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SORTIE: a resource mediated, spatially-explicit and individual-tree model that simulates stand dynamics in both natural and managed forest ecosystems

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ABSTRACT

SORTIE was originally developed in the early 1990s for mixed deciduous forests in eastern North America. One of the major distinctive features of SORTIE, compared to the JABOWA-FORET family of gap models, is that the model structure originated from field experiments and heavily relies on the input of data from field studies. During the past four years, the model has been extensively modified for the temperate mixed-species forests of northwestern British Columbia (SORTIE/BC). Significant changes were made to the original SORTIE model to take into account unique features of western forests and unique challenges posed by use of the model for management planning. Currently, work is underway to use SORTIE for southern hardwood forests in Quebec, boreal mixedwood and black spruce forests of Canada, temperate forests of New Zealand and tropical forests of Puerto Rico.

The SORTIE model consists of a mixture of mechanistically and empirically-derived relationships (i.e. hybrid model) and is comprised of four basic submodels: (1) seedling recruitment – a function of parent tree proximity and seedbed substrate; (2) resource availability – predicts understory light dynamics as a function of species specific light extinction coefficients; (3) subcanopy tree growth – function of light availability and previous growth history and; (4) tree mortality – function of recent growth rates. We are currently working to add an understory vegetation submodel and to improve our prediction of growth and mortality of mature canopy trees. The model is ideal for examining stand dynamic and succession after small- to intermediate-scale disturbance in structurally complex mixed or single-species stands. From a forest management perspective, the model has a very flexible user-interface to allow incorporation of a wide range of partial cutting strategies (e.g., understory protection, diameter limit, shelterwood, variable retention). The model easily simulates prescriptions that retain complex stand structures, especially the influence of retained canopy trees on recruitment, growth and mortality of sub-canopy trees. Current model predictions include: (1) spatial distribution and sizes of all individuals in a simulated stand; (2) DBH and height distributions by species; (3) changes in basal area and density, by species, over time; (4) tables of basal area and densities of both adult and juvenile trees and; (5) distribution of subcanopy light levels.

Three examples are provided that demonstrate the ecological and silvicultural questions that can be addressed by SORTIE in both the temperate and boreal forests of North America. We are currently re-engineering the model in order to facilitate and improve the continuously changing requirements of the SORTIE users and developers.

INTRODUCTION

The discipline of silviculture in Canada has strong traditions based largely on European forest practice developed in the 19th century (Troup 1926; Smith 1986). Development and refinement of these silvicultural practices over time relied heavily on long-term observations of forest responses to traditional or trial-and-error manipulations (Weetman 1996). The end result was a suite of traditional silvicultural systems that describe a cycle of activities in which a stand is harvested, regenerated and tended over time (Matthews 1989). These silvicultural activities have been supported in Canada and elsewhere by the development of the science of silviculture, which in the 20th century tended to follow an agricultural model that focused primarily on tree- or tree-related issues such as reproduction methods, provenance testing, genetics, growth prediction, protection from pests and wildfire and development of planting, tending and harvesting techniques. In the later half of the century, as logging rapidly expanded in the temperate and boreal forests of Canada, foresters tended to strive for simple stand structures with an emphasis on even-aged, single species stands and the normalization of the forest. This style of management is still common today.

Since the mid-1970s forest ecologists have increasingly studied the role of disturbance in forests, especially the implications of varying frequency, intensity and pattern of disturbance on population or community dynamics and ecosystem processes (White 1979; Picket and White, 1985; Special feature on "Gaps in Forest Ecology" in Ecology (Vol. 70, No.3, 1989); Turner et al 1998; Hunter 1999). Emerging from this work has been a clearer understanding of the importance of structure in forest stands (e.g., several tree species, trees of varying size, retention of large trees, snags, and down logs) and landscapes for many species and ecosystem processes (Angelstam, 1998; Hunter 1999; Franklin et al. 2000). This has resulted in a major reassessment of the relationship between forestry and the disturbance processes that operate in natural, unmanaged environments (Attiwil, 1994). The role of the agricultural model in forestry, with its attendant simple stand structures, is now the subject of much scientific and social debate. Foresters are beginning to view silviculture treatments more in terms of stand structural goals rather than simply the regeneration and growth of the next crop. Managers must strive for sustainable forestry rather than the narrower objective of sustained timber yield, however, they are often asked to achieve what are still perceived as conflicting objectives: removal of forest products while maintaining the structure and diversity of a natural forest. In Canada, the Sustainable Forest Management Network (SFMN) is undertaking a multi-disciplinary and multi-scale approach to understand natural disturbance processes with the intent to develop concepts and solutions that can be used in managed forests to achieve sustainable forestry (Veeman et al. 1999).

Global demands require that forest management decisions be based on sound science and that forest management must demonstrate sustainability. Forestry research can help with experiments that lead to improved understanding and better predictions of the consequences and trade-offs involved for sustainable forestry in the use of different management systems. The sustainability of practices, however, must be assessed over long time frames and, probably, at multiple scales. Unfortunately, in Canada, only a few long-term silvicultural experiments have been established (e.g., Decie 1957; Glew 1963; Lees 1964; Hughes 1967), and even fewer have been followed for more than a decade or two due to changing priorities and funding problems. Silvicultural systems research is particularly plagued by a lack of good experimental data because of the long-term nature of such studies and the difficulty of conducting research on what were fundamentally descriptive management systems. In recent years there have been a host of new long-term experiments established in Canada and elsewhere to look for alternatives to the agricultural model or to compare and contrast effects of natural and human disturbances in forest ecosystems (e.g., Special Issue of For. Chron. Vol. 75, 1999; Special Issue of Northwest Sci. Vol. 73, 1999; Coates et al. 1997; Arnott and Beese 1997; McClellan et al. 2000). Many of these experiments may quietly fade into history as well before long-term results are available.

While we fully support the need for and absolute importance of long-term research in forestry, here we present an approach of combining short-term empirical studies with development of a forest simulation model as a means of providing insight into long-term forest response to natural or human disturbances. We think linking empirical studies to models is the best approach for answering the many questions foresters and ecologists have regarding site, stand and landscape conditions in future forested landscapes given the variety of silvicultural approaches that are applied or under consideration (Kimmins, 1997; Messier et al. 1999a). Our reliance on models that can simulate future forest conditions at different scales can only increase as we try to understand the implications of managed stands becoming more structurally complex due to special habitat requirements or the use of new silvicultural strategies that include continuous retention of canopy trees and management of multiple tree species with different life history characteristics.

The objectives of this paper were to: (1) describe the research philosophy and structure of the model SORTIE; (2) describe where SORTIE has been calibrated, where work is currently underway and how SORTIE fits into the research program of the SFMN; (3) provide examples of SORTIE simulations in temperate deciduous and temperate conifer dominated mixed species forests, and in mixed boreal forests; and (4) describe how SORTIE can directly address the global demands that forest management be based on sound science and demonstrate sustainability.

