Implementing a Prognosis^{BC} Regeneration Sub-model
for Complex Stands of Southeastern and Central British Columbia

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A collaborative research project between

Research Branch, Ministry of Forests,

Forest Resources Management Department

University of British Columbia, and ESSA Technologies, Inc.

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Project Overview

The specific objectives of this project were to:

(i) assess the predictions of Prognosis^{BC} natural regeneration model against the Mountain Pine Beetle (MPB) data,

(ii) study the effect of varying degrees of partial cutting on long-term model results, and;

(iii) further develop and enhance the natural regeneration model software including any database design changes and updates.

There are two separate reports in this document. The first report presents the research associated with objectives (i) and (ii) and is titled "Implementing a Prognosis^{BC} Regeneration Sub-model for Complex Stands of Southeastern and Central British Columbia: Use in MPB-Affected Stands and Results of Long-Term Projections in Partially Cut Stands". The second report titled "A Regeneration Model for Prognosis^{BC}" provides details of the work associated with objective (iii).

The natural regeneration model and data described in these reports constitute an integral part of the Prognosis^{BC} growth and yield simulator and will be made available through the growth and yield website of the Ministry of Forests. Research results will also be made available through the Prognosis^{BC} website at the University of British Columbia.

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Implementing a Prognosis^{BC} Regeneration Sub-model for Complex Stands of Southeastern and Central British Columbia: Use in MPB-Affected Stands and Results of Long-Term Projections in Partially Cut Stands

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ABSTRACT

Forests in the southeastern and central British Columbia originated via a variety of natural and managed disturbances and are diverse in species, sizes, and ages (complex). In many stands, partial cutting has been used to mimic natural small-scale disturbance to preserve species and structural complexities. In recent years, lodgepole pine (*Pinus contorta* var *latifolia* Dougl.) stands of Interior Douglas-fir (IDF), Montane Spruce (MS), and Sub-Boreal-Pine-Spruce (SBPS) biogeoclimatic ecological (BEC) zones have been affected by an unprecedented catastrophic mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopk) outbreak. While both partial harvesting and beetle-caused mortality cause changes in the growing space, alter stand structures, and create more favourable light conditions for natural regeneration, these two types of disturbances influence forest dynamics, including regeneration, differently. The dynamics of regeneration following MPB disturbance is governed not only by the rate of mortality, but also by snag dynamics.

The primary objective of this research program is to complete the implementation of a Prognosis^{BC} natural regeneration sub-model for partially harvested complex stands and beetle affected stands found in the central and southeastern of BC. The specific objectives for this particular project were to assess the predictions of the Prognosis^{BC} natural regeneration model against natural regeneration data from Mountain Pine Beetle (MPB) affected stands, and to study the effect of varying degrees of partial cutting on long-term regeneration model predictions

For the first objective, data collected in 2001 from 20 stands affected by the mountain pine beetle, along with the Prognosis^{BC} regeneration database data collected over a period of five years in partially harvested stands in the interior of BC were used. The MPB-affected stand data were from three BEC zones (IDF, MS and SBS) and included snag information. Site data such as aspect, site series, and slope were available only at the stand level. The Most Similar Neighbour (MSN) estimation approach was used to predict natural regeneration by four height classes and three species groups for the MPB-affected stands using the Prognosis^{BC} regeneration sub-model and 1) reference data from the MPB-affected stands only, 2) the Prognosis^{BC} regenerated stands database, and 3) the combination of these two datasets. The Prognosis^{BC} regenerated stands database has a complete set of site information variables collected at the plot level. However, because the MPB-affected stands database lacks site information at the plot level, a reduced set of variables was used to impute natural regeneration to the MPB affected plots. The variables used were elevation, basal area per ha, number of trees per ha, crown competition factor, and quadratic mean diameter. Some of these variables were further stratified by species shade tolerance groups.

Since data for SBPS were available for the MBP-affected stands only, and the data for MS are sparse, imputation was restricted to IDF, prevalent in both databases. For the MPB-affected stands, estimated regeneration using MSN estimation based on the local MPB-affected stands data or those based on the combined data was more accurate than

using the partial harvesting regeneration database alone. The poor performance of the model that used regeneration data from partially harvested stands as a reference could be attributed to differences in stand dynamics following partial harvesting and those associated with MPB disturbances. Natural regeneration is highly related to residual stand variables such as basal area, number of trees per ha, and crown competition factor. The use of imputation methods based on data from partially harvested stands to estimate natural regeneration in MPB-affected stands ignores the effect of snag dynamics on future regeneration and only uses information on residual live trees. The inclusion of other key variables for MPB-affected stands, such as initial and subsequent mortality along with snag dynamics, may further improve predictions. Based on these results for MPB-affected stands in IDF, we recommend that the existing Prognosis^{BC} regeneration model be modified before being added to the MPB stand dynamic component to better estimate regeneration in MPB-affected stands.

With regard to the second objective of this study, we found that the Prognosis^{BC} regeneration model was more sensitive to time since disturbance, stand basal area, and crown competition factor and is less sensitive to the total number of stems per hectare. This was due to the inclusion of ingrowth or advance regeneration in the residual stand estimates in Prognosis^{BC}. The contribution of these small trees to stand basal area and crown competition factor is negligible; however, they inflate the number of residual stems at the plot level and affect the average size of trees in a stand, as measured by the quadratic mean diameter. The use of a larger diameter limit cutoff in computing overstory attributes needs to be considered. Using the imputed regeneration, the effects of varying levels of partial harvesting on long-term model projections mostly followed expected trends. When a stand approached the maximum carrying capacity for the site, the model predicted low amounts regeneration compared to more open stands. Although projections of species composition closely reflected the expected response of the different species to disturbance, species composition based on stems per ha varied greatly over the different cutting intensities. Further examination of these differences is recommended.

