ågren (1983) (kilograms of production per kilogram of foliage nitrogen), but differs in that in FORECAST foliage efficiency is corrected for shading. Foliage nitrogen is assumed to be a good index of the magnitude of the photosynthetic apparatus (Brix, 1983; Ågren, 1983), and the correction for shading accounts for the reduction in photosynthetic activity as a function of declining light intensity. FNE is obtained by dividing simulated net primary production (NPP) by simulated foliage nitrogen content. NPP is estimated from a combination of input and simulated data: e.g. for trees, NPP = net biomass accumulation [input data] + above-ground mass of litterfall [simulated] + mass of fine root turnover [simulated] + mass lost from individual tree mortality [simulated]. Foliage nitrogen content is calculated from data on foliage biomass (simulated) and foliage nitrogen concentration (empirical input data). Shade correction is achieved by simulating shading profiles and by using photosynthetic light saturation curves. Simulation of litterfall, root mortality and individual plant mortality is based on a combination of input data and simulated variables.

The product of simulated foliage nitrogen levels, the internally estimated shade-corrected FNE values, and the simulated light (PAR) availability for any particular time step gives the potential growth for that species in that time step. Attainment of this potential depends on the simulated availability of the nutrient(s) being represented in the model, and which are required for the production of the new biomass.

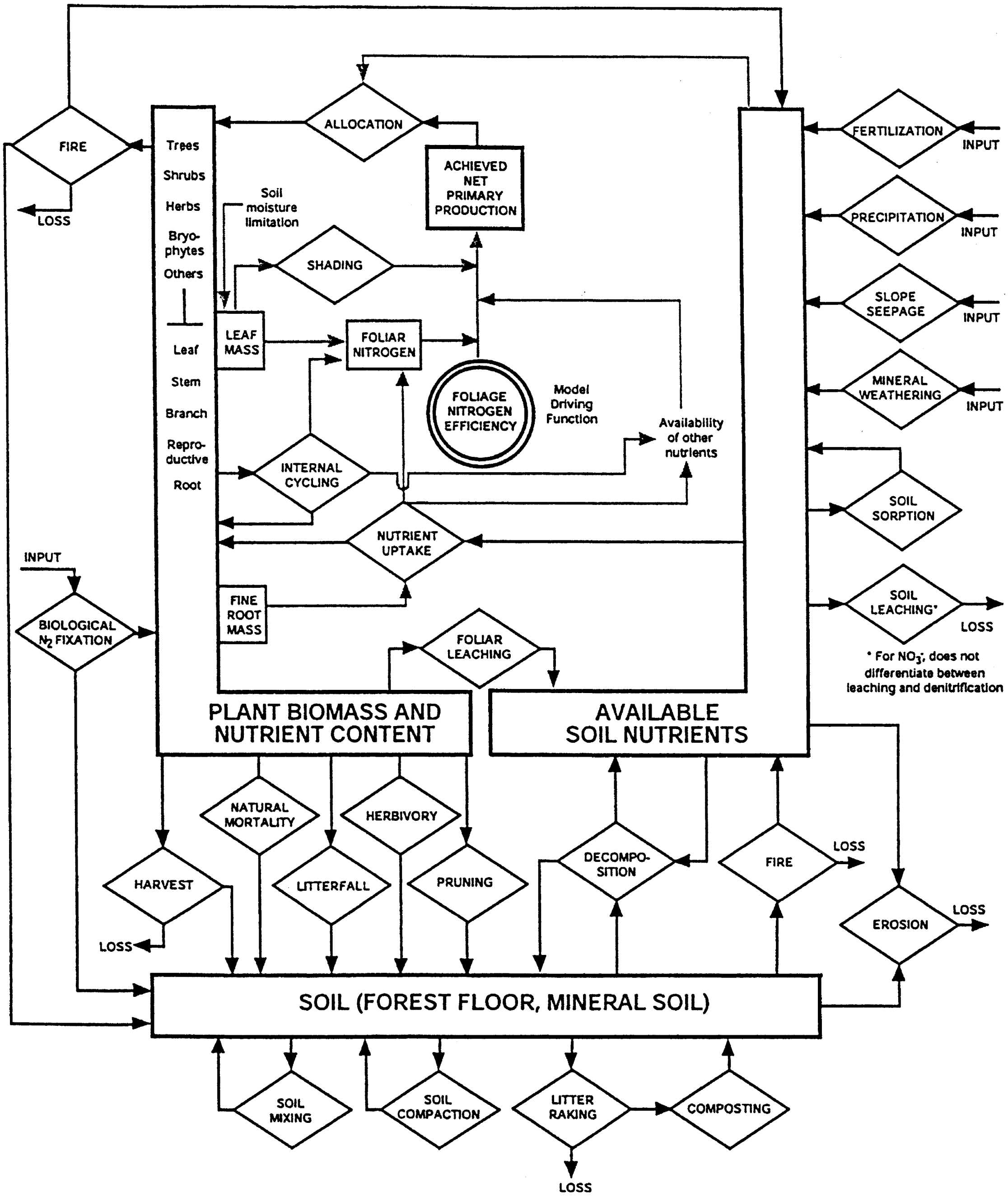


Fig. 1. Major components and transfer pathways represented in FORECAST.

