ABSTRACT

A linked-modelling approach, using PrognosisBC and SORTIE-ND, was tested for predicting natural regeneration and forecasting future stand conditions in mountain pine beetle (Dendroctonus ponderosae Hopkins - MPB) attacked stands using data collected from the Interior Douglas Fir (IDF), Sub-Boreal Pine Spruce (SBPS), Sub-Boreal Spruce (SBS) and Montane Spruce (MS) biogeoclimatic zones of central and southeastern British Columbia. PrognosisBC is a growth model calibrated for use in complex stands and is capable of providing accurate estimates of small and large tree growth when used over projection periods of less than 50 years. The lack of an effective sub-model capable of predicting the abundance and species composition of natural regeneration for MPB-attacked stands is a major limitation of PrognosisBC. Obtaining regeneration estimates from the light mediated growth model SORTIE-ND, was identified as a possible alternative to the Most Similar Neighbor regeneration imputation techniques used by PrognosisBC. A method to link estimated tree-lists for trees less than 7.5 cm dbh from SORTIE-ND to PrognosisBC was developed. Using a 25-year projection period, the timing of the tree-list hand-off from SORTIE to Prognosis was tested at five and ten years post-MPB attack and compared to simulations using PrognosisBC only and SORTIE-ND only for the entire projection period. For spruce and aspen trees less than 7.5 cm dbh, the 10 year hand-off simulation provided the best estimate of trees per hectare when compared to actual observations. For lodgepole pine trees less than 7.5 cm dbh, the 5 year hand-off simulation provided the best results. Although use of the linked-model approach provided slight improvements over using PrognosisBC only or SORTIE-ND only, overall results were generally poor. In particular, densities of lodgepole pine were largely underestimated for smaller trees. Further testing using an extensive dataset and further parameterization of the SORTIE-ND model is likely required if improvements are to be seen.

KEYWORDS: natural regeneration, individual tree growth model, PrognosisBC and SORTIE-ND, mountain pine beetle.

INTRODUCTION

Accurate growth and yield estimates are an important component in the development and implementation of sustainable forest management practices (Boisvenue et al. 2004). Mid- to long-term timber supply estimates rely heavily on growth and yield models (Hyytiainen et al. 2006). In the absence of reliable growth estimates, current allowable annual cut volumes could be inadvertently set too high or too low (Pedersen 2003). In complex forest systems, where multi-species and multi-cohort stands form a mosaic pattern across the landscape, model projections of...
growth and yield for periods greater than 50 years can become increasingly unreliable (Zumrawi et al. 2005a). This may, in large part, be attributed to the high variability in stand structure and species composition, which is a result of frequent small scale gap disturbances and less frequent but more extensive disturbances such as fires and insect outbreaks (Oliver and Larson 1996). Added to the mix are the various silvicultural practices (e.g., partial cutting and variable retention) that are currently being employed in these complex stands. Given these conditions, few, if any growth and yield models have been able to excel in both managed and unmanaged stands (Robinson and Monserud 2001). Finding the best management strategies for complex stands continues to be an evolving process (Coates et al. 2004).

Given this complexity, it is not surprising that the province of British Columbia (BC) currently supports eight growth and yield models. This allows foresters to match their specific requirements to an appropriate growth model. One such growth model that is currently being used in complex stands of central and southeastern BC is PrognosisBC (Snowdon 1997, Zumrawi et al. 2002, Hassani et al. 2004). Adapted from the U.S. Forest Service Forest Vegetation Simulator (FVS) that was originally developed by Stage (1973), PrognosisBC is best suited for projecting existing stands and can simulate a wide range of silvicultural treatments. Although the small tree and large tree growth components of PrognosisBC were calibrated to the Interior Douglas Fir (IDF) and Interior Cedar Hemlock (ICH) biogeoclimatic zones, efforts to calibrate the regeneration sub-model did not fare well (Boisvenue 1999, Zumrawi et al. 2005a). Nevertheless, PrognosisBC has been able to provide reliable landscape-level estimates of growth for projection periods of 50 years or less; a result of the many permanent sample plots (PSP) that were used to calibrate the model.