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INTRODUCTION

Forests of British Columbia cover 59 million ha, about two-third of the provincial area (BC Ministry of Forests 2003). Mountainous terrain combined with a variety of climates has resulted in diverse forest ecosystems. Forests of southeastern and central British Columbia are often complex (multi-species and multi-cohort). These types of forests are provide esthetic quality and wildlife habitat, protect watersheds, enhance biological and structural diversities, and generate sustainable economical returns. These complex stands have resulted from a variety of natural disturbances (Parminter 1998), particularly fire, insect defoliators, bark beetles, dwarf mistletoe, and root rot. The recent increase in the use of partial cutting as a management practice aims to maintain the structural complexity of stands (J.S. Thrower and Associates 1995). Predictions of all aspects of forests succession and future stands development have become more difficult as stands become even more complex.

The BC Ministry of Forests has adopted the growth and yield model, Prognosis (Stage 1973) as a tool for examining the impacts of forest management and harvesting system on the forests (termed Prognosis^{BC}). Prognosis^{BC} has been calibrated for use in a number of Biogeoclimatic Ecosystem Classification (BEC) subzone variants in southeastern and central BC to forecast future stand conditions based on the expected growth and mortality of individual trees within a stand following partial cutting. Calibrations of large tree and mortality components used permanent sample plot data established in these regions (Robinson 1997; Temesgen and LeMay 2000; Zumrawi *et al.* 2002), while calibration of the regeneration sub-model used temporary sample plots measured for a variety of residual stand types. The initial calibration of the Northern Idaho regeneration model was not satisfactory for use in BC (Boisvenue 1999), and was not implemented. Instead, model users have had to specify the amount and composition of natural regeneration following simulated partial harvesting and thinning. This limited the use of Prognosis^{BC} in making reliable long-term projections under different forest managements and silvicultural regimes. Imputation approaches using the Most Similar Neighbour (MSN) techniques were developed to predict natural regeneration in the Interior Cedar Hemlock (ICH), Interior Douglas-fir (IDF), and Montane Spruce (MS) biogeoclimatic ecological (BEC) zones (Hassani *et al.* 2002; Martin *et al.* 2002; Froese *et al.* 2003; Hassani *et al.* 2004). The MSN approach can be used to predict several regeneration variables at once, while avoiding the burden of meeting distributional assumptions required for other approaches including regression analysis. Furthermore, all data collected from the different BEC zones to calibrate the regeneration and small tree height growth components of Prognosis^{BC} were consolidated in a database (Lencar 2003). This Prognosis^{BC} regeneration database and the MSN imputation software are being linked and will be available for public users of Prognosis^{BC}.

Unlike partial cutting disturbance that selectively removes an individual or a group of trees, epidemic insect and disease attacks could have significant impacts on many trees in a stand. Although the mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopk) is a natural part of the forest ecosystem dynamics in western North America, southeastern and central BC forests have been undergoing an unusually severe mountain pine beetle infestation since 1994 (BC Ministry of Forests 2003; Carroll *et al.* 2003 and 2004). The MPB infests an average of 50,000 ha annually in the endemic stage and 450,000 ha annually during epidemics in BC (Wood and Unger 1996). Even though natural disturbances play important role in maintaining forest health, the current rate of spread and the attack intensity have spectacularly increased and affected 4.2 million hectares solely in the year 2003 (BC Ministry of Forests 2003). About 2.0 million hectares were affected in the previous year. The MPB is considered the largest natural disturbance and is currently the most destructive agent affecting mature pine forests in the south and central of BC (Mitchell 1994; Hawkes *et al.* 2002). The abundance of mature lodgepole pine (*Pinus contorta* var *latifolia* Dougl.) and the relatively warm weather conditions experienced in recent years in interior forests were reported as being the main factors that contributed to the recent MPB epidemic level (2003 and *et al.* 2004; Roth *et al.* 2004).

Because of the economical and ecological importance of lodgepole pine in the interior BC, substantial resources and efforts have been spent to study the effect of the MPB outbreak on the lodgepole pine stand dynamics. Models such as MPBSim (Safranyik *et al.* 1999) and MPB-Seles (Fall *et al.* 2001) were consequently developed to assess the current extent and future progression of the infestation, and to predict short- and long-term impacts of the MPB on the forests across a range of spatial scales. Also, prototype versions of the Westwide Pine Beetle Model and the Parallel Processing Extension of Prognosis^{BC} (PPE), (Crookston and Stage 1991) were used in MPB affected areas of interior BC to evaluate the utility of the model in simulating MPB and *Ips* impacts at both stand and landscape levels (Beukema and Robinson 2004).

In the absence of any control on the climate, the current catastrophic beetle infestation and the uncertainty associated with its future progression has prompted the BC Ministry of Forests to adopt a short-term management plan to reduce the loss of timber in the infested areas. Annual Allowable Cuts (AAC) for the affected areas have been temporarily increased by salvage-harvesting standing beetle-killed trees. The shelf life[1] of beetle-killed lodgepole pine is weather-dependent and has been reported to be more than 15 years in dry and warm sites and less than 10 years in wet and cold sites (BC Ministry of Forests 2003). Given the size of the infested area, the current rate of spread of the infestation, problems in accessing some affected stands, and the short shelf life of lodegepole pine, salvage will likely not take place in some areas.