SORTIE

Model development and history

SORTIE is a resource mediated spatially explicit mixed-species forest dynamics model that was originally developed in the early 1990s (Pacala et al. 1993) for transitional oak – northern hardwood forests in northeastern North America. It can be considered a small- to intermediate-scale disturbance model. The purpose of the model was to extrapolate from measurable fine-scale and short-term interactions among individual trees to large-scale and long-term dynamics of forest communities (Pacala et al. 1996). One of the major distinctive feature of SORTIE, compared to the earlier JABOWA-FORET family of gap models (Botkin et al. 1972, Shugart 1984), was that the model structure originated from field experiments and heavily relies on the input of data from field studies (Canham et al. 1994; Pacala et al. 1994; Ribbens et al. 1994; Kobe et al. 1995). A full description of the structure, dynamics, parameter estimation and error analysis of SORTIE can be found in Pacala et al. (1996).

In the late 1990s, the original SORTIE model was extensively modified and calibrated for the conifer dominated transitional coast-interior forests of northwestern British Columbia (Kobe and Coates, 1997; Wright et al. 1998, 2000; Canham et al. 1999; LePage et al., 2000). The broad objective of this research was to add a spatial and temporal component to the Date Creek silvicultural systems study (Coates et al. 1997) so that long-term and spatially explicit questions could be addressed, specifically: (1) how do natural mature and old-growth forests, subject to low intensity, small-scale natural disturbance, change over long time horizons and (2) how does partial cutting, with variable levels and spatial arrangements of retained canopy trees, affect forest development in terms of tree growth, changes in species composition, and changes in stand structure over time?

Currently, research is underway to calibrate and modify the model for use in the following forest types: temperate hardwood forests of southern Quebec, boreal mixedwood forests of the Clay Belt of Quebec and Ontario, spruce/aspen boreal forests of Canada, temperate forests of New Zealand and tropical forests of Puerto Rico. The calibration of SORTIE for biomes of the boreal forest of Canada is part of a major research program in boreal forests initiated by the SFMN (http://sfm-1.biology.ualberta.ca/english/research/eregen.htm). Within the SFMN, the calibration and implementation of both stand and landscape models are being conducted with the long-term goal of being able to address various theoretical questions and develop and test alternative silvicultural and forest management scenarios inspired by an understanding of natural disturbance dynamics in boreal forests. The SFMN modeling approach will permit the testing of different management scenarios at multiple scales in order to develop management strategies that meet the goals of sustainable forest management

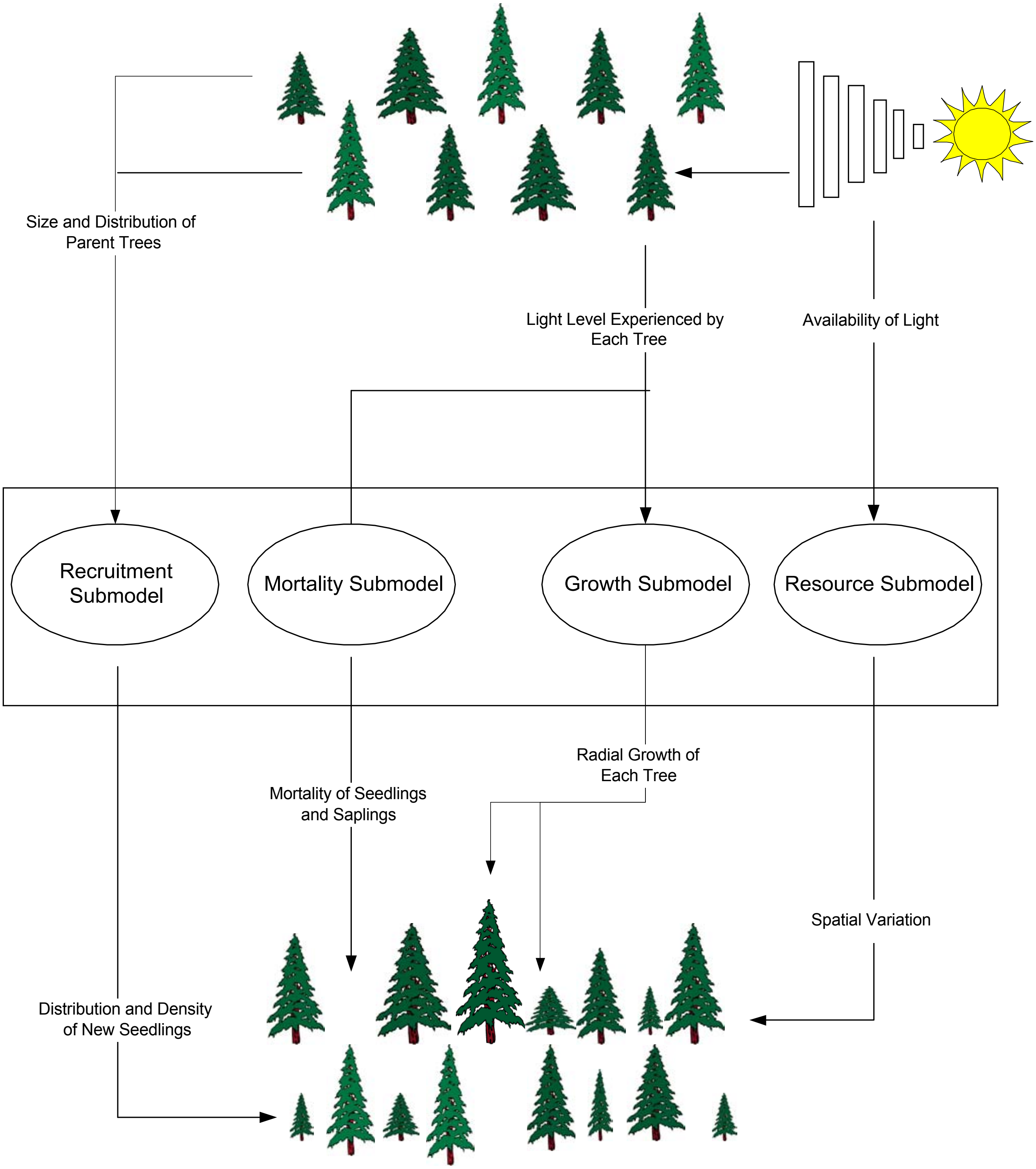
Model structure

The model makes population dynamic forecasts by predicting the fate of every individual tree throughout its life. The model contains a record of every individual tree's diameter, species identity and *x*- and *y*-coordinates. SORTIE simulations use a mixture of mechanistically and empirically derived relationships (i.e., hybrid model) found in four basic submodels: seedling recruitment, resource depletion, growth and mortality (Figure 1). SORTIE does not uses site-specific variables such as site index. We are currently working to add an understory vegetation submodel and to improve our prediction of growth and mortality of mature canopy trees using a neighbourhood competition approach (Canham et al., in prep.; ongoing boreal studies). All SORTIE submodels were designed simultaneously with the field methods and published along with appropriate maximum likelihood estimators derived from the field data. Changes were made to each of the original SORTIE submodels during the British Columbia calibration to take into account unique features of conifer-dominated forests. Further changes to the overall model structure were implemented to make the model more flexible for management planning.