In place of the regeneration sub-model, model users currently have two options: 1) specify the amount and composition of natural and/or planted regeneration, or 2) use the most similar neighbour (MSN) regeneration sub-component. The former option limits the use of PrognosisBC to short-term projections unless new regeneration lists are added at the end of each growth cycle. The latter approach was designed to impute natural regeneration by predicting several regeneration variables at once (Hassani et al. 2004). To be successful, the MSN approach requires a large amount of data collected from stands with natural regeneration and which have developed under a wide range of ecological conditions (LeMay et al. 2006). Its ability to accurately predict regeneration in under-represented ecological conditions is therefore limited (Moeur and Stage 1995, Hassani et al. 2004). The prevailing ecological conditions in lodgepole pine dominated stands, which have been (and are being) created in BC’s interior the wake of the current outbreak of mountain pine beetle (Dendroctonus ponderosae Hopkins - MPB) is one example where the applicability of the MSN approach is currently limited. The immense magnitude of the current outbreak has created ecological conditions that, until now, were less common and therefore under-represented in most PSP datasets (Hawkes et al. 2004).

Our search for an alternative means of estimating natural regeneration post-MPB attack lead us to an existing forest simulation model, SORTIE-ND (Kobe and Coates 1997). This model is an adaptation of the original SORTIE model (Pacala et al. 1993) developed for use in the deciduous forests of northeastern United States (Canham and Burbank 1994). The current SORTIE-ND model (Version 6.07) has been calibrated for use in BC’s ICH and Sub-boreal Spruce (SBS) forests using long-term PSP data (Kobe and Coates 1997; Astrup et al. 2007). More recently, efforts to calibrate SORTIE-ND using data from managed stands have made it useful for application in silvicultural planning (Coates et al. 2004). However, our use of SORTIE-ND for this study is motivated by the need for a method to accurately estimate a tree-list comprised of new seedling recruits and advanced regeneration that can be transferred into PrognosisBC.

In our search for alternative methods we had two main criteria, namely that the method be able to predict multiple dependent variables and be feasible given the plot data available and the data requirements of PrognosisBC. SORTIE-ND satisfied both of these conditions (LeMay et al. 2006). A method was then developed to link regeneration estimates from SORTIE-ND to PrognosisBC. It was envisaged that using these two models as a linked set would allow us to take advantage of the strengths of each model. In the case of SORTIE-ND, the advantage was related to the model’s
flexibility and the ability to adjust model parameters related to regeneration establishment, while in the case of Prognosis we could make use of the well developed, empirically-based small and large tree growth models.

In this paper, we describe the model flow of the linked-model approach and present the results of an initial test using tree measurements collected from stands that experienced a MPB attack roughly 25 years ago.

METHODS

Study Area
Potential stands for sampling were selected from an area which had been attacked by MPB between the late 1970s to the late 1990s, within approximately 200 km of Williams Lake, BC. Many of the sampled stands were located on the Fraser Plateau, within the former Cariboo Forest Region. This area has gentle slopes and an elevation between 900 and 1500 m. There are four major biogeoclimatic ecosystem classification zones in this area: Sub-Boreal Pine-Spruce (SBPS), Sub-Boreal Spruce (SBS), Interior Douglas-fir (IDF), and Mountain Spruce (MS).

Plots were mainly located in stands dominated by lodgepole pine (Pinus contorta Dougl. ex Loud. var. latifolia Engelm). Overall, species composition in selected stands included lodgepole pine (about 80%), Douglas-fir (7%) (Pseudotsuga menziesii var. glauca (Beissn.) Franco), and hybrid spruce (5%) (Picea engelmannii x glauca (Moench) Voss). Trembling aspen (Populus tremuloides Michx.) and subalpine-fir (Abies lasiocarpa (Hook.) Nutt.) were present, but in small numbers overall.