Achieved growth is limited by the extent to which the simulated combination of internal cycling, symbiotic and/or asymbiotic fixation of nitrogen, uptake of nutrients from precipitation or throughfall, and uptake of nutrients from the soil satisfies the nutrient demand created by this potential growth. For users who do not wish to use the nutrient-limitation aspect of FORECAST, nutrient regulation of growth can be switched off, reducing the model to a light-driven, light-competition model. Users can also choose not to include nitrogen fixation (N-fixation), internal cycling and foliage leaching aspects of nutrient cycling if they lack suitable calibration data, or they believe that these processes are not significant for the ecosystems and species they are simulating. However, for some species in some ecosystems, the omission of these processes can be expected to result in significant prediction errors. The ability to add or remove simulations of different processes is a feature of FORECAST, which can be configured from a simple, single species, tree-population, light-competition model up to a multi-species, multi-life form, multi-age, multi-nutrient ecosystem-management model.

The FORECAST model is a mechanistic representation of ecosystem processes. It is a multi-component model in which the rates of transfer processes or state changes are controlled by a set of simulation rules that are derived directly from input data using a smoothing-interpolation routine, or are derived internally in the model by inference from a combination of our understanding of various processes, and field measurements of the products of these processes.

FORECAST requires calibration data that describe the following factors for each of the species in the simulation. This dataset is needed for each of at least two (preferably three) sites that vary in nutritional quality, and span the range of nutritional conditions that are expected to result from the simulated natural disturbances and/or stand management:

1. Trends over time in well-stocked monoculture stands for: biomass accumulation in different biomass components; tree height and stand density (in naturally thinned stands); stem size frequencies; litter decomposition (loss of mass and change in nutrient concentration over time).
2. Data that define: shade as a function of foliage biomass; foliage light adaptations (photosynthetic light saturation curves); tissue nutrient concentrations (if nutritional limitation of growth and nutritional site quality are to be simulated) and various aspects of nutrient cycling (e.g. N-fixation, foliage leaching); litterfall and age of tissue senescence; non-growing season photosynthesis by evergreens and shade effects on height growth.

As noted above, the degree of detail required in this calibration set will depend on the user's simulation objectives, the type of ecosystem and species being simulated, and the availability of calibration data. These and certain other largely optional data are used in a "setup" program to establish various indices of canopy function, resource allocation, nutrient uptake, demand and internal cycling, shade-related tree and branch mortality, and tree size frequencies. They also provide a set of simulation rules that guide to how tree growth and various ecological processes vary as soil nutrient availability changes. The output from these setup programs constitutes the set of simulation rules used in the ecosystem simulation and management/natural disturbance scenario simulation program. Kimmins et al. (1990, 1999) and Kimmins (1993) described the data requirements of the model in more detail.

Datasets prepared by Sachs (1992) were used as a primary source for this study. Most of the data were from published studies from sites with a similar climate (temperature and precipitation) to that of the study area. Data on decomposition of woody debris and associated asymbiotic N-fixation rates for both harvested and wildfire-killed sites were supplemented by data from Wei et al. (1997) and Wei and Kimmins (1998).

2.3. Creation of initial ECOSTATE files

Once the "setup" programs have been calibrated, and the quality of the input data and the ability of the derived simulation rules to reproduce the historical input data trends have been evaluated by means of the setup output graphs, the various indices and growth descriptions (i.e. the "simulation rules") derived from these "setup" programs are used in the ecosystem-management simulation program ECOSYSTM. Before conducting any simulation, however, it is necessary to define the "initial state" of the simulated ecosystems. This initial state, which is described in the ECOSTATE file, describes the initial values for all the state variables (compartments) in the model. This establishes the "biological legacies" that remain from the previous stand or non-forest land use. These legacies are an important source of nutrients for new tree and minor vegetation growth. The ECOSTATE file also defines populations of herbs, shrubs, bryophytes and tree seedling/sapling banks that are deemed to be present at the start of the simulations.

The ECOSTATE file initializes values for all of the types and ages of decomposing organic matter in the forest floor and levels of soil humus at the start of the run. Instead of attempting to define this ecosystem starting condition through the measurement of hundreds of state variables for a given site, an initial ecosystem state is established by running the ECOSYSTEM model without nutrient feedback. This forces the vegetation to grow as it has historically and to allow the ecosystem to accumulate soil organic matter, forest floor litter, snags and coarse woody debris as expected under a defined historical scenario, together with their reserves of nutrients. Experience with FORECAST to date indicates that the model's predictions are very sensitive to the initial ecosystem state as defined by ECOSTATE (Morris et al., 1997; Wei et al., 2000). Careful preparation of an appropriate ECOSTATE file can be just as important a modeling activity as getting highly accurate calibration data, especially if the user only simulates a single rotation, the performance of which is strongly influenced by the levels of biological legacy.

We created the initial ECOSTATE file for medium site quality, based on the following history of disturbance regimes: three successive 80-year periods of lodgepole pine stand growth were simulated in the no-nutrient feedback mode. At the end of each 80-year period, lodgepole pine was killed by wildfire, and left on the site to simulate natural wildfire disturbance without salvage harvesting. The percentages of biomass components consumed by the fire and converted to ash were 10% for stemwood, and 40% for stembark, branch and foliage. This simulation was then repeated with nutrient feedback (i.e. a representation of nutrient cycling, nutritional-regulation of growth, and nutritional site-quality dynamics) switched on. At the end of each 80-year period, SOH was applied, removing 90% of stemwood and stembark. This created an initial ECOSTATE file with a total mass of decomposing litter of 89.3 Mg/ha and a soil humus level of 33.0 Mg/ha. The site-quality index for medium quality sites is 15.8 (average dominant tree height in meters at 50 years). The simulation of fire does not include the difference in decomposition between charred and un-charred logs. Two additional ECOSTATE files reflecting various levels of organic matter or "legacy" were also generated for comparisons or sensitivity testing.