During times of endemic outbreaks, management activities commonly prescribe removal of dead trees, followed by reforestation of cut areas either by planting or through natural regeneration. However, in the presence of catastrophic epidemic outbreaks, such as the current one, planting of non-salvaged stands is problematic and the fate of natural

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[1] The number of years when standing dead trees remain merchantable.

regeneration remains unknown. Future management of non-salvaged areas will depend greatly on the ability to predict the abundance, composition and growth of natural regeneration.

At the present time, there are no tools available to predict natural regeneration following MPB infestation. However, the regeneration sub-model of Prognosis^{BC} may have potential to be used for this purpose. In order to do this, the West Wide Pine Beetle model would have to be further investigated, calibrated, and linked to the core Prognosis^{BC} model, and the natural regeneration model of Prognosis^{BC} would have to be extended to MPB affected stands..

The first objective of this current research was to evaluate regeneration predictions of MPB-affected stands using the Prognosis^{BC} natural regeneration sub-model and reference data from 1) the MPB-affected stands only, 2) the Prognosis^{BC} regenerated stands database, and 3) the combination of these two datasets. We hypothesized that since the dynamics of partially harvested stands are different from those disturbed by MPB attacks, the set of variables used to predict natural regeneration following one disturbance is not suitable for predicting regeneration under the other disturbance. The second objective was to study the effect of varying degrees of partial cutting on long-term model results. The third objective was to further develop and enhance the Prognosis^{BC} software including any database design changes and updates needed to predict impacts of MPB on stand dynamics.

METHODS

Site Descriptions

Interior Douglas-fir Zone

The Interior Douglas-fir (IDF) BEC zone occurs at elevations that range from 500 to 1500 m in south-central interior of British Columbia (Hope *et al.* 1991). The zone occurs above the Ponderosa Pine and below the Montane Spruce zones. It has a continental climate characterized by a long and warm growing season. The stands experience substantial moisture deficits during the summer period. Mean annual temperatures ranges between 1.6 and 9.5°C and the annual precipitation ranges from 300 to 750mm and (Meidinger and Pojar 1991).

Pure climax stands of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Beissn.) Franco) are very common throughout the zone. Open to closed forests of Ponderosa pine (*Pinus ponderosa* Laws, also called yellow pine), lodgepole pine (*Pinus contorta* Dougl. var. *Latifolia*), and hybrid spruce (*Picea engelmannii* Parry x *glauca* (Moench) Voss) are also present. Western red cedar (*Thuja plicata* Donn) is sometimes found in moist pockets in the drier parts of the zone. Trembling aspen (*Populus tremuloides* Michx) and lodgepole pine are serial species and occur in sites that are not dry. Open grasslands are common in drier regions. The most important natural agents of disturbance in the IDF are fire, insect defoliators, bark beetles, and root rot (Wong *et al.* 2003). Bark beetles have significant effects on stand dynamics in the zone (Heath and Alfaro 1990) and the area disturbed by insects and diseases can exceed that affected by wildfire (Parminter 1998). The Dry Cool Interior Douglas-fir (IDFdk) constitutes the modal subzone and the Dry Mild Interior Douglas-fir (IDFdm2) is distinguished from other variants by the presence of western larch (*Larix occidentalis* Nutt.).

Sub-Boreal Pine Spruce Zone

The Sub-Boreal-Pine-Spruce (SBPS) zone occupies the high plateau of the west central interior in the shadow of the Coast Mountain range and lies mostly within the Chilcotin area (Steen and Demarchi 1991, Meidinger and Pojar 1991). The SBPS occurs on high elevations; in the northern part of the zone elevations range from 850 to 1300 m and vary between 1100 and 1500 m in the southern part (Steen and Coupe 1997). The zone generally occurs above the IDF and below the MS zones.

The SBPS has a continental climate characterized by cold, dry winters and cool and dry summers. Mean annual temperature ranges from 0.3 to 2.7^{o}C, while annual mean precipitation varies between 335 to 580 mm. About 30 to 50% of the annual precipitation falls as snow (Meidinger and Pojar 1991). Forests of the SBPS are reported to have resulted from mixed to severe disturbances, mainly fire (Steen and Coupe 1997). Lodgepole pine dominates the landscape of the zone and constitutes the unique climax species on most of the areas. This has resulted from extensive and frequent fire history that creates young, even-aged and dense pine stands. White spruce and trembling aspen, are the only common tree species restrictively found in wet parts of the zone. Other species are occasionally found on specific parts of the landscape. Lodgepole pine trees dominated the regeneration on zonal sites. In the absence of fire, spruce can slowly dominate the regeneration.

Along with a history of frequent fires, mountain pine beetle and spruce beetle can also cause extensive mortality when they reach epidemic population levels. Interactions between fire and mountain pine beetle were reported to have historically driven forest dynamics in lodgepole pine (Steen and Coupe 1997). The very dry cold subzone (SBPSxc) is the driest and occurs on the southwest part of the SBPS (Steen and Coupe 1997).

Montane Spruce Zone

The Montane Spruce (MS) zone occurs on mid-elevation slopes and plateaus in the mountains of the dry southern interior of British Columbia (Braumandel and Curran 1992). Elevations range from 1100 to 1500m in the wetter climatic areas and from about

1250 to 1650 m in the drier regions (Meidinger and Pojar 1991). MS is a transitional zone between the lower dry Interior Douglas-fir forests and the wetter, colder, and higher elevated forests of the Engelmann Spruce-Subalpine Fir (ESSF) zone. The climate is continental characterized by cold winters and moderately short and warm summers (Meidinger and Pojar 1991). Mean annual temperature is between 0.5 and 4.7°C and the annual precipitation ranges between 380 and 900 mm. The snow pack in winter usually averages between 60 and 100 cm, and the long period of drought in the summer often leads to forest fires (Meidinger and Pojar 1991).