Historically, outbreaks of MPB have been common within the study area and have served to shape the forested landscape (Aukema et al. 2006). In the absence of stand-replacing fires, regional outbreaks of MPB have served to create gaps in the forest canopy. Depending on stocking levels and the composition of the understory, previous MPB attacks have resulted in either the release of an existing understory or the recruitment of new seedlings (Campbell et al. 2007). In either situation, such events resulted in the creation of uneven-aged, mixed-species stands (Hawkes et al. 2004).

Field Sampling and Data Collection
Candidate stands for sampling were selected following reconnaissance of stands selected from forest inventory maps and anecdotal information provided by local foresters and researchers. Two to six plots were established in each selected stand, depending on the size. Systematic sampling with a random start was used. The distance between each plot centre ranged between 50 m and 150 m, with a minimum distance of 50 m from a road or any other significant opening. The plot edges were at least 20 m from any logging area or skid trails.

A total of 175 plots from 55 stands were sampled. Each plot consisted of seven circular sub-plots: one for large trees (11.28 m radius), another for small trees (5.64 m radius), and five for regeneration (2.07 m radius). In the large tree plot (overstory trees), all trees ≥ 7.5 cm diameter at breast height (dbh) were measured. Each dead standing or downed tree was assigned a decay class based on a nine class scale created by combining class one to four from the wildlife tree classification (Backhouse and Lousier 1991) and class five to nine from the coarse woody debris classification for downed trees (Stevens 1997). Height to live crown (m) was measured for all live trees. Species, dbh (cm), and height (m) of each standing tree, live or dead, were recorded. For downed trees in decay class seven or greater, species, dbh, and height were recorded. For trees with broken tops, the height to the broken top (m) was measured, and the total height of the tree was estimated. Crown width was measured along two axes at right angles for two trees selected randomly for each species. In the small tree plot, all trees from 2.0 cm to < 7.5 cm dbh were included and species, dbh, status (live or dead), visual estimate of live crown ratio (live only), and height was recorded for each tree. In the regeneration subplots, the number of live seedlings less than 2.0 cm dbh and over 15 cm in height were recorded by species into four height classes: 1) >0.15 to ≤ 0.50 m; 2) >0.50 to ≤1.0 m; 3) >1.0 to ≤1.5 m; and 4) >1.5 m.
m in height and < 2.0 cm dbh.

Data Preparation

The overstory conditions at each plot shortly after time of attack were reconstructed using the measures of live and dead trees in the large tree plot. Two time of MPB-attack cohorts were present in the data collected: (1) attack approximately 25 years ago; and (2) attack approximately eight years ago. Each live tree was grown back in time by subtracting estimated 10-year diameter growth (DG), using functions previously fitted by Zumrawi et al. (2005b). For plots that were 25 years post-MPB attack, this process was repeated for three intervals, with the third period prorated at half of the estimated growth rate. Since measures of competition are used in the DG functions, these were summarized for each 10-year interval and used in estimating the DG. For plots that were eight years post-MPB attack, the 10-year DG was prorated for eight years. Once dbh shortly after the attack was estimated for each live tree, heights were estimated from dbh using existing regression equations developed in the process of calibrating PrognosisBC. These were localized for each tree by multiplying by the ratio of measured height to estimated height for the 2006 measures. For standing dead or fallen trees, the decay class was used to decide whether the tree was live or dead shortly after attack. For all trees that were alive at some point after the MPB attack, the crown ratio was estimated using crown ratio functions developed for this area. Ten-year DG was then estimated using the estimated crown ratio. The same process was followed for trees that were alive at the time of sampling. Following these approaches, an estimated tree-list of all live and dead trees greater than or equal to 7.5 cm dbh was obtained for each plot shortly after attack, and coupled with the regeneration (less than 7.5 cm dbh) measured in 2006, eight or 25 years following MPB attack.

