Evaluation of an ecosystem-based approach to mixedwood modelling

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1. Introduction

Mixedwood forests consisting of a broad range of species combinations, successional stages, and spatial patterns cover a large area throughout BC. From a resource perspective they are highly valuable both as sources of fiber and as areas rich in biodiversity. Research into the production ecology of mixedwood ecosystems has illustrated that mixtures of conifers and broadleaf species can be more productive and relatively more healthy (lower risk of disease and pest attack) than pure stands (e.g. Man and Lieffers, 1999; Simard et al. 2004). Explanations for such benefits have focused on the differential utilization of resources (light, nutrients and water) and the positive impacts of broadleaf species on nutrient cycling rates and mycorrhizal networks. The exceptionally dynamic nature of mixedwood forests presents a number of management challenges, not the least of which is how best to project the growth and development of different types of mixedwoods and associated management systems. Accordingly, the research community has devoted much effort and resources to measuring and trying to understand forest growth processes with the often-stated goal of improving our capabilities to model the growth of complex stands. Yet, presently in BC, there is a fundamental disconnect between the majority of models being used to simulate growth and yield in mixedwood stands and the underlying biological processes governing forest growth dynamics in such stands. For example, two of the more prominent models, the Mixedwood Growth Model (MGM) and PrognosisBC, rely on the development of statistical relationships derived from measurements of past height and diameter growth to predict future height and diameter growth. While such a modeling approach may be reasonable under relatively constant conditions, the ever-changing management objectives and environmental conditions in our forests (including the threat of climate change) suggest that we cannot afford to rely solely on past observations of diameter and height growth to project future growth dynamics. Rather, to meet the broader objectives of sustainable forest management, we must expand our modelling capabilities to develop and incorporate a better understanding of the biological processes regulating forest growth dynamics so that we can make reasonable long-term projections of forest growth under changing conditions (c.f. Korzukhin et al. 1996; Johnsen et al. 2001).
One such model utilizing a more mechanistic approach to projecting forest growth and ecosystem dynamics is FORECAST (Kimmins et al., 1999). FORECAST, developed at the University of British Columbia, was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics, and various biophysical and social indicators of non-timber values. It uses derived measures of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth and ecosystem dynamics under changing management and environmental conditions (a detailed description of FORECAST is provided in Section 2.1).

During the past 5 years the model developers have made significant improvements to FORECAST including: a) its capability represent shifts in carbon allocation under different light and nutrient levels, b) a simplification of the calibration process to utilize readily available yield table data, and c) its capability to produce growth and yield output for a wide range of management options. During this period the model has been used by industrial partners for a wide variety of applications including growth and yield, projection of stand-level habitat elements, and carbon storage. In addition, a number of papers have been published on the application of FORECAST in various mixedwood stand types (e.g. Welham et al. 2002; Seely et al. 2002; Seely et al. 2004). However, to establish the model as a useful decision support tool for mixedwood management it is necessary to validate its performance against long-term, mixedwood forest growth data.

1.1 Project Objectives

The primary objective of this project was to evaluate the capability of the ecosystem management model FORECAST to project patterns of stand growth and dynamics in mixedwood forests by comparing model output against data from long-term field trials in different mixedwood stand types in both the SBS and ICH BEC zones. Specific objectives included the following:

1) Evaluate (qualitatively) the species-specific growth properties derived and used in the model to project growth and other ecosystem process (based on existing knowledge of the autecology of each species);

2) Assess the capability of the model to project both short and long-term growth dynamics and yield in both aspen/conifer mixedwoods (SBS) and birch/conifer
mixedwoods (ICH) by comparing model output with data from selected silviculture trials.

3) Describe the role of an ecosystem-based modelling approach in augmenting statistically based growth and yield models with respect to expanding our capacity to project and evaluate growth and yield dynamics and trends in mixedwood stands.