2.4. Defining the disturbance scenarios and sustainability indicators

Characteristics of disturbance can be best described by the frequency (return intervals for wildfire and rotation lengths for harvesting) and intensity (severity for wildfire and utilization levels for harvesting) of disturbance. Based on input from local ecologists and soil scientists, we defined three severity categories (low, medium and high) and three fire return intervals (40, 80 and 120 years) for wildfire simulations, and two utilization levels (SOH and WTH) and three rotation lengths (40, 80 and 120 years) for harvesting simulations. A description of those severity and utilization categories is given in Table 1. Each scenario was then simulated commencing with the initial ECOSTATE file described above. The unrealistically short 40-year rotation length was included in the study in order to compare harvesting at this frequency with fire, and because it helps to define a response curve (Powers et al., 1994).

Four output parameters (production, mass of decomposing litter, total available soil nitrogen and nitrogen removal) were used in the assessment of the sustainability of site productivity. Total production is a direct indicator of achieved productivity, while decomposing litter, total available soil nitrogen and nitrogen removal are indirect or potential indicators of site productivity potential. Woody debris, as part of decomposing litter, is also a source of asymbiotic N-fixation (Wei and Kimmins, 1998), and can protect soil from erosion and play an important role in maintaining some aspects of biodiversity (Harmon et al., 1986; Hunter, 1990).

2.5. Some limitations of the FORECAST approach

As is the case with all models, FORECAST has a number of limitations in its application that should

Table 1
Definition of disturbance intensity for both wildfire and harvesting for simulations of lodgepole pine forests

Disturbance	Severity/intensity	Biomass burned or removed for each component (%)							
		Stemwood	Stembark	Branch	Foliage	Large root	Medium root	Small root	Cones
Wildfire	Low (fire-L)	0	10	10	20	0	0	10	10
	Medium (fire-M)	15	60	50	60	20	20	20	60
	High (fire-H)	50	95	95	100	30	30	60	95
Harvesting	SOH[a]	90	90	0	0	0	0	0	0
	WTH[a]	90	90	90	90	0	0	0	90

[a] SOH: stem-only harvesting; WTH: whole-tree harvesting.

be considered by the user. For example, many of the representations of soil processes in FORECAST are relatively simplistic. The lack of representation of soil horizons, soil mixing and root distribution limits the ability of FORECAST to address issues of soil compaction and soil erosion. The model's approach to estimate ephemeral litterfall may result in an overestimate of littlefall in the first few time steps of the simulation, and this may contribute to the higher values of shade-corrected FNE early in the simulation. The early overestimated of litterfall rates, however, are applied to a very small biomass, so in terms of rotation-length simulations, the error involved should be very small. The representation of the tree canopy in FORECAST as an "opaque blanket" (individual tree canopies and their horizontal locations are not simulated; the vertical distribution of foliage in the canopy is) also poses some limitations for the simulation of individual tree growth, thinning response and mixed-age stand management. In spite of these limitations, experience to date suggests that, within the limits of model design, FORECAST performs predictably and that it is able to address most of its design objectives as a stand-level ecosystem-management simulator.

3. Results and discussion

3.1. Impacts of disturbance frequencies (rotation length or intervals)

As expected, the total productivity over a 240-year simulation increased with the length of the interval between successive disturbances for all disturbance types (Fig. 2a). This is clearly related to lower nitrogen losses over the 240-year simulation period (Fig. 2b) and consequently more nitrogen and forest floor accumulation (Fig. 2c and d, respectively). This indicates, as expected, that the sites we studied would be more productive under less frequent disturbance by the regimes defined in this study.

The rate of increase in productivity between disturbance scenarios varies, with a sharp increase from intervals of 40–80 years, but only a modest increase from 80–120 years. This reflects not only the difference in percentage change in interval length between these two scenarios, but a decrease in stem mass accumulation at stands ages greater than 80 years. The combined effects of genetically-determined, age-related decline in growth rates and the altered geochemical balance at longer disturbance intervals results in a declining sensitivity of total productivity to disturbance frequency at intervals longer than 80 years.

Fig. 2a also shows that the difference in total productivity between the five disturbance types becomes progressively smaller as the disturbance interval increases, suggesting that these lodgepole pine ecosystems are fairly resilient in the face of a disturbance interval of 120 years. This is particularly evident for timber harvesting (SOH and WTH) and low-severity wildfire disturbance. However, rotation lengths of longer than 120 years may not be suitable from a timber-management perspective because: (1) they lead to little gain of productivity within a rotation, and a decline of total productivity over the 240-year simulation period; and (2) they increase problems with mistletoe. Therefore, we conclude that 120 years would be the upper limit for rotation length in terms of maximization of site productivity for the medium quality site.

The trend of site productivity over multiple consecutive rotations is a useful indication of sustainability.