Linked Model Approach

The process of linking SORTIE-ND and PrognosisBC began by importing tree-lists representing individual stands into each model. The tree-lists imported into the models were from the reconstructed dataset and thus represented stand conditions for the years immediately following MPB attack. Since each model has its own data input specifications, some additional data preparation was required. In the case of SORTIE-ND, for example, imported tree-lists must contain spatial coordinates for each tree. As this type of information was not collected during field sampling, a random number generator algorithm was used to assign coordinates to each tree within a simulated 9 ha plot. Additionally, SORTIE-ND requires the user to provide parameter estimates for the specific model behaviours that have been selected. For this study, we used the collected data to obtain parameter estimates for allometric relationships, including height-diameter relationships and crown dimension relationships. Parameter estimates were also obtained for the SORTIE-ND snag fall-down model, which is used to define the rate at which dead standing trees become downed trees. Lastly, the fraction of the forest floor occupied by different substrates was defined. All other parameters within SORTIE-ND, including light and growth parameters, were obtained from Astrup et al. (2007). PrognosisBC did not require any parameterization as it has been calibrated to the study area using permanent sample plots.

For the analyses presented in this report, we restricted our list of potential stands to those stands that were attacked 25 years ago. Thus, the total length of each model projection period was 25 years. Once loaded, the stand-level tree-lists were projected forward in time in each model. For SORTIE-ND, each growth cycle was defined as a single year, while in PrognosisBC, the initial growth cycle was five years with subsequent cycles operating on a ten year basis. The transfer of tree-list projections from SORTIE-ND to PrognosisBC was restricted to five years and ten years following MPB attack, referred to as the five year hand-off simulation and ten year hand-off simulation. For the five year hand-off simulation, a list of trees < 7.5 cm dbh was obtained from SORTIE at the end of the fifth growth cycle. Since this list represented the number of trees over a simulated 9 ha plot, a value of 0.11 stems per hectare was given to each tree in this list so that it would be compatible with the tree-list requirements of PrognosisBC. Trees selected from SORTIE-ND were appended to the tree-list from PrognosisBC following the initial five year growth cycle, replacing any trees < 7.5 cm dbh that were in the PrognosisBC tree-list but retaining all trees > 7.5 cm dbh. The new composite tree-list was then projected forward for 20 years using PrognosisBC. A similar approach was used for the ten year hand-off simulation, except that tree-lists following the tenth growth cycle were joined and projected forward in PrognosisBC for 15 years.
The results of the five and ten year hand-off simulations were compared to actual values as well as estimated values obtained by using Prognosisbc and SORTIE-ND separately over the 25 year projection period. To evaluate the four model simulations, we compared the estimated number of trees per hectare (tph) across the six stands that were tested. Bias, defined here as predicted minus observed, was calculated by species group (Pine, Spruce-Aspen) and by dbh size class. Two individual stands, one a low density stand (425 tph) at the time of MPB attack and one a high density stand (1184 tph), were examined to gauge the effectiveness of the models under different stand densities.

RESULTS

Plot data were summarized to provide initial stand conditions following reconstruction (1981 data), as well as observed 2006 conditions (Table 1). All stands, with the exception of stand 25, had at least a minor component of spruce and/or aspen in the understory. All stands were dominated by lodgepole pine in the overstory. Understory densities at the time immediately following attack ranged from 92 tph to 183 tph, while overstory densities ranged from 267 tph to 883 tph. Compared with recorded observations from 2006, all stands with the exception of stand 18, showed an increase in the total tph following MPB attack. Understory densities in 2006 ranged from 433 tph to 2234 tph, while overstory densities ranged from 375 tph to 609 tph.

< Table 1—Reconstructed (1981) and recorded (2006) stand level densities by species group and dbh size class for the six tested stands