2. Methods

2.1 Model Description

2.1.1 General Overview

FORECAST is a management-oriented, stand-level forest growth and ecosystem dynamics simulator. The model was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. The projection of stand growth and ecosystem dynamics is based on a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources (a representation of moisture competition is being completed) (Fig.1). The rates of these processes are calculated from historical bioassay data (e.g. biomass accumulation in component pools, mortality, litterfall, etc.) by relating ‘biologically active’ biomass components (e.g. foliage and small roots) with calculations of nutrient uptake, the capture of light energy, and net primary production. In essence the model is calibrated internally such that the combination of linked processes and their derived rates reproduces the patterns of species and site-specific growth observed in the historical bioassay data. The model uses this method to generate information (simulation rules) for each tree and plant species to be represented. These simulation rules are subsequently used to model growth as function of resource availability and competition in the case of multi-species stands. The following list is an example of some of the simulation rules governing future tree growth derived from the set-up internal calibration process.

- **Photosynthetic efficiency per unit foliage biomass**: based on relationships between foliage biomass, simulated self-shading levels, and net primary productivity accounting for litterfall rates and mortality.
• **Nutrient uptake requirements**: based on rates of biomass accumulation and literature-based estimates of nutrient concentrations in different biomass components on different site qualities

• **Light-related measures of tree and foliage mortality**: Using stand density input data in combination with simulated light profiles, light levels at which foliage and tree mortality occur are estimated for each species.

As a management model, FORECAST can simulate a wide variety of activities including fertilization, brushing, partial harvesting, mixedwood management, etc. Disturbances such as fire and insect defoliation may also be represented. Volume projections generated by FORECAST are ultimately constrained by the potential yields of single species stands as specified in the calibration data for a range of site qualities. Growth and yield in complex stands is based on a simulated partitioning of limited resources (light and nutrients) among species and age cohorts. The biological properties of individual species determine their relative competitiveness for limited resources. A more complete description of model functionality and further details of FORECAST calibration are provided in Kimmins et al. (1999), Seely et al. (1999), and Seely (2004).

2.1.2 Representation of Individual Stems

Though FORECAST performs many of its calculations at the stand level, it includes a submodel that disaggregates stand-level growth into the growth of individual stems. This is done using a method which takes information about stem size distributions at different stand ages to simulate differential growth rates in individual stems (see Kimmins et al. 1999). Using this approach, the distribution in projected stems sizes widens as stands age. DBH and top height and are calculated for each stem and subsequently used to calculate a merchantable volume using a taper function approach (Kozak 1988). In addition to DBH and top height data, FORECAST also estimates the height along the stem where the canopy begins (e.g. where live branches start) based on a simulation of the light profile through the canopy and species-specific parameters related to shade tolerance. This information can subsequently be used to estimate log grades for different sections of the stem. The capability of the model to generate accurate individual stem output data was evaluated as part of a recent Forest Science Program (FSP) funded project (Seely 2005). The results of the study showed that diameter class frequency distributions produced by the model for both aspen and spruce stand analysis units in
the Fort Nelson TSA (BWBS zone) were consistent with those measured in analogous regional permanent sample plots.

Figure 1. Diagrammatic representation of the fundamental ecosystem components and processes simulated within FORECAST including pathways of CO₂ loss to the atmosphere.

2.1.3 Decomposition & Nutrient Cycling

Decomposition and nutrient cycling are simulated in FORECAST using a method in which specific biomass components are transferred at the time of litterfall or mortality, to one of a series of litter types. Each litter type has unique properties in terms of decomposition rates, nutrient concentrations and humus formation. Decomposition rates of the specific litter types are defined based on the results of extensive field incubation experiments conducted across British Columbia and Canada (e.g. Camiré et al., 2002). Mean residence times for active and passive humus types are estimated from climate...
data utilizing a $Q_{10}$ multiplier. Residence times for ecosystem types within British Columbia typically range from 25 to 50 years for active humus and 400 to 750 years for passive humus.

The model employs a mass balance approach to keep track of the total pool of nutrients within the ecosystem and any import or export of nutrients to and from the ecosystem (Fig. 2). Nutrient storage and release from decomposing litter and soil organic matter represents the largest source of nutrients into the plant available pool. Tree growth is ultimately limited by available nutrients such that if the availability of nutrients is less than that required to support the expected annual biomass increment of the trees, the actual growth rate will be restricted to an increment level supported by its simulated nutrient uptake.