Fig. 3 shows that with a harvest (WTH, SOH) or low-severity wildfire interval of 80 years or longer, site productivity is sustainable over a 240-year simulation. In contrast, site productivity at 40-year frequency is only sustainable with SOH; the other four scenarios were not shown to be sustainable (Fig. 2a and Table 2). Therefore, 80 years appears to be the lower limit of sustainable rotation lengths of the three examined for the management system that we simulated, and 80–120 years would probably be the range

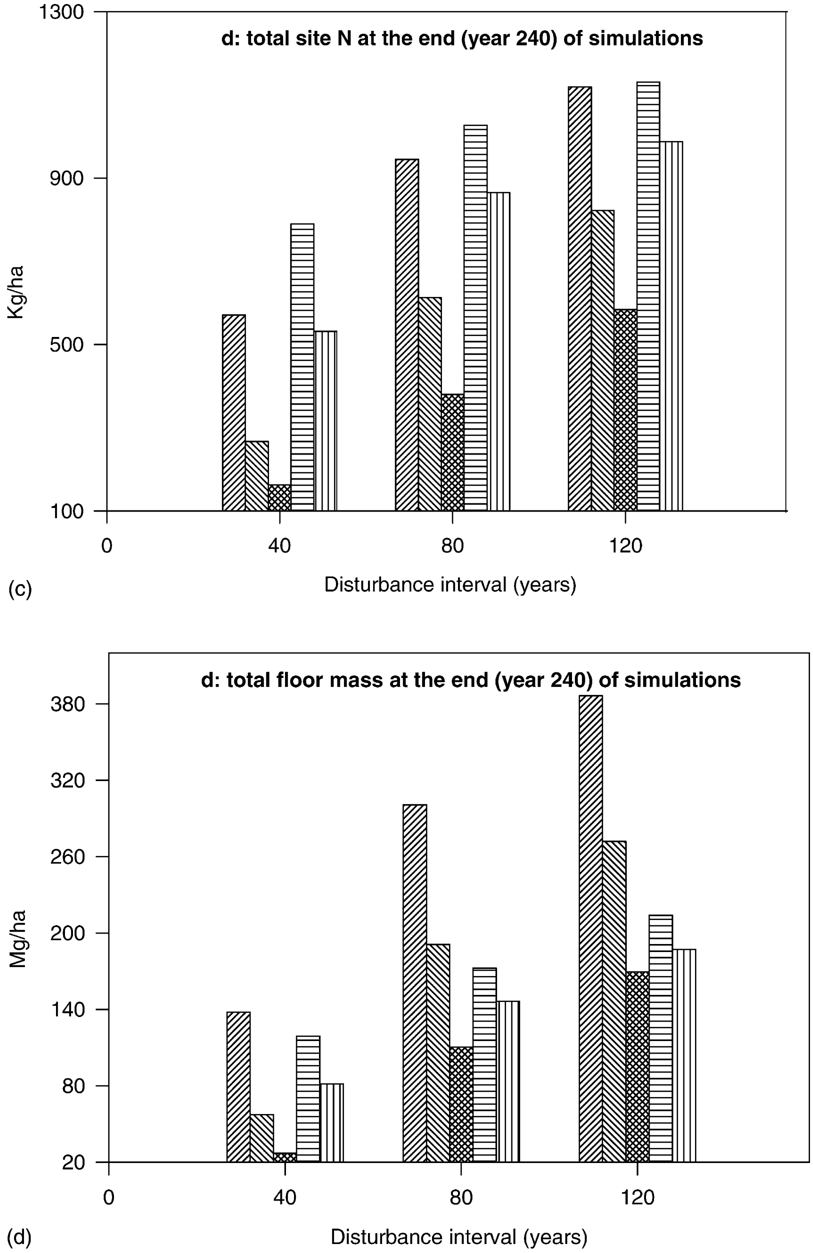
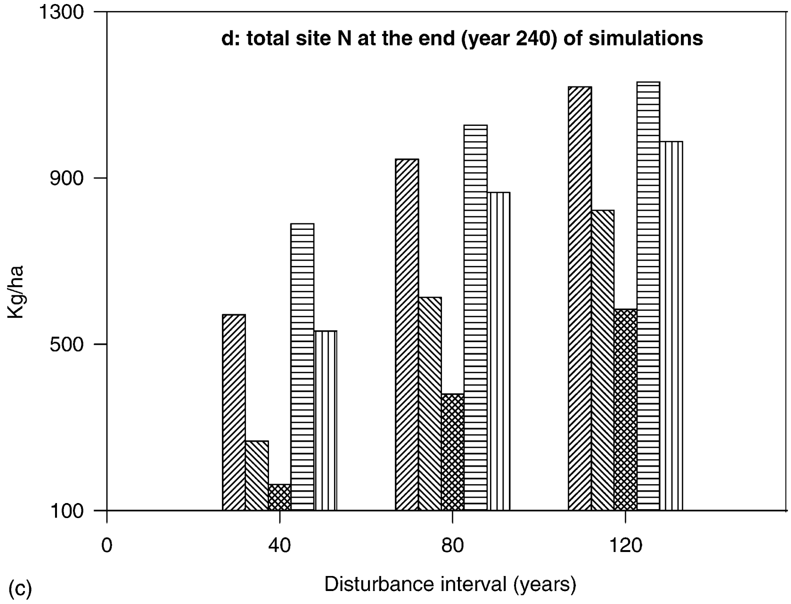
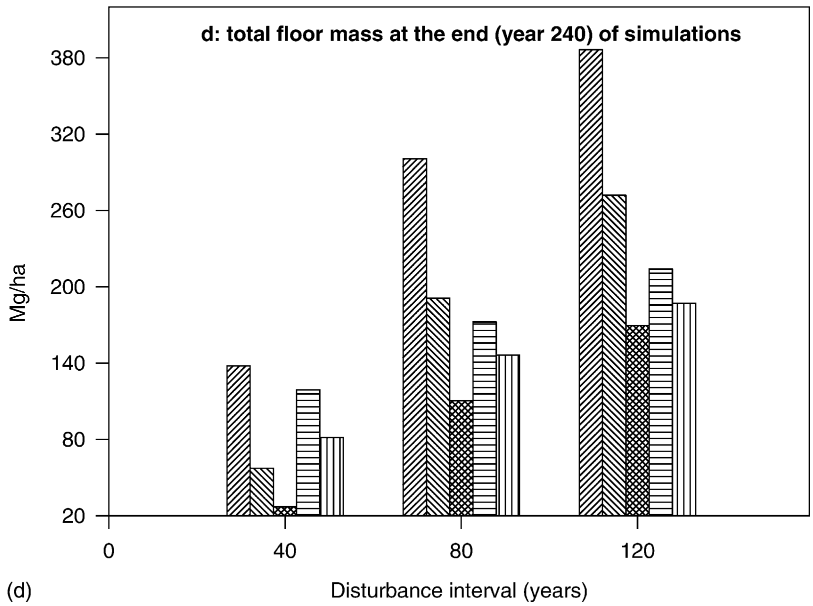