A history of wildfire has contributed to extensive seral stands of lodgepole pine throughout the landscape of the zone. Subalpine fir and hybrid spruce are the main climax species found prevalently mixed with lodgepole pine in the cooler areas of the MS. Other common species found are western redcedar, trembling aspen, and cottonwood (*Populus trichocarpa* Torr. & Gray). Stand-replacing wildfires and severe outbreaks of the mountain pine beetle constitute the two major disturbance agents.

The MSdk is one of the five recognized subzones in the MS zone (Meidinger and Pojar 1991). It occurs in the southeast of the province and occupies the mid-slopes of the Rocky Mountain Trench and in valley bottoms and lower valley slopes of the eastern Purcell and Rocky Mountains.

Interior Cedar Hemlock Zone

The Interior Cedar Hemlock (ICH) zone is located in the wet-belt of Columbia-Shuswa and Rocky Mountains of southern BC and in the Nass and Skeena river basins in the northern part of BC. The zone is found at low to mid-elevations, which range from 500 to 1450 m in the northern part of its range, and from 1200 to 1450 m in the southern part. The ICH extends south into eastern Washington, Idaho, and western Montana (Ketcheson *et al*. 1991). The ICH has an interior, continental climate typified by cool wet winters and warm dry summers. The mean annual temperature ranges from 2 to 8.7°C and the mean annual precipitation varies between 500 to 1200 mm. Up to 50% of the precipitation falls as snow (Meidinger and Pojar 1991).

The ICH is the largest and the most productive zone in the interior of BC (Meidinger and Pojar 1991, Delong 1997). The moist warm 2 variant of the Interior Cedar-hemlock (ICHmw2) carries the highest species diversity and supports over 14 commercial tree species. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar dominate mature climax stand found in this subzone. Hybrid white spruce, grand fir (*Abies grandis* (Doug.) Lindl.), subalpine fir, western larch, Douglas-fir, lodgepole pine, and western white pine (*Pinus monticola* Dougl.) are common in the central and southern parts of the subzone. Influential disturbance agents in the ICH are frequent low-severity to rare stand-replacing fires, high incidence of root rot, bark beetle, avalanches, defoliators, and dwarf mistletoes (Wong 2001).

Regeneration Imputation in MPB-Affected Stands

Data description

MPB-affected stand data were collected as part of a Natural Resources Canada project established in 2001 to investigate the impact of MPB on stands located in the IDF (80 plots), SBPS (75 plots), and MS zones (20 plots,). The project was based on work initiated 1987 (Shore and Safranyik 1996). Initially, 10 variable radius plots with basal area factors (BAF) of 10 ft^2/ac (2.30 m^2/ha) or 20 ft^2/ac (4.59 m^2/ha) were established in 30 stands in the former Cariboo Forest Region, five stands in the former Kamloops Forest Region, and six stands in the former Nelson Forest Region. The BAF varied among stands, but was the same for all plots within a stand. In the summer of 2001, the original stands were revisited and only those stands that were not heavily disturbed by logging or wildfire were relocated and retained for remeasurement. Fifteen stands were relocated in the former Cariboo Forest Region, four in the former Kamloops Forest Region, and one in former Nelson Forest Region. The data collected in 2001 was used in this analysis.

Within each selected stand, the 10 variable radius plots were established in two parallel lines of five plots each, spaced at approximately 100 m intervals. The choice of the basal area factor (BAF) to establish the plots ensured the inclusion of a minimum of eight to ten trees per plot ("in" trees). Once the plot centers were relocated and marked using GPS, species of "in" trees were identified and the trees that were measured in the initial study were relocated. Diameters at breast height (DBH) of standing trees (alive and dead) were recorded. Metal tags were hammered onto new trees that had grown "in" to the prism plots. Living trees were assessed for any pathological conditions. Understory trees and regeneration were measured using fixed radius circular plots of different sizes. The regeneration was tallied by species and into four height classes (0-0.10 m, 0.10-0.50 m, 0.50-1.0 m, and 1.0-1.5 m) within a 3.1 m radius plot. Trees taller than 1.50 m and less than 7.0 cm DBH were recorded by species into two DBH classes (0-3.9 cm or 3.9-7.5 cm) within a 5.64 m or 7.98 m radius plot. To avoid the overlap of trees between the different DBH or height strata, any tree that was counted as "in" tree in the overstory was excluded from the understory count.

The second set of data used in this research project came from the Prognosis^{BC} Microsoft Access regeneration database (Lencar 2003; Zumrawi *et al.* 2003). The database contains a compilation of regeneration, small (≥ 2.0 and < 7.5 cm DBH), and large trees (≥ 7.5 cm DBH) data collected over a period of five years (from 1998 to 2001) across IDF (dk1, dk2, dk3, dk4 and dm2 variants), ICH (mw2 variant), and MS (dk subzone) zones. The database also contains site information such as slope, aspect, elevation, site series, site preparation, and geographic locations. Detailed protocol and sampling techniques used to collect data were presented in Lencar (2003). Plot establishment within each subzone covered wide ranges of residual basal area, residual trees per hectare, and site factors such as elevation, aspect, site treatment, and slope. Large trees were sampled with either circular fixed area plots of 8 m or 11.28 m radius, or with variable radius plots (IDFdk3 only). Along with species and DBH, height was measured for a sub-sample of large trees. Small trees were measured within 2 m, 5.64 m, or 11.28 m radius plots in the IDF zone, and within 3.99 m radius plots in the ICH and MS zones. The DBH and height of each small tree was recorded. Some small trees were sub-sampled for age and height increment by measuring the last 5-year height growth increment.