SORTIE now has a user-interface that allows incorporation of a wide range of partial cutting strategies (e.g., understory protection, diameter limit, variable retention, shelterwood, single or group selection) or silvicultural treatments via inclusion of a harvesting and planting user-interface. The model easily simulates prescriptions that retain multiple tree species and complex stand structures. Trees can be cut or seedlings planted on a grid or random distribution at any time step during a model simulation. Within a simulated plot up to five subplots can be identified for separate model output summaries. This is especially useful to compare different logging prescriptions or silvicultural practices during one model simulation. The SORTIE interface is file-based with species dynamics controlled by a parameter file. The model algorithm is written in C++ and simulations have a 5-yr time step.

Current model predictions include: (1) spatial distribution and sizes of all individuals in a simulated stand; (2) DBH and height distributions by species; (3) changes in density and basal area, by species, over time for juvenile and adult trees; (4) distribution of sub-canopy light levels. SORTIE does not simulate biomass, wood products or wood quality, or any economic state variables.

Figure 1. Overall structure and organisation of the model SORTIE (Gendron, 2001).



Submodels

Recruitment: The recruitment submodel predicts the number and spatial distribution of seedlings using species-specific equations based on parent tree proximity, size and abundance (Ribbens et al. 1994) and, additionally in the BC model, the abundance and favourability of seedbed substrates under four levels of canopy openness: full canopy, partial canopy, large gaps and clearcuts (LePage et al., 2000).

Light: The light submodel predicts incident radiation at any given location within a forest as a function of (1) species-specific light transmission coefficients, (2) variation in crown geometry as a function of tree size, (3) the identities, sizes, and spacing of trees in the immediate neighborhood, and (4) the local sky brightness distribution (Canham et al. 1994, 1999). The light submodel is an extraordinarily simple representation of the underlying complexity of light transmission through forest canopies and gaps (Lieffers et al. 1999). The parameters required by light submodel are operationally defined, and can be readily estimated directly from field data. In particular, the modeling approach is designed to predict the light levels experienced by individual seedlings and saplings at any point in the understory, in the same units that are used in the field to measure growth as a function of light level (e.g., Pacala et al. 1995, Wright et al. 1998; Beaudet et al. 2001).

Growth: The light submodel allows the prediction of the light level experienced by each individual in the forest. Light is arguably the most important factor influencing tree growth in different forest biomes (Denslow and Hartshorn 1994; Pacala et al. 1996; Lieffers et al. 1999; Messier et al. 1999b), and is certainly the factor most directly manipulated by forest management actions. Clearly, other resources and physical conditions will vary with ambient light level, but these are more difficult to quantify and to manipulate. The growth submodel consists of species-specific equations that predict radial growth of juvenile trees based on growing season light availability (Pacala et al. 1995, Wright et al. 1998). Empirical relationships are used to convert tree diameter (at 1.3 m height, DBH) to tree height. A new feature of both our fieldwork and the model is the ability to incorporate species-specific growth functions that account for past periods of suppression and release (Wright et al. 2000). We believe this is very important function as silvicultural practices shift to various forms of partial harvesting where alternating periods of suppression and release are likely to become even more characteristic of the process of canopy recruitment in managed forests. Species-specific adult tree growth rates are estimated from repeatedly measured permanent sample plots. As mentioned above we are currently working to replace these empirical functions with more mechanistically derived functions based on neighbourhood competition (SFMn project titled “Spatial and non-spatial modelling of canopy tree dynamics in boreal forests” lead by Vic Lieffers). The juvenile growth function grows trees from the seedling stage to a diameter of 10 cm (DBH). The diameter where the adult growth function takes over is species specific and can be changed in the model interface.

Mortality: The mortality submodel takes advantage of the well-documented empirical relationship between growth rates and survival of understory seedlings and saplings.

Species-specific equations predict the probability of survival for each juvenile tree as a function of recent radial growth rates (Kobe et al. 1995; Kobe and Coates 1997). The parameter values from this analysis also provide a quantitative measure of the shade tolerance of each tree species. The mortality submodel also includes a user specified random background mortality rate for juveniles and adults, and for dense even-aged and single-species stands self-thinning functions can be implemented for specific model simulations. These parameter values should be estimated from locally available data, for example from repeatedly measured permanent sample plots.

MODEL SIMULATIONS

As mentioned earlier, foresters have historically manipulated forest stands primarily by implementing one or more of the traditional silvicultural systems (Matthews 1989). They are generally viewed as resulting in the development of even-aged (clearcut, strip-cut, seed-tree, shelterwood, or coppice methods) or uneven-aged (group- or single-tree selection methods) forest stands. Their names generally reflect the type of reproduction method employed and the extent of the original forest canopy structure remaining after the initial harvest. The growing of timber has been the most common objective of forest management this century, resulting in the dominant use of a system that combined efficient harvesting with promotion of rapid growth rates for regenerating trees; i.e., even-aged management via clearcutting.

It is worth mentioning that debate on the virtues of the different silvicultural systems for timber production (especially even-aged versus uneven-aged management), and the conditions under which they can be applied, has been ongoing without any real resolution for decades (Jones 1945; Bradshaw 1992; Emmingham 1998). It is unrealistic to expect silvicultural systems designed for the degraded forests of 19th century Europe to be appropriate for addressing the complex issues facing forest management today in Canada, where extensive tracks of natural forest remain. We are more typically trying to retain some of the existing stand structure (i.e., legacies), a goal not contemplated by the traditional systems. Traditional practices reflect neither broadened societal objectives for forests nor the scientific findings of the past thirty years (Franklin 1995). We think one of the unique challenges to developing prescription strategies for sustainable forestry is the management of patchiness in the distribution of both harvested and residual trees and how that patchiness affects future stand dynamics.

Below we provide three examples of how management of the spatial arrangement or size of residual trees affects future forest development. For each simulation we try to answer a specific management question. These examples are designed to show the reader the potential uses of the SORTIE model for addressing forest management issues today. They are not intended to be an exhaustive analysis of each management question.

1. Conifer dominated temperate forests of northwestern BC. During logging trees can be removed in either a uniform pattern or by discrete groups or patches. At a fixed rate of removal, how does the spatial arrangement of the retained canopy trees affect future stand development?

2. Deciduous dominated temperate forests of southern Quebec. Tree removal alters light conditions near the forest floor that in turn affect survival and growth of regenerating tree species. Southern Quebec temperate forests contain trees species with a wide range of shade tolerances, but they have been managed under the selection system with a narrow range of removal rates and uniform canopy retention. This system has not favored the survival and growth of yellow birch, a tree of intermediate shade tolerance. Given low removal rates, how does varying the spatial arrangement of tree removal alter stand level light environments?

3. Trembling aspen – white spruce boreal forests. Prescriptions that strive to protect residual understory white spruce while removing overstory trembling aspen are being considered or implemented across Canada. One prescription is strip cutting. How will strip cutting affect future stand development in aspen-spruce stands?