Fig. 2. (a–d) Four simulation output indicators (total productivity, total nitrogen removal, available soil nitrogen and forest floor mass) under five disturbance scenarios on a site of medium quality over a period of 240-year simulation.



(c)



(d)

Fig. 2. (*Continued*).

of suitable rotation lengths for medium quality sites in the study area. Simulations at intermediate rotation lengths would be needed to define sustainable rotation length more accurately.

Lodgepole pine forests in the study area are thought to have been recycled for thousands of years under natural wildfire return intervals of about 100–125 years (Parminter, Ministry of Forests, Victoria, personal communication). This is similar to the disturbance interval that was estimated by this simulation to be sustainable, and suggests that the study of natural disturbance regimes can be helpful in designing

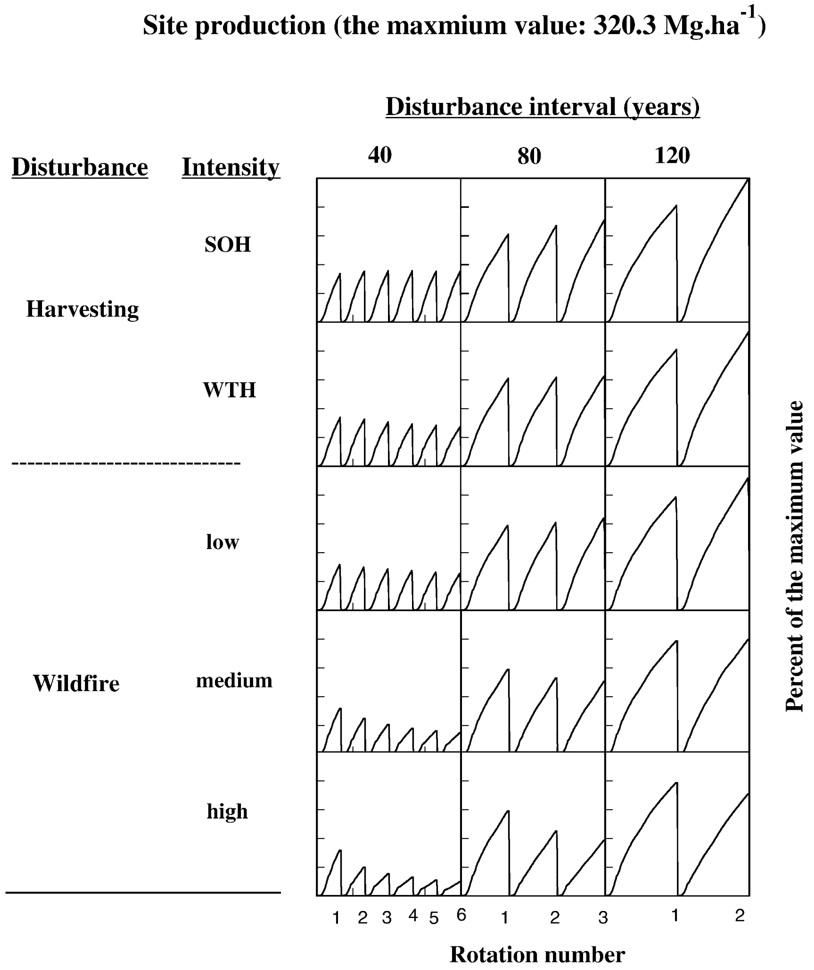


Fig. 3. Dynamics of site productivity under five disturbance scenarios on a site of medium quality over a simulation period of 240 years.

sustainable management strategies. However, although the average wildfire return interval is 100–125 years in the study sites, its variability is very high, ranging from 40 to 200 years (Pojar, 1985). This is much different from human-caused disturbance such as timber harvesting which tends to apply roughly equal harvest frequencies in a specific type of forest. The variability in frequency of natural disturbance may be important for the maintenance of certain ecosystem values because it affects the dynamics of woody debris loading and stand structures. The study conducted by Wei et al. (1997) has demonstrated that both above-ground and below-ground woody debris play an important role in the nitrogen economy in these lodgepole pine forests. The implications of this natural disturbance variability for other ecological attributes, such as wildlife habitat, remain unknown and are beyond the scope of this study, as are the implications of imposing a more uniform disturbance frequency.