Regeneration was defined as seedlings below 7.5 cm in DBH and above 15 cm in height and was sampled using a 2 m or 2.07 m fixed radius plots. Regeneration was measured in the regeneration center plot and in four satellite plots of the same size located in the cardinal directions at the periphery of the large plot, except for IDFdk3, dk4, and xm, where regeneration was measured for a center plot only. Regeneration was tallied by species and into four height classes: (1) under 50 cm, (2) 50 – 99.9 cm, (3) 100 – 129.9, and (4) 130 cm and over. Height and age were measured for a sub-sample of trees from each regeneration center plot.

Data preparation

Compiled data for IDF were extracted from the Prognosis^{BC} database. The MPB-affected stand data was compiled to provide plot-level attributes, and separated by BEC zone. For consistency with the Prognosis^{BC} database, the regeneration of the MPB stands was reclassified into the four height classes used in the Prognosis^{BC} database. Also, species were grouped into three shade tolerance groups: 1) the shade tolerant species group included grand-fir, subalpine-fir, western redcedar, hemlock, and spruce; 2) the shade semi-tolerant species group contained Douglas-fir and white pine; and 3) the shade intolerant species group was composed of lodgepole pine, yellow pine, western and subalpine larch (*Larix lyallii* Parl.), cottonwood, trembling aspen, white birch (*Betula papyrifera* Marsh.), Douglas maple (*Acer glabrum* Torr. Var. *douglasii* (Hook.) Dipp.), alder (*Alnus* sp.), and willow (*Salix* sp.). Juniper (*Juniperus* sp.) is shade tolerant in its early stages of development, but becomes shade intolerant as a grown tree. It was classified with shade tolerant species in the regeneration and shade intolerant in residual trees.

Imputation analyses

Most Similar Neighbour (MSN) Imputation (Crookston *et al.* 2002, Version 2.12) programs were used to estimate regeneration in beetle-impacted stands, and statistics were compiled using SAS, Version 8.2. The analyses were similar to those employed by Hassani *et al*. (2003). For the imputation, the regeneration per ha variables (stems per ha by species group and height class, resulting in 12 $\underline{Y}$ variables) were the variables of interest, and site and overstory variables were used as auxiliary ($\underline{X}$) variables. Regeneration was imputed to a target plot by searching the database (reference plots) for a similar plot, in terms of site and overstory auxiliary variables, and assigning (estimating) the regeneration from the similar plot to the target plot.

Three different sets of reference data were compared for estimating the regeneration using MSN. The first set consisted only of data gathered for MPB-affected stands, the second used data in the existing Prognosis^{BC} regeneration database, and the third used the combined datasets. Also, since Prognosis^{BC} version 3.0 is not calibrated for the SBPS zone and little data have been gathered on regeneration in MS, imputation of regeneration was only assessed for the IDF for the later two reference data sources.

Using the MPB-affected stand data, the auxiliary or explanatory variables ($\underline{X}$) included elevation and stand variables that were derived from the information collected on residual trees within each plot. Stand variables used were: residual trees per ha (TPH), residual basal area per ha (BA) (both by the shade tolerance groups), quadratic mean diameter (QMD), and crown competition factor (CCF). Other site information such as aspect, slope, and BEC site series were not present in the MPB-affected plot data. Data splitting (75% reference, 25% target data) was used to assess the accuracy and the robustness of the MSN imputations (Snee 1977), assuming that only the site and overstory variables were available for the target data. The assessment was repeated four times, using a different 25% as the target data for each repetition, and repeated for each BEC zone (IDF, MS, and SBPS).

Using only the Prognosis^{BC} regeneration database as the reference set of data, the regeneration for the target plots from the MPB-affected data (25% of all MPB-affected data) was estimated (IDF only). The process was repeated four times, using the same four sets of target data as when the MPB-affected data, only, were used as the reference set. The process was also repeated using the combined MPB-affected plot data and the Prognosis^{BC} database (mixed MSN model) as reference data (IDF only).

The same set of auxiliary variables was used for all three imputation models, since these variables were available for both datasets. These were not the same auxiliary variables used in previous applications of MSN imputation for regeneration (e.g., Hassani *et al.* 2003), since not all of these previously used variables were available for the MPB-affected stand data.

Comparison of imputations using the three different databases

Using observed and estimated regeneration for each plot of the target data, bias, mean absolute deviation (MAD), and root mean-squared error (RMSE) values were calculated for each of the 12 regeneration stems per ha variables as follows:

$$Bias = \sum_{j=1}^{m}\sum_{i=1}^{n}\left[\frac{\left(y_{ij} - \hat{y}_{ij}\right)}{nm}\right]$$

$$MAD = \sum_{j=1}^{m}\sum_{i=1}^{n}\left[\frac{\left|y_{ij} - \hat{y}_{ij}\right|}{nm}\right]$$

$$RMSE = \sum_{j=1}^{m}\sqrt{\sum_{i=1}^{n}\left[\frac{\left(y_{ij} - \hat{y}_{ij}\right)^2}{n}\right]}\Bigg/ m$$

where y_{ij} is the observed regeneration stems per ha for each target plot i and regeneration class j; $\hat{y}_{ij}$ is the predicted regeneration stems per ha; n is the number of target plots, and m is the number of regeneration classes (12) as defined by three species tolerance groups and four height classes.

Statistics were calculated for each target data set (four sets, representing 25% of the MPB-affected stand data for each set), and using each of the three reference databases (75% of MPB-affected plot data only, Prognosis^{BC} regeneration database only, and the combination of the two datasets).