Figure 2. A schematic diagram illustrating the representation of the mass balance approach to nutrient cycling employed in the FORECAST model. The three main pools of for nutrient storage are shown as well the specific processes regulating the movement of nutrients between pools and into/out of the ecosystem. Green diamonds indicate biological processes while red and blue diamonds indicate the geochemical cycle and management impacts on nutrient cycling, respectively.
2.2 Selection of Test Sites

The criteria used to identify test sites for model evaluation included the following: 1) must fall within the target BEC zones (see Section 1.1), 2) must include common mixedwood species combinations (see Section 1.1), 3) sites must have repeated measures over a minimum of 10 years, 4) plots must be large enough to avoid scaling error, 5) treatments to be examined in the context of the model must have a proper control. Unfortunately, there are very few data sets which meet these requirements. While several silviculture trials have been established around the province, few have been sampled for ten or more years. Chronosequence-based data sets are not useful for model evaluation as they invariably contain many uncertainties with respect to stand origin and management or disturbance events prior to measurement. Three test data sets were ultimately identified and compiled with input and assistance from project partners (Chris Hawkins, UNBC and Suzanne Simard, UBC).

2.2.1 Spruce-Apsen mixedwood (SBS)

The spruce-aspen mixedwood validation data set used for this project was derived from long-term monitoring plots established as part of a study of pine weevil attacks on young spruce plantations manipulated to have varying degrees of aspen cover (see Taylor and Cozens 1994 for a complete description). The study area contained 3 separate sites intended as replicates, but differences in species and density among the sites prevented there use as such here. Rather, Site #2 was selected as the best candidate for the model evaluation. An overview of the study site, plots, treatments, and measurements are provide below.

- Site Description: The study site is located approximately 50 km east of Prince George in the SBSwk1 variant. The site was established in 1985 in an area that was clearcut in 1969, broadcast burned in 1970, and planted in 1971 with 2+1 bareroot white spruce (Picea glauca) seedlings. Despite the burning, the plantations had a vigorous regeneration of aspen (Populus tremuloides) such that by 1985, when the plots were established, the aspen canopy was well above that of the spruce.

- Treatments & plot establishment: Long-term plots were established in 1985 to examine the impact of two levels of aspen removal on both weevil attack rates and spruce growth. The first treatment was the mechanical removal all of the aspen (henceforth referred to as ‘brushed’) and the second treatment was a
partial removal of the aspen using strip cuts (henceforth referred to as 'alternate brushed'). A control plot was also established in which no aspen removal occurred. All plots were rectangular in shape with dimensions of 50 m * 115 m. In the alternate brushed plot, strips of 5 m in which no aspen were removed were left adjacent to 7 m strips in which all the aspen were mechanically removed. The strips were made perpendicular to the long axis of the rectangular plot. This treatment resulted in the removal of approximately 60% of the overstory aspen.

- Measurements: All spruce trees were measured (top height & diameter at breast height (DBH)) in each plot in 1986, 1988, 1991 and 2003. Mortality was also recorded. Aspen trees were only measured (top height & DBH) in 2003. Estimates of total volume and stem biomass were made for both species in years where both height and DBH data were available using standard species specific volume (BCFS 1976) and biomass equations (Standish et al. 1985).

2.2.2 Douglas-fir / Birch mixedwoods (ICH)

The Douglas-fir-birch mixedwood validation data sets used for this project were derived from the PROBE study established by the BC Ministry of Forests in 1991 (c.f. Simard et al. 2001; http://farpoint.forestry.ubc.ca/FP/). In general, the PROBE study was designed to examine the effects of brushing treatments on the growth and development conifer seedlings and associated vegetation complexes in southern interior British Columbia. For the purposes of model validation, specific data sets were taken from the specific study sites called Probe 1 and Probe 2.