1. Date Creek - spatial pattern of residual trees

The implications of partial cutting on timber yield are complex and difficult to predict. The expected yield after partial cutting will depend on the contribution of newly established regeneration and the abundance, composition, and vigour of residual trees. Light-demanding species will respond differently than shade-tolerant species and large old trees probably will respond differently than more vigorous young trees.

At a given level of retention, the spatial distribution of retained canopy trees (uniform or patch applications), can dramatically affect the growth rates of both residual and newly regenerating trees (Palik and Peterson 1996; Coates, 2000; Canham et al., in prep;). The issue of how a partially retained canopy affects the survival and growth of newly established regeneration is the topic of this model simulation. Given equal volume removal, we expect performance of newly established trees under a spatially uniform canopy to be much poorer than that in discrete canopy openings. This simulation was designed to assess this hypothesis by establishing equal densities of planted hybrid spruce (*Picea glauca* x *sitchensis*), a tree of intermediate shade tolerance, under different spatial arrangements of retained canopy trees.

Methods

Here we use the fully calibrated model from our work in the conifer dominated northern temperate forests of British Columbia, Canada (Kobe and Coates, 1997; Wright et al. 1998, 2000; Canham et al. 1999; LePage et al., 2000). Our simulation was based on forests at the Date Creek Silvicultural Systems Study (55° 22' N, 127° 50' W; 370-665 m elevation) where mature stands typically comprise a mixture of six conifer and three deciduous tree species (Coates et al. 1997).

Five tree removal treatments were compared in 4 ha simulation plots over a 100 yr time period: (1) no tree removal (the uncut forest); (2) 40% uniform removal across all species and diameter classes; (3) 40 % removal in sixteen 50 x 20 m (0.1 ha) small gaps; (4) 40% removal in eight 50 x 40 m (0.2 ha) medium gaps; and (5) 40% removal in four 80 x 50 m (0.4 ha) large gaps. Each treatment was planted with a total of 2,560 spruce stems (30 cm tall) at the end of the first time step (yr 5). In the uncut and uniform removal treatments 640 stems per hectare (sph) were randomly planted in the understory. In gaps, 1,600 sph were randomly planted in each gap.

The parameter file used in the simulation was a mature stand established after a stand destroying fire in 1855 (unit C3 at the Date Creek experiment, Coates et al. 1997). To simplify the model simulation all residual spruce trees were removed (about 6% of the total stand basal area) and the natural regeneration sub-model was turned off. Stand density in the uncut forest was high with 1166 sph 10 cm or larger in diameter and 2676 smaller stems. Western hemlock (*Tsuga heterophylla*) dominates stand composition, followed by western redcedar (*Thuja plicata*) and minor amounts of subalpine fir (*Abies lasiocarpa*), amabilis fir (*Abies amabilis*), lodgepole pine (*Pinus contorta* var *latifolia*), paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) (Table 1).

Results and discussion

The spatial pattern by which 40% of the basal area of a stand was removed (about 26 m^2 ha^{-1}) greatly impacted planted spruce survival and growth (Table 1). In these dense stands, uniform removal did not create high enough light levels in the understory for the long-term survival of the planted spruce trees. After 10 and 20 yrs only 23 and 3%, respectively of the planted spruce seedlings had survived. Survival was much better in the gaps regardless of gap size. After 20 yrs 78, 87 and 86% of the planted spruce were present in small, medium and large gaps, respectively. All spruce seedlings planted in the understory of the undisturbed forest died. The model simulation results are consistent with observed mortality rates of planted spruce in understory and gap environments at the Date Creek experiment (Coates 2000). At the end of the simulation all three gaps sizes had roughly equal densities of spruce: 196, 218 and 228 sph (averaged over the 4 ha simulation plot) in small, medium and large gaps, respectively.

Total spruce BA after 100 yrs slowly increased with increasing gap size (Table 1). Spruce BA represented 29, 34 and 38% of stand basal area in small, medium and large gap cuts, respectively. Spruce BA in the uniform removal cut was insignificant in terms of total stand BA (Table 1). The uniform removal treatment resulted in the lowest stand BA after 100 yrs, producing only 70.5% of the large gap removal treatment BA (Table 1). The forest matrix (area with retained canopy trees in all five removal treatments) grew at a faster rate in the gap cutting treatments, especially the small gap treatment (Table 1), that created the highest level of edge environment for the release of residual trees. The higher basal area production of the gap cutting treatments compared to the uniform removal was a combination of greatly improved survival of planted spruce combined with the release of residual trees adjacent to the canopy openings.

Table 1. Basal area (m^2 ha^{-1}) in a 145 yr old northern temperate forest (starting conditions) and predicted basal area 100 yrs later after five tree removal treatments. Basal area is presented by stand component and tree species. No trees were removed in the uncut treatment. In the other four treatments, 40% of the basal area was removed in different spatial patterns. Each treatment was planted with equal numbers of hybrid spruce at the start of the simulation. The recruitment submodel was turned off for the simulations, thus no natural recruitment occurred.

	Matrix[1]				Stand[2]	Gaps only[3]	Stand total[4]
Tree species	Hemlock	Cedar	Other	All	Spruce	Spruce	All species
Starting conditions	36.1	18.6	10.4	65.1			
After 100 yr simulation							
uncut	28.1	15.8	2.9	46.8	0	na	46.8
uniform	21.3	13.0	1.6	35.9	0.03	na	35.9
small 0.1 ha gaps	34.3	20.1	3.3	57.7	14.1	35.5	48.8
medium 0.2 ha gaps	32.1	17.6	3.7	53.4	16.8	42.3	48.9
large 0.4 ha gaps	31.6	18.8	2.6	53.0	19.1	47.6	50.9

[1] The forest matrix is all areas with retained canopy trees in each removal treatment, i.e. the entire area in the uncut and uniform removal treatments and the area between the gaps in the gap removal treatments.
[2] Spruce basal area for the stand is averaged over the 4 ha simulation plot.
[3] Spruce basal area in the logged gaps is given on a per hectare basis.
[4] Stand total basal area is the basal area in each 4 ha simulation plot after 100 yrs.

2. Duchesnay Forest - understory light conditions

The establishment and promotion of yellow birch, a tree of intermediate shade tolerance with a high economic value, is a management objective in many northern hardwood forests of Quebec. Yellow birch regenerates well from seed under most light conditions given appropriate seedbeds (e.g., mix of humus and mineral soil) are available (Godman and Krefting, 1960; Willis and Johnson, 1978; Houle and Payette, 1990; Houle 1992). Yellow birch seedlings are thought to need intermediate light conditions for good survival (White et al., 1985; Seymour, 1994), however, few quantitative data are available, apart from those published by Kobe et al. (1995). They predict high (>95%) survival over a 2.5 yr period when light levels exceed 10% of full sunlight. For optimal growth and development yellow birch require approximately 50% of full sunlight (Godman and Krefting, 1960; Erdmann, 1990). For the purposes of our model simulation we will assume that >20% full sunlight is required to insure adequate survival of yellow birch seedlings and saplings over the full length of a cutting cycle since light tends to decrease rapidly and then slowly over time following partial cutting (Beaudet and Messier, 2001), and that light levels >50% full sunlight should provide conditions required for optimal growth.