Effects of Varying Levels of Partial Cutting on Long-term Prognosis^{BC} Model Projections

To study the effect of varying degrees of partial cutting on long-term Prognosis^{BC} model projections, three different harvesting scenarios were simulated. Ten undisturbed plots from the IDF (five from the IDFdk1 and five from IDFdm2) were randomly selected from the Prognosis^{BC} regeneration database. For each selected plot:

1. Partial cutting from above was simulated by removing large trees of all species to obtain three residual basal area per ha values: 5, 10, and 20 m^2 /ha residual basal area;
2. Each plot and partial cutting level was projected forward 10-years (30 projections, three partial cutting levels for each of 10 plots);
3. At 10 years after disturbance, the Prognosis^{BC} MSN-based natural regeneration model was used to predict (impute) natural regeneration based on the site and overstory data represented in each plot projection using the projected tree lists from the 10 year projection. All IDF plots in the Prognosis^{BC} regeneration database were included as refererence plots, except for the plot selected for projection; and
4. The imputed regeneration was added to the projected tree list for each plot projection, and the Prognosis^{BC} simulation was continued for another 50 years.

For the regeneration imputations of Step 3, the overstory and site auxiliary variables (e.g., site series, basal area per ha, trees per ha, crown competition factor, and quadratic mean diameter) year since disturbance, and species composition) of each projected plot and the selected most similar neighbour were compared as an indication of which variables were more influential in selecting a neighbour. Long term projections for the different partial cutting scenarios were contrasted, with respect to the amount of imputed natural regeneration, the final trees per ha, basal area per ha, and total and merchantable volumes per ha. The total yield (harvested plus final volumes per ha) were also compared across the three partial cutting scenarios.

RESULTS

Regeneration Imputation in MPB-Affected Stands

The MPB-affected stands database was divided into four sets for each BEC zone, and one set was used as the target for testing (Table 1). Because some site variables such as slope, aspect, and BEC site series were not obtained as the plot level in the MPB-affected plot data, these variables could not be used in the imputations.

Table 1. Bias, mean absolute deviation (MAD), and root mean squared error (RMSE) averaged over the 12 regeneration variables (stems/ha) for each of the four MPB-affected stands test data sets by BEC zone.

		No. of		Stems/ha	
Zone	**Test**	**Target Plots**	**Bias**	**MAD**	**RMSE**
IDF	1	18	-290	446	712
	2	18	-86	286	537
	3	20	-44	257	544
	4	24	136	295	563
MS	1	5	77	158	250
	2	5	5	344	513
	3	4	5	105	150
	4	6	-17	347	442
SBPS	1	17	-129	223	314
	2	17	-61	167	249
	3	20	-30	170	245
	4	21	56	220	323

Biases differed somewhat depending on what data were reserved as the target (regeneration assumed to be missing) data. Since negative and positive biases cancel out in calculating the average bias, the MAD and RMSE are more useful. Again, these statistics did vary depending on the target data. Since the MPB-affected database is quite small, particularly for the MS zone, the number of reference plots that can be used in the imputation is quite small. Locating a match for a target plot is therefore more difficult, and a poor match for less represented plots occurs. However, the highest RMSE was 712 stems per ha, and most were below 600 stems per ha. For the 2.0 m radius regeneration plot (0.0013 ha), this would be, at most, 1 tree.

By shade tolerance group and height class, the highest bias (absolute values), MAD, and RMSE values occurred for the shade intolerant species group for IDF (particularly the smallest height class, both over- and under-estimated) and SBPS (particularly the largest height class, where regeneration was over-estimated) (Tables 2, 3, and 4). However, for MS, biases were higher for the shade tolerant group, whereas MAD and RMSE values were similar for across species and height groups. Since only a small number of MPB-affected plots were available for MS, results were not as accurate as for the other two BEC zones.

Table 2. Bias (stems/ha) for each of the 12 regeneration variables by test data set and BEC zone.

Zone	Test	tol1	tol2	tol3	tol4	semi1	semi2	semi3	semi4	int1	int2	int3	int4
IDF	1	-14	3	14	-36	-8	6	6	-56	-2,744	-250	-122	-275
	2	25	6	-3	14	56	6	6	97	-1,020	-250	-133	164
	3	15	-5	-3	-70	-63	-15	0	25	408	-45	-15	-755
	4	56	31	-17	190	-23	-21	-13	19	1,157	63	-50	240
MS	1	470	140	90	350	-290	90	-20	0	0	30	0	60
	2	70	20	-10	300	-291	-130	20	-20	80	30	20	-30
	3	-75	100	63	125	125	0	-25	-200	0	25	0	-75
	4	100	33	0	117	-542	133	-17	-92	17	0	0	50
SBPS	1	-6	6	0	24	6	0	0	0	-121	-221	-147	-1,092
	2	0	0	0	-29	0	-6	0	0	-218	38	-18	-494
	3	5	0	0	0	-5	5	0	0	-78	-15	-7	-270
	4	5	0	0	38	-5	0	0	0	-379	55	57	896

(Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Table 3. Mean absolute deviation (stems/ha) for each of the 12 regeneration variables by test set and BEC zone.

Zone	Test	tol1	tol2	tol3	tol4	semi1	semi2	semi3	semi4	int1	int2	int3	int4
IDF	1	42	25	14	36	86	28	6	83	3,244	667	311	809
	2	25	6	3	25	145	39	17	131	1,170	573	295	1,003
	3	40	25	8	140	118	25	0	190	998	450	150	940
	4	106	81	46	194	102	29	13	56	1,566	454	259	640
MS	1	590	180	90	390	290	130	20	80	40	30	0	60
	2	70	20	10	300	3,112	150	60	140	80	50	20	110
	3	75	150	63	275	325	0	25	200	50	25	0	75
	4	100	33	0	133	3,127	150	83	458	17	0	0	67
SBPS	1	6	6	0	35	6	0	0	0	568	362	177	1,516
	2	0	0	0	29	0	6	0	0	300	227	124	1,313
	3	5	0	0	10	5	5	0	0	518	270	148	1,081
	4	5	0	0	38	5	0	0	0	608	379	219	1,392

(Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Table 4. Root mean squared error (stems/ha) for each of the 12 regeneration variables by test data set and BEC zone.