**Probe 1**

Site Description: The study site is near John Creek in the Kamloops forest district within the ICHmk1 variant. The site was clearcut in 1982, piled and burned in 1983, and planted in 1984 with 1+0 interior Douglas-fir (*Psuedotsuga menziesii* var. *glauc*a) seedlings. At the time of plot establishment in 1991 the Douglas-fir was 8 years old and approximately 1 m in height. The seedlings were overtopped by paper birch (*Betula papyrifera*) (~ 52% cover, 2.6 m in height)

**Probe 2**

Site Description: The study site is near Upper John Creek in the Kamloops forest district within the ICHmw3 variant. The site was clearcut in 1976, had manual site preparation
in 1978 and was planted in 1979 with 2+1 interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) seedlings. At the time of plot establishment in 1991 the Douglas-fir were 14 years old and approximately 2.1 m in height. The seedlings were overtopped by paper birch (*Betula papyrifera*) (~ 40% cover, 5.9 m in height)

**Probe 1 & 2**

Treatments, plot establishment, and measurements: Long-term plots were established in 1991 to examine the impact of birch removal (cut stump-glycophosphate treatment) on Douglas-fir survival and growth. Each PROBE site is approximately 1.6 ha in size, and consists of a treatment plot (treated operationally with the rest of the opening) and a control plot (area left untreated in the same opening) that have similar site history and ecosystem characteristics. Thirty-six crop tree-centered subplots were established on a grid within each of the treatment and control plots, within which conifer crop tree size (top height and DBH), condition, damage, and degree of overtopping were assessed. These measurements were taken before installation, then at 1, 3, 5, and 10 years after treatment. Top heights were also measured for birch in a subset of years. Since all trees were not sampled, it was not possible to calculate per hectare estimates of volume and/or biomass. However, volume and stem biomass was calculated for each Douglas-fir stem. Stem biomass was calculated based on its volume (BCFS 1976) and an estimated wood density of 0.45 g/cm³ (Gonzalez 1990). Allometric biomass equations could not be used as the individual trees were too small.

**2.3 Model Preparation**

The FORECAST datasets used for this project were based on two existing calibration datasets assembled as part of an internal dataset development project funded by the Canadian Foundation for Innovation (CFI). Specifically, a general Sub-Boreal Spruce (SBS) zone dataset with minor changes made to spruce height growth curves (to match local height over age data) was used for the simulation of the spruce-aspen mixedwood. For the representation of the Douglas-fir-birch mixedwood, a general Interior Cedar Hemlock data set (for the southern interior) was used. The only changes made to this data set were to update the birch height growth curves based on output from the Variable Density Yield Predictor (VDYP) software for the specific site qualities represented in the dataset. For a description of the calibration process employed to create these datasets refer to Seely (2004).
Upon completion of the calibration datasets, the calibration set-up programs were run to perform the internal calibration process necessary for FORECAST to derive species-specific rates for the ecosystem processes represented in the model (see Section 2.1). A summary of this output is provided in Section 3.1.

Prior to using the model to simulate the growth of the different mixedwood stands and associated treatments, it was necessary to run the model in set-up mode to establish initial site conditions. In this stage, the model is run with nutrient feedback turned off to allow it to accumulate vegetation, litter and soil organic matter representative of the site(s) to be modeled, and which reflects the historical patterns of accumulation. This is typically achieved by simulating the known or estimated natural disturbance and/or management history of the site (see Seely et al. 1999 for a detailed description).

2.3.1 Spruce-aspen mixedwood
In the case of the spruce-aspen mixedwood site, the model was run for 2000 years with a fire return interval of 125 years to allow it to accumulate representative levels of soil organic matter and forest floor material. A final setup run was conducted to represent the clearcut harvest of a mature forest with a spruce and aspen component followed by a medium intensity slash burn. The simulated ecosystem condition at the end of this sequence was used as the starting condition for the test simulations.

2.3.2 Douglas-fir-birch mixedwoods
In the case of the Douglas-fir-birch mixedwoods, a fire return interval of 125 years was also run for 2000 years. The final set-up run for both of the PROBE sites included a clearcut harvest of a 125 year-old Douglas-fir dominated stand with a birch component. Once the initial conditions had been established for the test mixedwood forest types, the model was used to simulate the development of the test stands and the effects of the various treatments on stand growth and development (see Section 2.4).