<table>
<thead>
<tr>
<th>Year</th>
<th>Stand</th>
<th>No. of plots</th>
<th>Pine &lt; 7.5cm dbh</th>
<th>Pine &gt; 7.5cm dbh</th>
<th>Spruce and Aspen &lt; 7.5cm dbh</th>
<th>Spruce and Aspen &gt; 7.5cm dbh</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>4</td>
<td>3</td>
<td>58 (tph)</td>
<td>308 (tph)</td>
<td>100 (tph)</td>
<td>83 (tph)</td>
<td>550</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>3</td>
<td>150 (tph)</td>
<td>242 (tph)</td>
<td>8 (tph)</td>
<td>25 (tph)</td>
<td>425</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>3</td>
<td>50 (tph)</td>
<td>742 (tph)</td>
<td>150 (tph)</td>
<td>141 (tph)</td>
<td>1084</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>3</td>
<td>91 (tph)</td>
<td>384 (tph)</td>
<td>92 (tph)</td>
<td>167 (tph)</td>
<td>734</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
<td>167 (tph)</td>
<td>350 (tph)</td>
<td>0 (tph)</td>
<td>83 (tph)</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>3</td>
<td>67 (tph)</td>
<td>751 (tph)</td>
<td>25 (tph)</td>
<td>42 (tph)</td>
<td>884</td>
</tr>
<tr>
<td>2006</td>
<td>4</td>
<td>3</td>
<td>567 (tph)</td>
<td>225 (tph)</td>
<td>467 (tph)</td>
<td>158 (tph)</td>
<td>1416</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>3</td>
<td>2167 (tph)</td>
<td>284 (tph)</td>
<td>67 (tph)</td>
<td>33 (tph)</td>
<td>2550</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>3</td>
<td>233 (tph)</td>
<td>317 (tph)</td>
<td>233 (tph)</td>
<td>292 (tph)</td>
<td>1075</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>3</td>
<td>1800 (tph)</td>
<td>183 (tph)</td>
<td>433 (tph)</td>
<td>259 (tph)</td>
<td>2675</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>3</td>
<td>750 (tph)</td>
<td>317 (tph)</td>
<td>0 (tph)</td>
<td>58 (tph)</td>
<td>1125</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>3</td>
<td>400 (tph)</td>
<td>409 (tph)</td>
<td>100 (tph)</td>
<td>58 (tph)</td>
<td>967</td>
</tr>
</tbody>
</table>

Bias values related to tph across all six stands were much larger for lodgepole pine than for spruce-aspen. The density of lodgepole pine less than 7.5 cm dbh was underestimated in all four simulations, with the 2.5 to 5.0 cm dbh class showing the poorest results for all simulations (Figure 1). For lodgepole pine trees with a dbh greater than 7.5 cm, the 10 year hand-off simulation had the best results, although all four simulations had similar results and provided reasonably good estimates of tph. Overall, estimates of tph for spruce and aspen were much lower than actual values (Figure 2). Estimates for the spruce-aspen species group were poorest in the 2.5 to 5.0 cm dbh class, with densities being under estimated by as much as 850 tph in the 10 year hand-off simulation. The lone exception was in the simulation that used SORTIE-ND for the entire 25 year projection period. Here, the 7.5 to 15 cm dbh class had the
poorest results, under-estimating densities by 870 tph. The best approximation of stand-level densities for spruce and aspen trees larger than 7.5 cm dbh was provided by the simulation that used Prognosis™ only.

< Figure 1—Average biases (predicted - observed) of estimating the number of trees per ha of lodgepole pine across all dbh classes for the four different simulations following a 25 year projection. >
In order to gain some insight into how each simulation performed given a different stand density immediately following MPB attack, we compared the results of two stands. The first stand we looked at had a total density of 425 tph in 1981, while the second stand had a density of 1184 tph in 1981. The stand with a low density in 1981 showed poor results for all tree species less than 7.5 cm dbh in both of the hand-off simulations (Figure 3). This is not surprising given the tendency for all simulations to drastically underestimate densities of small trees and the fact that this stand turned out to have one of the highest densities of small trees 25 years after MPB attack. For the stand with a high density in 1981, the 10 year hand-off simulation provided the best estimate of tph for trees less than 7.5 cm dbh (Figure 3). In fact, this simulation actually overestimated tree densities in the 0 to 2.5 cm dbh class. However, it is important to note that actual small tree densities recorded in 2006 were low relative to the other six stands, although stand densities were high in 1981. It appears that the general tendency of the four simulations was to dramatically underestimate tph; however, the magnitude of this discrepancy may be lower in stands where low tph values for trees less than 7.5 cm dbh were recorded in 2006.
DISCUSSION