There are many different harvesting options available to forest managers in the northern hardwood forests of Quebec, however, much debate exists about which cutting practices are best for yellow birch management. Over the last fifteen years, traditional single- or group-selection were the most commonly used silvicultural systems (Matthews 1989). Recently, due to changes in forest policy, managers have greater flexibility in choosing cutting practices in these forests. Newly available options include large group selection (with 500 to 1500 m^2 gaps in a matrix of single-tree selection cutting), and patch cutting (1 to 2 ha openings in a matrix of single-tree selection cutting).

Although various silvicultural experiments have been established over the years (e.g., Roberge, 1988a,b,c; Majcen, 1995), it is still unclear which silvicultural approach is best to regenerate mid-shade tolerant species such as yellow birch. Silvicultural experiments tended to look at the effect of different silvicultural treatments on the density or stocking of regeneration. Moreover, the studies usually reported stand average information about regeneration, without discriminating among the variable micro-habitats that each silvicultural option created**.** Few experiments have examined the relationship between canopy opening, understory light availability and regeneration (but see Beaudet 2001 for a study in selection cuts). This is not surprising. Field-based comparisons of silvicultural systems require extensive field set up and time-consuming measurements to characterize the light conditions because of the temporal variation and spatial heterogeneity of light intensity.

Methods

In this model example we use SORTIE to determine the effect of different silvicultural treatments on the proportion of microsites with optimal light conditions for survival and growth of yellow birch. The SORTIE light module has been calibrated and tested with empirical data from the Duchesnay Forest Station, Quebec **(**comprised between 46° 50’ N and 47° 00’ N, and between 71° 35’ and 71° 45’ W) (Beaudet et al. 2001). We used data from the Duchesnay Forest Station to create a base tree map file for a 9 ha stand with 27 m^2/ha basal area (BA) and composed of 70% sugar maple, 20% yellow birch and 10% beech (% of BA for stems >10 cm diameter at 1.3 m height [DBH]). The total BA, species composition, tree density by DHB class, and density of saplings (1-10 cm DBH) were specified to SORTIE, but the position of each tree was randomly determined by the model.

We simulated light conditions in five tree removal scenarios: (1) no tree removal (the unlogged forest); (2) 20% BA removal with uniform single-tree selection; (3) 30% BA removal with uniform single-tree selection; (4) 30% BA removal with a cutting pattern that utilized large group selection (nine evenly distributed 900 m^2 gaps) and uniform single-tree selection (20% removal) in the forest matrix between the large gaps; and (5) 30% BA removal with patch cutting (one 1.4 ha openings) and uniform single-tree selection (20% removal) in the remaining area.

The output requested from SORTIE was a list of predicted GLI (Gap Light Index) values at 0.2 m aboveground along a 5 m x 5 m grid covering the entire 9 ha. We then calculated the frequency distributions of predicted GLI for each tree removal treatment. All simulations were performed with SORTIE version 4.1.

Results and Discussion

Figure 2 illustrates the main results obtained. In the uncut forest (Fig. 2 A), no microsites received more than 20% full sunlight. Clearly, light conditions were not favorable to yellow birch survival or growth in such closed canopy stands. The simulated stand may be more closed than normally found in old-growth northern hardwood stands (Dahir and Lorimer, 1996). Stands in our study area have been high-graded heavily in the last 100 years, which may have promoted the development of younger and denser stands. The uniform 20% removal cut (Fig. 2 B) increased slightly the area receiving >20 % of full sunlight (approximately 2% of the microsites), but no microsite received >50% of full sunlight. The uniform 30% removal cut (Fig. 2 C) increased the percentage of microsites receiving more than 20% light to almost 10%, but still did not create any microsites with optimal growing conditions (>50% sunlight). Large group selection (Fig. 2 D) did not increase by much the proportion of microsites receiving between 20 and 50% of full sunlight compared to the uniform 30% removal cut, but created a few microsites (3%) receiving > 50% of full sunlight. Finally, patch cutting (Fig. 2 E) varied little from uniform 30% removal and large group selection in the proportion of microsites receiving between 20 and 50% of full sunlight, but produced more microsites (15%) receiving > 50% of full sunlight.

The low removal rates (20-30%) commonly used in the northern hardwood forests of Quebec will generally not favour the establishment, survival and growth of yellow birch unless careful attention is paid to the spatial distribution of the retained canopy trees. The partial cutting systems currently being applied (i.e. an uniform 30% selection cut) for these forests resulted in poor growing conditions for yellow birch. Survival of newly established seedlings after cutting may be reasonable initially, but the combining effects of rapidly increasing size, increasing light requirements (Givnish, 1988), and decreasing light availability, especially in smaller gaps, as reported by Beaudet and Messier (2001) might be detrimental for yellow birch if they quickly reached what Messier et al. (1999) have called their "maximum sustainable height". In our large group selection and patch cut treatments the forest matrix between the discrete gap cuts was harvested at a 20% removal rate by single-tree selection. Moving toward a gap-based cutting system with little cutting in the forest matrix between the gaps will create better conditions for yellow birch establishment, survival and growth. New gaps can be created or existing gaps expanded in size every 20-30 years.

Of course, forest management objectives should not be limited to regenerate only a few desirable species, but should rather aim at recreating the full spectrum of stand structure and composition that is found in nature. Designing the right harvesting pattern to reach such an objective is complex and models like SORTIE could be very helpful tools to achieve such a goal.