Table 2
Difference in total tree productivity (Mg/ha) between disturbance intensity scenarios and between disturbance interval scenarios over a period of 240-year simulation

Disturbance interval (years)	Disturbance intensity				
	Fire-L	Fire-M	Fire-H	SOH	WTH
40	1157	847	709	1457	1275
80	1745	1525	1349	1887	1801
120	1942	1843	1734	2034	2002

SOH: stem-only harvesting; WTH: whole-tree harvesting.

In some forest types, and depending on how it is done, clear-cut harvesting reverts the ecosystem to an earlier stage of the sere (defined as the sequence of plant and animal communities which successively occupy a site over a period of time). However, in some forests, or with some techniques, clear-cutting may simply recycle the existing seral stage, promptly replacing the mature trees with young trees of the same species with little or no change in the understory. In other forests, clear-cutting in the absence of fire and soil disturbance may accelerate succession by facilitating earlier development of the subsequent seral stage. This generally involves the release of shade-tolerant seedling of the next seral stage. Clear-cutting in pure lodgepole pine forests in the study area generally tend to recycle the existing seral stage.

3.2. Impacts of disturbance intensities

Fig. 2a–d show that medium- and high-severity wildfire had the largest impact on most of the simulated indicators. Total productivity (Fig. 2a) and total soil nitrogen (Fig. 2c) are much less for the moderate and severe fire simulations than for the harvested or low-severity wildfire simulations. This reflects the greater loss of N in the medium- and high-severity wildfire simulations (Fig. 2b).

The simulations suggest that timber harvesting (SOH, WTH) is a relatively nutrient conservative disturbance compared to wildfire. All simulated indicators for the harvesting treatments are within the range of the wildfire treatment (Fig. 2a–d), and close to those for the low-severity wildfire treatment. These simulation results support one of the conclusions from our field investigation of the differences between harvested and fire-killed stands in the study area: the nutrient removals caused by harvesting were within the estimated range of nutrient removals caused by wildfire (Wei et al., 1997).

The difference in all indicators between SOH and WTH treatments declined as the rotation lengths increased (Fig. 2a–d). There is only a minor difference in total productivity over the 240-year simulation at a rotation of 120 years. This suggests that both WTH and SOH are acceptable harvesting methods for the maintenance of long-term site productivity in these lodgepole pine forests if a rotation of 120 years is used. However, the simulations suggest that WTH could reduce productivity by up to 20% compared with SOH if the rotation length was as short as 40 years. SOH is a more nutrient conservative harvest method because it leaves more of the relatively nutrient-rich crown materials on the ground, and should be used instead of WTH for rotations less than 80 years.

Wildfire removes the crown material and forest floor, but leaves most large woody material in the ecosystem. In contrast, timber harvesting removes most large woody debris, but leaves the nutrient-richer forest floor and part of the crown materials, depending on harvesting technique (i.e. SOH versus WTH). Our simulation results (Fig. 2d) and field studies (Wei et al., 1997) demonstrate that the total mass of decomposing organic matter on wildfire-killed sites, particularly for long-interval, lower-severity wildfires, would be much higher than on harvested sites. This reflects the larger accumulation of above-ground coarse woody debris on the wildfire-killed sites, and slower decomposition of this material on fire sites than on harvested sites because much of it is suspended above the ground on branch-stubs on the burned sites (Wei et al., 1997). The woody debris left on the harvested sites is smaller in diameter and in closer contact with the ground, resulting in faster decomposition and, therefore, lower persistence. The lower level of decomposing litter on high-severity wildfire sites (Fig. 2d) is attributed to much larger loss of forest floor and crown materials compared with lower severity fire. Because of these differences, harvesting conserves nutrients more than wildfire does at time of disturbance. However, because decomposing litter on wildfire sites consists largely of persistent woody debris that supports asymbiotic N-fixation, even severely burned sites eventually recover from nutrient losses caused by fire. The woody debris may also play an important role in providing wildlife habitat and microclimatic shelter for regeneration.

WTH has been a common harvesting method in the study area. SOH has been applied recently as a result of concern over nutrient removal caused by WTH. While SOH leaves much more of the fine woody debris (<2.5 cm) and crown materials on the ground, both SOH and WTH leave the same mass of stump and root systems (Wei et al., 1997). In harvested lodgepole pine forests, the mass of this largely unseen below-ground woody material is normally much greater than the mass of the visible above-ground