2.4 Simulation of test sites
2.4.1 Spruce-aspen mixedwood
Using the initial condition described in section 2.3 as a starting point, FORECAST was run 3 times to represent each of the 2 treatments (brush & alternate brush) and the control. In each simulation spruce was planted in year 1 at 1500 stems per hectare and aspen regeneration occurred in year 1 (e.g. 1971) at 2000 stems per hectare. A small
population (5% cover) of a general (medium height) Vaccinium shrub was also initiated in year 2. In the case of the brushed treatment, 100% of the aspen was harvested in year 15 (e.g. 1985) and regenerated at 5000 stems per hectare the following year. In the case of the alternate brushed treatment, 60% of the aspen stems were thinned with removed stems distributed evenly across all size classes. Since FORECAST has an aspatial representation of tree distribution, the model assumes that the thinned trees are removed evenly and uniformly from the stand. While this is not a ‘true’ representation of reality, it was assumed that the removal strips were narrow enough (5 m) that the spruce would behave as if the residual aspen were distributed evenly throughout the treated area, particularly as the residual aspen matured and crown expansion occurred. It was assumed that there was some regeneration of aspen (2500 stems per hectare) following the thinning treatment. This regeneration was treated as a new aspen cohort in the model and modelled separately from the residual aspen. The control scenario had no management interventions following the initial planting of spruce. Each treatment scenario was simulated for 100 years.

2.4.2 Douglas-fir-birch mixedwoods

Using the initial condition described in Section 2.3 as a starting point, FORECAST was run to represent both the treated and control scenarios for each PROBE site.

PROBE 1

Prior to planting and immediately following the clearcut harvest, a slash burn (using burn piles) was simulated in 1983 (as part of the final set-up run described in Section 2.3.1). 1-year-old Douglas-fir seedlings were subsequently planted in year 1 (1984) at 1400 stems per hectare. Birch regenerated at 7500 stems per hectare and a Rubus parviflorus shrub was established (5% cover) in year 2 (1985). In the brushed scenario, birch was harvested in year 8 (1991) and assumed to regenerate at 4000 stems per hectare in year 10 (1993, based on descriptions from Simard et al. 2001). No treatments were simulated in the control scenario after planting.

PROBE 2

Since there was a 3 year delay between the harvest in 1976 and planting in 1979, brich was assumed to regenerate in 1978 at 7500 stems per hectare in the control site and 5000 stems per hectare in the brushed site (as part of the final set-up run described in
Section 2.3.1). Birch density was reduced in the brushed plot to account for the fact that the Douglas-fir in this plot were slightly larger than those in the control site at the time of the initial treatment (1991). For the simulations, 2-year-old Douglas-fir seedlings were planted in year 1 (1979) and a *Rubus parviflorus* shrub was also established in year 1 (5% cover). In the brushed scenario, birch was harvested in year 13 (1991) and assumed to regenerate at 4000 stems per hectare in year 15 (1993, based on descriptions from Simard et al. 2001). No treatments were simulated in the control scenario after planting.

3. Results and Discussion

3.1 Derived Tree Attributes
The relative light response curves entered for each species as part of the calibration data (not derived by the model) are shown in Figure 3A. These curves were generated from a combination of light response studies and general knowledge about the shade tolerance levels of each species. As the curves illustrate, the most shade tolerant species was spruce followed by Douglas-fir, aspen and birch. Output from the calibration runs showing model-derived rates for a number of key ecosystem processes represented in FORECAST is shown for all species for the medium site quality (from both datasets) in Figure 3B-G. Model output indicates that birch and aspen require significantly greater levels of nitrogen (N) uptake during the first 50 years of growth relative to the conifers (Fig 3B). This result is consistent with the higher rates of early growth in deciduous relative to coniferous stands in interior BC. Spruce showed the lowest demand for N uptake, resulting from its relatively slow rate of growth (in young stands) and longer periods of needle retention relative to Douglas-fir. In terms of foliar N content, spruce achieved the highest level of foliage N content followed by Douglas-fir (Fig 3C). Again, the deciduous species had the highest foliar N contents in young stands. As expected, rates of total tree production per hectare were consistent with patterns in foliar N content (Fig 3D). The maximum rate of production was similar among all species but the deciduous species achieved the maximum rate at a much younger age. An examination of foliar N efficiency (Fig. 3E) shows that the deciduous species were most efficient followed by Douglas-fir and spruce. The fact that deciduous trees always have young vigorous leaves (turning over each year) allows for a high rate of production per unit foliage.
Figure 3. A) Photosynthetic rate under varying levels of light (specified by the user). Also shown are species-specific tree attributes derived within the model during the calibration run including: B) annual N uptake, C) foliar N content, D) total tree production, E) foliar N efficiency (production per unit foliage N), F) nutrient use efficiency (production per unit N uptake), and G) proportion of total tree production allocated below ground.
Another way to examine nutrient use efficiency is to divide total annual N uptake by total annual production. In this analysis spruce was the most efficient followed by aspen, birch and Douglas-fir (Fig. 3F). Since the production levels of each species were similar, these results were largely driven by the N uptake requirements (Fig. 3B). The relatively low uptake of spruce, translated in higher N use efficiencies. As discussed above, one of the reasons spruce is able to keep it uptake demands lower is that it holds its foliage for longer periods of time (8 yrs) relative to Douglas-fir (5 yrs) in the model. This means it has to replace less foliage each year and less foliage N compared to Douglas-fir. Somewhat surprisingly, Douglas-fir had the lowest N use efficiency as estimated by the model. This results from the combination of relatively high N uptake demands and medium levels of total production (less than the deciduous in early stand development and less than spruce in later stand development).