Zone	Test	tol1	tol2	tol3	tol4	sem1	sem2	sem3	sem4	int1	int2	int3	int4
IDF	1	125	75	59	142	209	78	24	161	5,151	962	427	1,133
	2	106	24	12	86	456	118	41	370	2,122	888	436	1,783
	3	119	81	25	489	408	92	0	445	2035	822	239	1773
	4	282	173	100	541	230	89	35	113	3,096	692	423	985
MS	1	1,088	361	180	554	312	178	45	89	63	50	0	77
	2	157	45	22	460	4,457	242	100	224	179	92	45	128
	3	150	255	103	427	350	0	50	255	71	50	0	87
	4	208	82	0	250	3,853	220	108	470	41	0	0	76
SBPS	1	24	24	0	103	24	0	0	0	883	556	331	1,822
	2	0	0	0	64	0	24	0	0	485	389	190	1,838
	3	22	0	0	32	22	22	0	0	751	412	219	1,460
	4	22	0	0	76	22	0	0	0	999	541	360	1,851

(Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Since there were few plots for MPB-affected stands, the use of the existing Prognosis^{BC} regeneration database was examined. In general, using a mixture of the MPB-affected plots data with the Prognosis^{BC} database (BOTH), gave better results than using the Prognosis^{BC} database alone (PROG) (Figure 1).

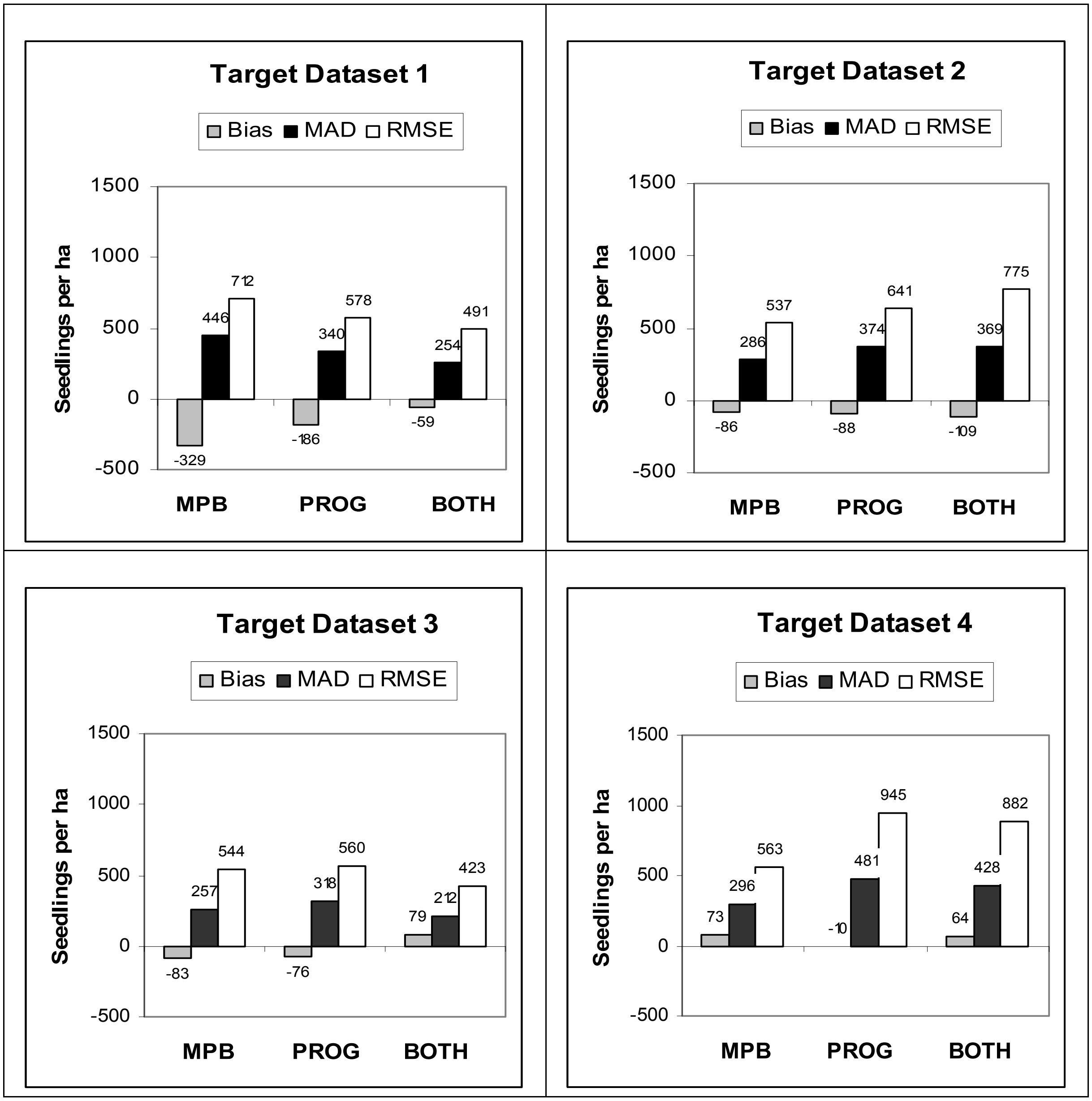

Figure 1. Bias, mean absolute deviation (MAD), and root mean-squared error (RMSE) averaged over the 12 regeneration variables (stems/ha) using the MPB-affects plots only (MPB), using the PrognosisBC regeneration database only (PROG), and using a mixture of the two database (BOTH) as reference data in imputing regeneration for MPB-affected target plots.