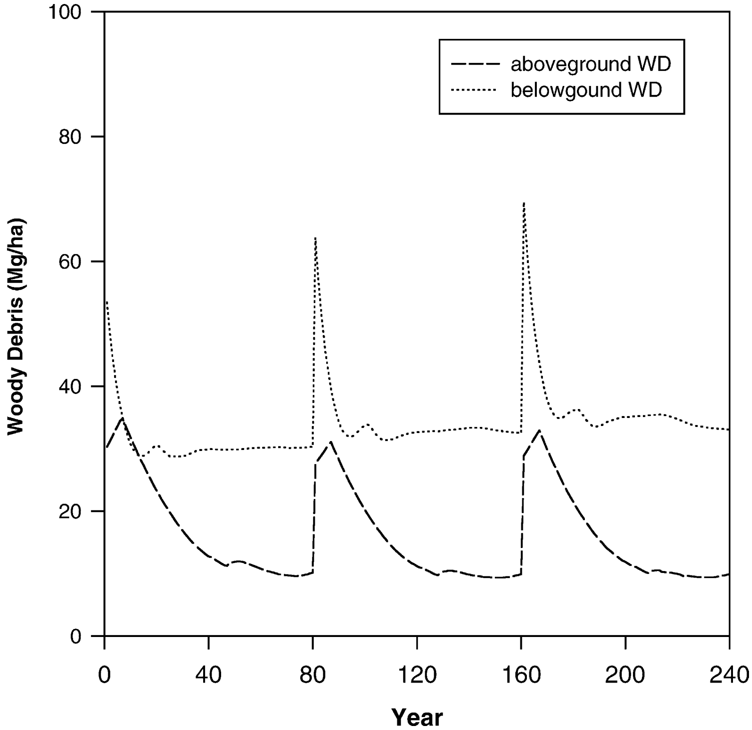


Fig. 4. Simulation of the mass of decomposing woody debris (WD) in above-ground and below-ground over three consecutive 80-year rotations in a stem-only harvested lodgepole pine forest. The shape of the above-ground curve reflects the simulation of log decomposition, in which it is assumed that it takes several years before all the mass of logs enters the decomposition process. This delay in the onset of decomposition is not simulated for the below-ground mass.

woody debris (Fig. 4), and asymbiotic N-fixation associated with the former is much higher than for the latter due to its higher moisture content (Wei and Kimmins, 1998). From a nitrogen perspective, below-ground woody debris in these forests is more important than above-ground woody debris, and consequently, the N-fixation associated with below-ground woody debris reduces the nutritional significance of differences in above-ground debris loading between SOH and WTH sites. The importance of this below-ground tree biomass also suggests that complete tree harvesting, which includes removal of stumps, major roots, and all above-ground biomass, would require much longer rotations for it to be sustainable.

3.3. Interactive effects of disturbance severity and frequency: the ecological rotation concept

Sustainability in stand-level forestry involves non-declining patterns of change. Such non-declining patterns require a balance between the frequency and severity of disturbance, and the resilience of the ecosystem in question. An ecological rotation is defined as the period required for a given site managed under a specific disturbance regime to return to an ecological state comparable that found in pre-disturbance condition, or to some new desired condition that is then sustained in a non-declining pattern of change. Too short a recovery period for a given disturbance and ecosystem recovery rate, or too large a disturbance for a given frequency and recovery rate, can cause reductions in future forest productivity and other forest values (Kimmins, 1974). Stand-level sustainability can thus be achieved by using the design of management on ecological rotations. However, estimating the length of ecological rotations is difficult, and will generally require the use of an ecosystem-management simulation model.

The ecological rotation concept asserts that stand-level sustainability can be achieved under several different combinations of disturbance severity and disturbance frequency, for a given level of ecosystem resilience. Fig. 3 shows that stemwood production is sustained over successive rotations for SOH-40 year and WTH-80 year harvest disturbances, and sustained production for low fire-80 year and medium fire-120 year combinations. The low fire-40 year, medium fire-80 year and the high fires-120 year combinations all show about the same degree of decline in productivity. These results support the concept of ecological rotations, and suggest the ecological rotation could be a useful template for the design of sustainable stand-level forestry. Managers may either choose harvest frequency based on economic, technical or other social/managerial considerations) and then limit the degree of ecosystem disturbance required by ecological rotation for the site in question with the chosen frequency. Alternatively, they may choose the level of ecosystem disturbance (type of harvest system; severity of post-harvest site treatment), but then be constrained in terms of how frequently this can be applied (i.e. the rotation length). If neither of these alternatives is acceptable, they can increase ecosystem resilience by means of silvicultural interventions.

Our FORECAST simulation results suggest that, from a nitrogen-related productivity perspective, the ecological rotation of the medium quality site would average about 100 years, with a possible range of 80–120 years. However, the ecological rotation should be evaluated in a broader context than soil fertility and site productivity. It should also be calculated for attributes such as understory vegetation, wildlife habitat, and soil physical and chemical conditions.

The ecological rotation for soil fertility is site-specific (Kimmins, 1974). For example, on a site receiving nutrients in seepage water or having large reserves of readily weatherable soil minerals, even substantial losses of nutrients may be replaced relatively rapidly. Similarly, on a site with very slow replacement and/or poorly developed nutrient accumulation mechanisms, even a small loss of nutrients may require a substantial period for replacement.

The concept of ecological rotation is defined and applied at the stand level. As noted above, sustainable management at this spatial scale implies non-declining patterns of change, rather than unchanging conditions. As a consequence, no single value or ecological process can be supplied from any one stand continuously. The objectives of sustainable management in terms of even-flow of values must, therefore, be evaluated at the landscape level. This requires that models such as FORECAST be incorporated into landscape-level models such as HORIZON (Kimmins et al., 1999).