Both the 5-year hand-off and 10-year hand-off simulations for stands following MPB attack produced minor improvements in density projections for trees less than 7.5 cm dbh over the simulation that used PrognosisBC or SORTIE-ND only. The most noticeable improvement, although still minor, was in the 10-year hand-off simulation when estimating densities for spruce and aspen. This may be due in part to low densities of spruce and aspen trees less than 7.5 cm dbh relative to the densities of small lodgepole pine trees. Testing the simulations on stands where the densities of small spruce and aspen trees are on the same order as lodgepole pine might reveal different results among the different simulations. The tendency for all simulations to underestimate densities of large spruce and aspen trees, although not as pronounced as was the case with smaller trees, was somewhat discouraging. Likewise, the tendency for all simulations to overestimate overstory densities of lodgepole pine seems to indicate that conditions in MPB affected stands may have been under-represented in the PSPs used in the calibration of PrognosisBC and SORTIE-ND.

Poor estimates of stand densities following MPB attack for trees less than 7.5 cm dbh for the two simulations that used the linked-model approach and the simulation that used SORTIE-ND only may be indicative of several factors. First, the results presented here are based on results obtained from only six stands. These stands were chosen for the initial tests of the linked-model approach as they were representative of the diverse range of stand conditions observed during sampling. However, increasing the number of stands tested may improve the overall results of the hand-off simulations. The results obtained from the low density stand and the high density stand would suggest that averaging
the results over more stands may reduce the biases of estimating densities.

Second, while the data collected in 2006 was used to provide parameter estimates for allometric relationships, substrate composition and snag fall down rates in SORTIE-ND, other parameters used by the model may not reflect the exact conditions of the stands used in the simulations. For example, the growth parameters provided to SORTIE from Astrup et al. (2007) were for the SBS biogeoclimatic ecological classification zone. Although some of our plots were collected within this zone, the majority of our plots were collected from the SBPS and IDF zones where annual rainfall levels are considerably lower and tree growth is generally slower (Mah and Nigh 2003). Using growth parameters that overestimate tree growth can cause SORTIE-ND to increase competition induced mortality rates, thus killing off more understory trees than would be expected. Since measurements collected for this study do not allow us to directly estimate many of the parameters used by SORTIE-ND, additional data may be required to improve the overall performance of SORTIE-ND.

Lastly, it is possible that the poor results obtained from the simulations are in large part due to the high variability of regeneration densities following MPB attack. This condition is cited as a likely culprit for the poor results obtained when using the MSN approach to estimate natural regeneration following partial cutting (Hassani et al. 2004). Since one of the sampling objectives was to collect data from a wide range of stand types affected by MPB, increasing the number stands used in the simulations may improve the results since there would be a better representation of the variability in overstory and understory densities.

CONCLUSION

In addition to an overstory tree-list, PrognosisBC requires the input of a natural regeneration tree-list to provide accurate mid- to long-term estimates of growth and yield in unmanaged complex stands. Our goal in linking regeneration tree-lists estimated by SORTIE-ND to PrognosisBC was to improve upon the MSN approach of estimating natural regeneration following MPB attack. Relative to the MSN approach, using SORTIE-ND to estimate natural regeneration, including species composition and density, allows for greater flexibility since the SORTIE-ND model parameters can be easily adjusted to fit a specific dataset. This method is potentially advantageous when estimates of natural regeneration are required for stands that are unusual or under-represented, as is the case for stands affected by MPB in central and southeastern BC.

Between the two different hand-off times studied, the hand-off of the SORTIE-ND regeneration tree list to PrognosisBC after 10 years showed the best results for small spruce and aspen trees when compared to the results obtained when using SORTIE-ND or PrognosisBC alone. Only marginal improvements in the estimates of small lodgepole pine were noted for both the five year hand-off and the 10 year hand-off simulations. The overall poor results obtained by using the linked-model approach would likely be improved with further parameterization of SORTIE-ND behaviours. Also, using a more extensive dataset with measurements collected from a larger number of stands should bring the estimates of small tree densities closer in-line with actual observations.

LITERATURE CITED