In terms of the relative allocation of total production to below ground biomass components, the species clearly separated into coniferous and deciduous groups. Greater total production of fine roots in the conifers was the main reason for the difference Although, the deciduous species had slightly higher turnover rates of fine roots, the greater overall size of the root biomass pools in the conifers led to higher levels of total production allocated to below ground biomass. These results are consistent with the findings of a recent review of root production (Li et al. 2003).

### 3.2 Evaluation of Model Performance

All evaluations of model performance presented here are based on graphical interpretations of model output relative to field observations. While this type of analysis is qualitative in nature, it provides the reader with a reasonable and accessible assessment of model performance. Additional, statistical analyses may be conducted prior to publication of results.

#### 3.2.1 Spruce- aspen mixedwood

Model projections of average top height for all stems and for the top 200 spruce stems were quite close to field observations for both species and all treatments (Fig. 4). A comparison of modelled versus measured DBH is shown in Figure 5. Model output is not provided for trees younger than 20 years age because the diameter equations used in the model to estimate the DBH of individual stems from modelled individual stem biomass are derived from trees > 15 years old and are thus unsuitable for very young
trees. In general the model tended to slightly over-predict DBH relative to the field measurements. This is partly related to the fact that the smaller trees in the modelled distribution are still smaller than the equation (with a positive y-intercept) can accommodate which in turn leads to an overestimate of mean DBH.

Comparisons of stand-level summaries of total volume and stem biomass are perhaps the best indicators of overall model performance as they represent an accounting of total production for both measured and simulated trees in the stand. As illustrated in Figures 6 & 7, the model performed well in projecting patterns of stem production for both spruce and aspen in both treatments and the control. Based upon these results and those for average tree size, the fact that the model represented the alternate brushing treatment as a uniform, dispersed retention harvest (rather than strip cuts) did not appear to lead to significant errors in projection. It was also encouraging that the model seemed to capture the essence of the competition between the spruce and aspen for available light and nutrient resources. Furthermore, the results presented here suggest that it also performed well in terms of representing the impact of the two treatments on these competitive interactions.

Figure 4. Measured versus modelled average top height by species for each treatment and the control.
Figure 5. Measured versus modelled average DBH by species for each treatment and the control.

Figure 6. Measured versus modelled stem volume by species for each treatment and the control.
To examine the potential long-term consequences of these treatments on the dynamics of spruce and aspen growth in this mixedwood type, model results were projected out to 100 years. Figure 8 shows the simulated treatment effects on spruce volume (panel A), mean annual increment (MAI) of spruce volume (panel B), aspen volume (panel C), and total stand volume (panel D). Two interesting results are evident from this analysis. First, the impact of the treatments on spruce growth rates was subtle for more than a decade following the treatment but was substantial over time (Fig. 8 A-B). Impacts on aspen volume happened quickly and were more dramatic (Figure 8C). This result illustrates the importance of long-term trials and modelling for the evaluation of alternative silviculture systems. Second, the impact of the treatments on total stand volume was subtle (Fig. 8 D) with the control stand producing slightly more volume than the treated stands at rotation age (~75 years). However, the aspen content of the total stand volume changed significantly with the different treatments. Thus, managers evaluating these options based on model output may make different decisions depending upon which species was favoured for specific resource values.
Figure 8. Simulation results for a 100-year time period show A) total Sw Volume, B) Sw mean annual increment (MAI), C) total At volume, and D) total volume for all species for the two treatments and the control site. The treatment occurred in year 15.