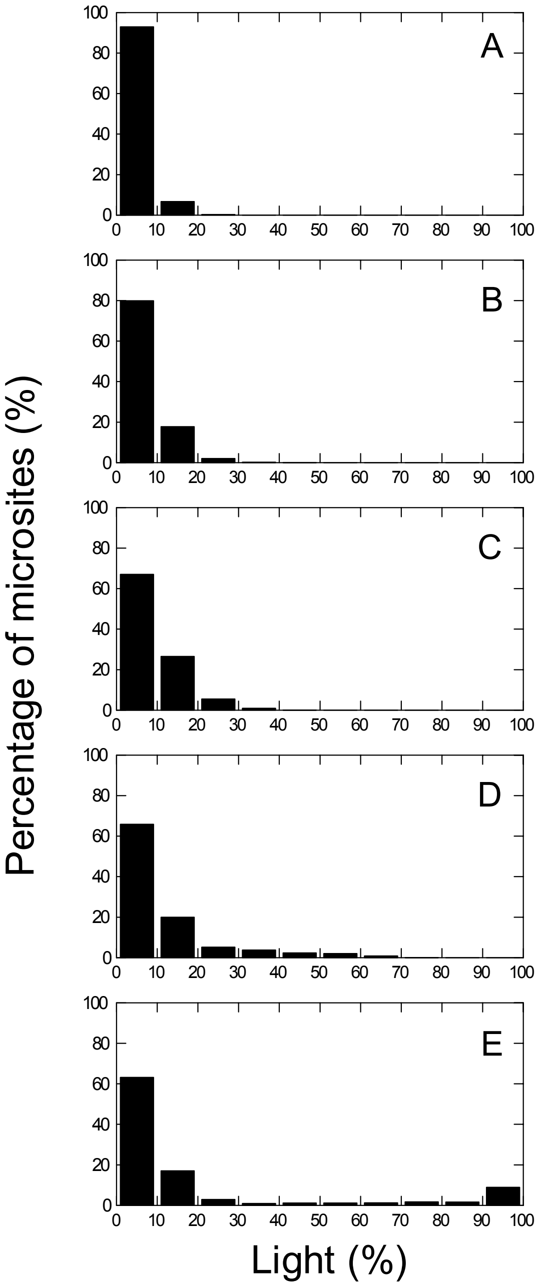


Figure 2. Frequency distribution of light availability above the forest floor (height = 0.2 m) predicted by SORTIE for a sugar maple – yellow birch – beech stand A) before harvesting; and after B) a uniform selection cut (20% of BA); C) a uniform 30% selection cut; D) group selection; E) patch cutting. More detailed information about harvesting scenarios are provided in the Method section of the text.

3. Boreal mixedwood – strip cutting

The trembling aspen and white spruce complex is a common stand type across boreal Canada. Historically, management practices strived to promote the dominance of either aspen or spruce after logging. Mixedwood management practices that retain both tree species are being advocated for a variety of ecological and silvicultural reasons (Man and Lieffers 1999). Here we use the model to examine a partial cutting silvicultural prescription where the objective was to retain both trees species in future managed stands.

Stand data was obtained from mixedwood stands near Fort Nelson, British Columbia (Lat and long). We used a combination of local data and published or ongoing SORTIE studies for model simulations. We used parameter values from our northwestern BC studies with the following exceptions. Parameters for aspen juvenile growth were based on data from Quebec boreal forests (Coates, unpublished data a=0.828; s=0.024). Self thinning functions for juvenile and adult aspen trees were fit from a compilation of data from available yield tables or studies that followed aspen self thinning through time, all of which were in general agreement regarding trends in aspen stand density over time (Bella 1975; Bella and De Franceschi 1980; Peterson and Peterson 1992; Lux 1998). Adult tree radial growth was derived from 33 permanent sample plots (PSP) in the Fort Nelson area. Allometric relationship between tree diameter (DBH), tree height and crown radius, and between tree height and crown length were derived from the PSP and data from ongoing studies in the Fort Nelson area (Richard Kabzems, BC Ministry Forests, unpublished data).

We simulated stand dynamics for 120 yrs following strip cutting (hereafter referred to as “cut strips” where all trees were removed) at three sites where we had stand table data (Table 2). Cut strips were 78 m wide with 18 m wide retention areas (hereafter referred to as “buffers”, where all residual trees were retained) between each cut strip. Each cut strip had four 6 m wide machine corridors. Between machine corridors were three 18 m wide harvest areas where all aspen and all merchantable spruce (DBH > 17.5 cm) were cut. Additionally, five years after the initial logging 10 % of the remaining spruce in the harvest areas were removed to simulate losses due to mechanical injury during the initial logging entry and subsequent wind damage. The total plot size simulated was 114 x 114 m for a total area of 1.3 ha. Additionally, all trees were removed from an 18 m wide strip across the top of the plot to simulate a roadside processing area (hereafter referred to as “road”). We controlled aspen regeneration so that aspen sucker density 5 yr after logging was approximately 20,000 sph in the logged areas of the cut strip and the road. We performed additional simulations using the Mile 308 stand with fixed aspen recruitment densities of 10,000 and 50,000 aspen after logging to examine the influence of differing levels of aspen regeneration on final stand composition.

Table 2. Stand descriptions for all three sites used as starting stands for SORTIE simulations.

Site	Aspen basal area (m^2 ha^{-1})	Aspen density (stems ha^{-1})	Spruce basal area (m^2 ha^{-1})	Spruce density (stems ha^{-1})
Capot Blanc	45.7	656	5.7	725
Mile 308	42.2	877	8.7	927
Simpson Trail Km 21	39.9	512	10.4	1145

Results and discussion

The strip cutting treatment gave similar results when applied to all three sites, so they were combined into one analyses (Fig. 3). Each site started with approximately 50 m^2 of total BA, the bulk of which was aspen. Aspen BA drops in the buffers and is minimal after 80 years with mortality of the older trees. This is reasonable given that aspen rarely live beyond 200 years in the area and most trees were over 80 years old at the start of the simulation. Spruce BA increased in the buffer area due to the longevity of the species. Aspen BA in the cut strips peaked 30 to 40 years following cutting and then declined slightly by 120 years. Spruce BA increased slowly in the cut strips, but ends up only slightly higher than in the original stand (see Table 2 for the original stand). The road processing areas were predominantly aspen with very little spruce regeneration. Total BA over the whole simulated plot was lower at the end of the simulation than at the start.

The aspen regeneration density experiment indicates that future aspen BA is strongly influenced by the initial density of aspen regeneration (Fig. 4). Spruce basal area was also affected, but only to a small extent. None of the three aspen regeneration densities allow for recovery of aspen BA to original levels, although the 50,000 stems per ha initial density was close. Our starting stands (Table 2) were of fire origin and likely had very high aspen densities at establishment (commonly 30,000 to 150,000 sph, see Peterson and Peterson 1992). Our simulations showed that higher starting densities of aspen led to more aspen BA at maturity. Also, the retained buffer strips would tend to lower basal area production by shading the regenerating aspen and through senescence of the retained mature aspen trees. Trends from the simulations are probably reasonable even if the absolute basal areas predicted may be low. Varying the amount of aspen regeneration or spruce residuals has predictable effects on the composition of the final stand.

One result from our simulations was at odds with a commonly held belief in aspen – spruce stand dynamics. It is generally assumed that new aspen suckers will not overtop residual white spruce greater than 4.5 m tall (Johnson 1986; Yang 1989). Yet, in our simulations aspen overtopped (by age 60) up to 10 m tall residual white spruce. Aspen in the Fort Nelson stands are growing taller and faster and reaching a greater maximum height than aspen in other boreal regions, whereas spruce height development in the study area was similar to other boreal regions (Fig. 5). This suggests that aspen may respond to an increase in site quality more so than spruce. The interaction between site productivity and height development of aspen and spruce could play a significant role in determining the size residual spruce must be to avoid overtopping by regenerating aspen. As an experiment, we used the Quebec aspen height – DBH relationship to drive SORTIE and repeated the standard strip cutting simulation using the Mile 308 stand. As expected, spruce remained taller than the aspen for the entire simulation. However, the Quebec aspen height data never allow aspen trees to grow taller than 26 – 27 m. This is clearly wrong for the Fort Nelson area where our input data show a significant number of aspen exceeding 30 m in height. The results of this project validate the need to link good local data and simulation models, and this is one of the basic premises behind the SORTIE approach. The SORTIE model proved quite capable of simulating complex harvest patterns in mixedwood stands.