3.4. *Effects of variation in the "biological legacy" of nitrogen*

Initial site quality reflects the amount of organic matter or "legacy" from previous stands that remains after the previous disturbance. This legacy has important effects on future ecosystem productivity and growth patterns (cf. Morris et al., 1997; Seely et al., 1999). Whether site productivity is sustainable in the future or not is affected by the site and soil conditions at the start of the evaluation period, as well as on what future disturbances forests experience. In order to test the impacts of initial site quality on ecological rotations, we generated three different ECOSTATE files reflecting various levels of organic matter "legacy", and then simulated tree growth trends on a site of medium quality over three 80-year consecutive rotations. A stem only harvest is applied at the end of each rotation. Fig. 5 clearly demonstrates that tree production, and therefore, ecosystem resilience and the ecological rotation are sensitive to initial conditions. When the initial organic matter loading is the highest, there is a declining growth trend (less sustainable) over the three rotations. In contrast, when the initial organic matter loading is the lowest, the opposite growth trend is seen. The medium loading level of initial organic matter resulted in a constant level of production over three consecutive rotations.

Productivity is site-specific and ecosystem-condition-specific, and its sustainability in a managed forest can only be defined in the context of the pre-management conditions of that ecosystem (Morris et al., 1997). This suggests that it is not possible, from a productivity perspective, to certify sustainable forest management without considering initial ecosystem conditions. However, in most situations, the conditions of a forest before it was managed are unknown, which renders sustainability assessment problematical in the absence of using an ecosystem-management model such as FORECAST.

The most developed models in the category of using the hybrid approach, designed for the assessment

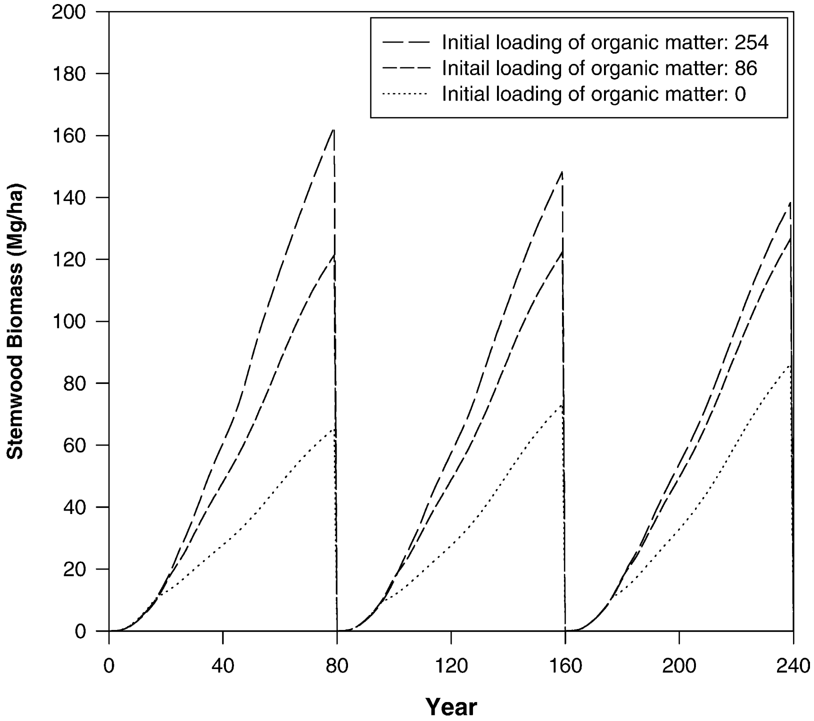


Fig. 5. Simulation of stemwood biomass over three consecutive 80-year rotations under three different initial loadings of organic matter (Mg/ha) in a stem-only harvested lodgepole pine forest.

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; e.g. Kimmins et al., 1999). These models take the production predictions from a historical bioassay model and modify these predictions according to a simulation of temporal variation in competition for light and in the availability of one or more nutrients. However, 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. A moisture and temperature submodel is being added to FORECAST to address this shortcoming (Seely et al., 1999).

FORECAST is a non-spatial stand-level model. Many of the important issues in forestry today are landscape and watershed-scale issues (Baskent et al., 2000), and landscape models are needed to deal with spatial scales. However, without stand-level modeling there would be insufficient details to study landscapes for many of ecological processes. This highlights importance of integration of stand-level models with landscape models for studying sustainable forest-management issues.

Neither the non-spatial FORECAST nor spatial landscape models can address the issue of complex cutblocks. This renders them unsuitable in their present format for the simulation of complex cutblock—the variable retention system and the emulation of natural forest disturbance (Kimmins, in press; Mitchell and Beese, 2002). To address this issue we are developing a complex cutblock simulator—local landscape ecosystem-management simulator (LLEMS)—which will deal with the spatial relationship and ecotonal effects of retaining within cutblock structures and patches. LLEMS is a small scale spatial application of FORECAST with a spatial resolution of 10 m × 10 m. The need for LLEMS is an example of the increasing inadequacy of existing models as decision support tools in forestry.

4. Conclusions

Based on our simulations and comparisons between various disturbance types, intervals and severities, timber-harvesting impacts in lodgepole pine forests in the central interior of British Columbia are within the range of wildfire disturbances defined in this study, and close to long-interval, low-severity wildfire regimes. Either of the current timber harvesting methods (SOH or WTH) can maintain long-term site productivity in the study area if rotations of 80–120 years are used. Shorter rotations should use SOH. Because of lack of validation, application of these simulation results must be cautious and adaptive.

This study demonstrates that FORECAST is a useful tool in identifying sustainable management strategies for long-term site productivity. Use of the model shows that it is impossible to certify sustainable forest management without understanding pre-disturbance conditions. The results of this study also support the use of the ecological rotation concept, in conjunction with an ecosystem-management simulation model such as FORECAST, as a template for the design of sustainable stand-level management.

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