3.2.2 Douglas-fir birch mixedwood

The evaluations of model performance with respect to the PROBE studies described in Section 2.2.2 were somewhat limited relative to those for the spruce-aspen mixedwood due to the fact the length of the study period was shorter for the PROBE study (10 years) relative to 17 years post treatment. In addition, the plot design in the PROBE study made it impossible to calculate stand-level (per hectare) summaries of total production. Lastly, the fact that the PROBE stands were quite young at the time of treatment posed some difficulties for model application and long-term evaluation of growth response in terms of mixedwood dynamics. The two variables available for model evaluation were average top height and average stem biomass. Average DBH,
while available from the field measurements, was not useful for model evaluation because the trees were too young and small for the model to produce estimates of DBH (see Section 3.2.1).

A comparison of projected mean top height to measured values indicated that the model was able to predict the impact of the birch removal on the increase in height growth in Douglas-fir with reasonable accuracy. The model appeared to under-predict height growth response slightly in both sites but more clearly in the younger PROBE 1 site. One reason for the under prediction may be the fact that the model does not account for soil moisture competition between the Douglas-fir and birch. Younger Douglas-fir seedlings with less developed root systems would likely be more vulnerable to this competition.

An examination of projected versus measured mean stem biomass also shows the capability of the model to represent the treatment effects on Douglas-fir growth rates. Again the model tended to under-predict growth response relative to field measured values, likely for the same reason described above. Also evident from the comparisons was that fact that the model appears to have a short lag in treatment response time relative to the field measurements. Although FORECAST can represent shifts in carbon allocation (e.g. more carbon allocated to foliage production) when light environments improve, there is a delay in response that is an artefact of the growth algorithm which requires foliage to grow more foliage (see Figure 1). In reality, trees can reallocate carbon from internal pools to new foliage growth to facilitate a quick response to increases resource availability (e.g. light). Despite, the lag in response, experience with the model from other evaluations suggests that it usually catches up over a 10-20 year period in terms of growth response following treatments that require shifts in foliage allocation (e.g. Blanco et al., in review).
3.3 Role of FORECAST as a Decision-Support Tool

The maintenance of a healthy forestry sector in British Columbia depends both on our ability to build public trust in our capabilities as good stewards of forest resources and to preserve and increase access to international markets. The forest resource industry in BC has made progress in these areas by adopting an ecosystem-based management strategy and by pursuing certification. To support these efforts it is essential that we continue to develop appropriate and scientifically credible decision support tools and systems. As management practices shift increasingly towards the management of complex stand types (to maximize non-timber values and ecosystem health) it is critical
that we develop a range of models with the capability to project the short and long-term impacts of alternative stand management systems on both timber and non-timber values. Given our general lack of field experience with many of the silvicultural systems employed under ecosystem-based management and the uncertainty associated with natural disturbance agents and changing climate, models which incorporate some level of causality and/or understanding through the representation of key ecological processes are generally better suited for this purpose than models driven predominantly by empirical relationships (Korzuhkin et al., 1996; Johnsen et al., 2001).

The results described in Sections 3.1 and 3.2 above provide evidence that FORECAST can project the growth of mixedwood stands and their response to management interventions with reasonable accuracy. While more validation work needs to be conducted in a range of different mixedwood forest types and management interventions (as datasets become available), the analysis described herein provides a level of confidence for the use of the model as a decision-support tool in these ecosystem types. In addition, the ability of FORECAST to provide output for a range of non-timber values as well as standard growth and yield output makes it a valuable tool for examining alternative management scenarios in the context of developing sustainable forest management plans. The model is currently under development to add a moisture balance model to allow it to include an explicit representation of soil moisture competition among tree species and between trees and understory vegetation.

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5. Literature Cited

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