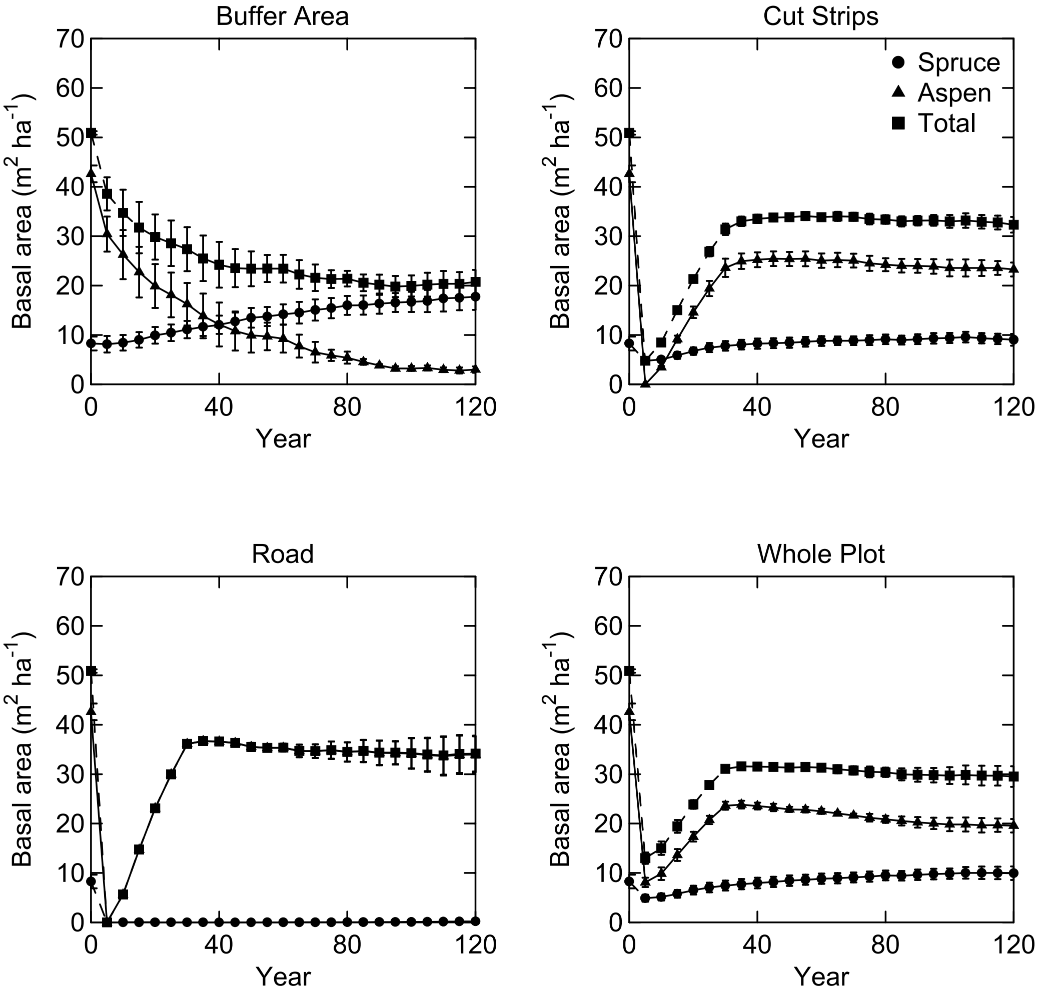


Figure 3. Average basal area trends over time in the three simulated stands combined in the buffer area, cut strips, road processing area and on average across the whole simulated plot.

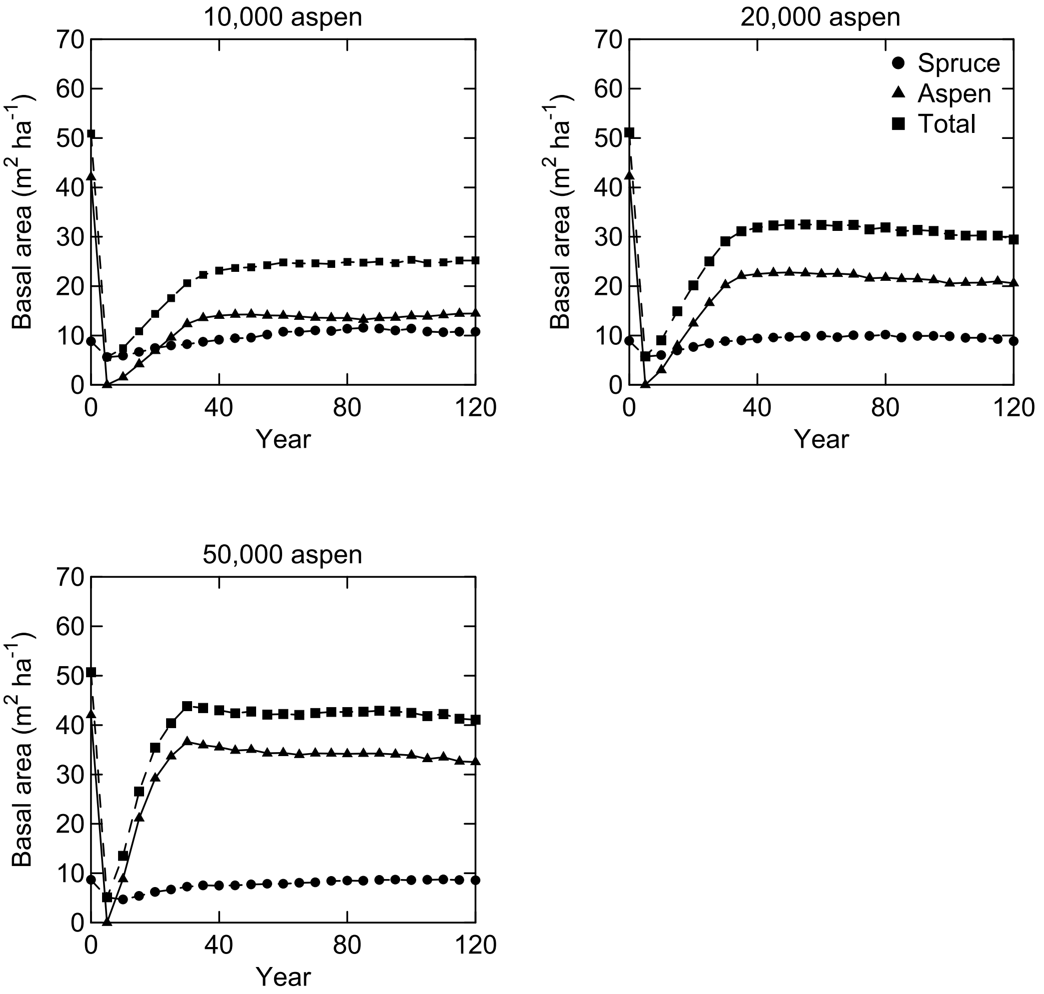


Figure 4. Basal area trends over time in Mile 308 stand after strip cutting treatment with regeneration of varying numbers of aspen per ha.

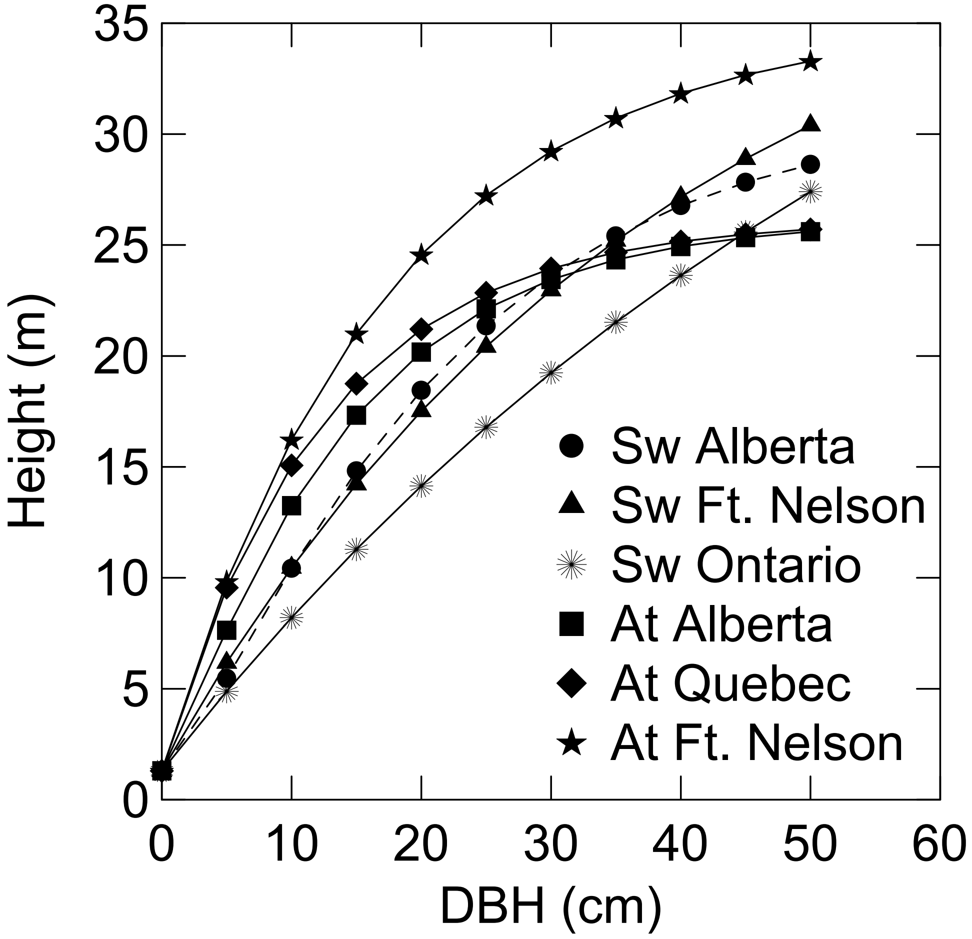


Figure 5. Comparison of predicted aspen and spruce tree height using species-specific diameter – height relationships from different regions. Sw=white spruce; At=trembling aspen. Relationships for Sw and At in Ft. Nelson and At in Quebec were determined from our analysis for SORTIE calibration; Sw Alberta from Huang et al. 2000; At Alberta from Huang 1994; Sw Ontario from Peng 1999.

Lessons learned in SORTIE calibration in BC and boreal

The calibration and modification of SORTIE for the temperate coniferous forests of northern British Columbia and the boreal mixedwood of Canada provided us with two major lessons. First, and most importantly, it confirmed the generality of the SORTIE research approach: understanding the response of individual trees to variation in light is fundamental to predicting the effects of partial cutting on future forest composition and growth. We found similar trade-offs in species performance in western coniferous (paper in prep), mixed boreal (paper in prep.) and deciduous eastern temperate forests (Pacala et al. 1996) were structuring tree community dynamics. These studies also showed that it is possible to combine studies of short-term, individual-tree interactions into an individually based, spatially explicit and resource mediated model to understand how various species trade-offs are structuring forest communities. Second, it demonstrated the value of designed experiments that emphasize the study of gradients, specifically gradients of canopy influence, rather than sets of predetermined treatments, such as contrasting one traditional silvicultural system to another. The experimental design applied in the Date Creek study (Coates et al. 1997) and the Duparquet Teaching and Research forest (Harvey, 1999) provided ideal conditions for calibration of the model and we were able to design and implement the required field studies with relative ease. All fieldwork was completed in two or three years of intensive sampling.

Our ongoing undertakings to calibrate the model for the boreal clay belt of eastern Canada and boreal mixedwood of Alberta have provided further lessons for model development. Here we tried to rely on a combination of data from already completed studies, because of the rich history of research in the experimental area and focused new field studies. While on the surface this would seem logical it has made us aware that the current architecture of SORTIE does not easily allow the reuse of components for other applications. In the future, we intend to work on the basic architecture of the model to make it easier to use a variety of approaches to model the same process. Ideally, we want the model to be more easily calibrated and modified by forest researchers working on various forest ecosystems all over the world.

SILVICULTURAL CONCLUSIONS

Among the greatest challenges for the discipline of forest ecology is to understand how community structure in forests develops over time following natural or human-induced disturbance. The “new” role of silviculture is thus to use this expanding knowledge of forest stand development to produce desired forest attributes and products over time. Silvicultural research must necessarily look beyond the establishment and early growth phase to time periods of decades and centuries to assess longer-term effects of stand management activities on forest community dynamics and succession. Traditionally, this was done by setting up long-term experiments. While we fully support such endeavor, we believe that there is a need for simulation models such as SORTIE that can address many of the long-term effects of “new” or “planned” silvicultural systems.

As a spatially-explicit model, SORTIE is ideally suited to address the unique challenges of managing patchiness in the distribution of both harvested and residual trees. Forest managers need help to determine the optimal spatial pattern of partial cutting (including the optimal mix of sizes and spatial distribution of discrete canopy gaps) in a given stand. The pattern will be a function of existing stand structure and composition, and desired stand structure and composition in the future.

As shown in this paper, SORTIE can be used to address various ecological and silvicultural questions in the temperate and boreal forest of North America. The model easily simulates prescriptions that retain complex stand structures. It can be used to model the consequences of a wide range of partial cutting strategies, at different spatial scales and over different time periods, an impossible undertaking for field-based research. In the three examples presented it is clear that the distribution of canopy trees after harvest should be a major consideration in harvest planning because of the strong negative influence of canopy trees on the survival and growth of regenerating trees. Uniform applications where canopy trees are evenly distributed after harvest would tend to favour the most shade tolerant species only. Patch applications where defined openings are created in the tree canopy should be favoured in order to optimize growth rates of regenerating trees and encourage the regeneration of the more shade intolerant tree species. We must emphasize, however, that the SORTIE model approach is toward modeling for exploration and explanation rather than to predict an outcome with a high level of accuracy, as tends to be the objective with traditional growth and yield modeling.

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