By shade tolerance group and height class, using MPB-affected plot data alone resulted in lower bias (absolute value), MAD, and RMSE values, generally (Tables 5, 6 , and 7), whereas for the shade semi-tolerant species group, using MPB-affected plot data alone provided better results. For the shade intolerant group (including lodgepole pine), results were mixed, but were generally better using the mixed datasets (all available reference data, MPB-affected and Prognosis^{BC}) for the taller height classes (greater than 1 m in height), and using the Prognosis^{BC} data for the smaller regenerated trees.

Table 5. Bias (stems/ha) of each of the 12 regeneration variables using each of the three reference datasets by test dataset and BEC zone.

MPB only													
Test	**n**	**tol1**	**tol2**	**tol3**	**tol4**	**semi1**	**semi2**	**semi3**	**semi4**	**int1**	**int2**	**int3**	**int4**
1	18	-44	-8	14	-47	-8	0	6	-81	-2,766	-378	-131	-509
2	18	-53	-44	-19	-14	89	17	6	83	-1,064	-172	-92	236
3	20	30	0	-8	-35	-8	-5	0	95	48	-143	-78	-888
4	24	-10	40	25	90	29	0	-4	6	876	-117	-46	-12
Prognosis^{BC} only													
1	18	-93	-69	-3	-88	-454	-396	-193	-346	13	-228	-164	-213
2	18	-206	-135	0	-47	-348	-195	-107	-370	-50	-69	26	445
3	20	-143	-64	-20	-71	-227	-87	-69	-33	490	-203	-95	-395
4	24	-30	-38	0	78	-796	-683	-149	-385	1265	-26	14	626
MPB+Prognosis^{BC}													
1	18	-17	3	14	-61	-127	-97	-14	-280	-336	42	31	129
2	18	-36	-14	0	-14	-395	-357	-66	-175	-602	-105	25	432
3	20	15	-2	-10	38	-63	-15	0	35	560	170	85	133
4	24	-73	-119	-68	-31	-322	-287	-136	-555	1503	176	40	641

(n = number of target plots; Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Table 6. Mean absolute deviation (stems/ha) of each of the 12 regeneration variables using each of the three reference datasets by test dataset and BEC zone.

MPB only													
Test	**n**	**tol1**	**tol2**	**tol3**	**tol4**	**semi1**	**semi2**	**semi3**	**semi4**	**int1**	**int2**	**int3**	**int4**
1	18	42	25	14	36	86	28	6	83	3,244	667	311	809
2	18	25	6	3	25	145	39	17	131	1,170	573	295	1,003
3	20	40	25	8	140	118	25	0	190	998	450	150	940
4	24	106	81	46	194	102	29	13	56	1,566	454	259	640
Prognosis^{BC} only													
1	18	138	69	3	88	459	396	193	374	655	448	258	994
2	18	207	146	0	69	560	251	118	598	635	475	202	1,232
3	20	158	64	25	97	257	107	69	189	1,127	400	216	1,112
4	24	197	77	17	156	813	691	149	435	1,597	382	228	1,033
MPB+Prognosis^{BC}													
1	18	44	25	14	61	189	130	25	307	947	464	220	627
2	18	36	14	0	19	606	402	99	375	1,188	483	169	1,041
3	20	40	23	15	38	128	25	10	170	1,051	320	110	608
4	24	227	161	85	274	380	287	136	588	1,578	383	215	824

((n = number of target plots; Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Table 7. Root mean squared error (stems/ha) of each of the 12 regeneration stems per ha using each of the three reference datasets by test dataset and BEC zone.

MPB only													
Test	**n**	**tol1**	**tol2**	**tol3**	**tol4**	**semi1**	**semi2**	**semi3**	**semi4**	**int1**	**int2**	**int3**	**int4**
1	18	125	75	59	142	209	78	24	161	5,151	962	427	1,133
2	18	106	24	12	86	456	118	41	370	2,122	888	436	1,783
3	20	119	81	25	489	408	92	0	445	2035	822	239	1773
4	24	282	173	100	541	230	89	35	113	3,096	692	423	985
Prognosis^{BC} only													
1	18	400	134	11	199	748	1,155	317	763	908	645	419	1,232
2	18	436	241	0	115	945	435	247	1,408	917	689	300	1,964
3	20	331	140	75	171	371	220	197	525	2,138	590	337	1,624
4	24	377	134	46	396	1,880	1,781	284	933	3,126	526	388	1,467
MPB+Prognosis^{BC}													
1	18	126	75	59	177	497	265	54	639	1,952	700	382	967
2	18	81	42	0	51	1,538	1,316	183	734	2,553	784	233	1,783
3	20	119	72	57	137	431	92	32	406	2,054	568	191	918
4	24	646	576	308	654	704	585	305	1,386	3,315	612	356	1,142

(n = number of target plots; Tol=shade tolerant; sem=semi-shade tolerant; int=shade intolerant species groups, for height classes 1 (0 to 0.5 m), 2 (0.5 to 1 m), 3 (1. to 1.3 m), and 4 (1.3 m plus)).

Effects of Varying Levels of Partial Cutting on Long-term Prognosis^{BC} Model Projections

The long-term effects of varying levels of partial cutting from above were simulated on 10 plots by removing the largest DBH trees, with planned residual basal areas of 5, 10, and 20m^2/ha. The pre-harvest basal area of the five selected plots from the IDFdk1 ranged from 17.4 to 48.7 m^2 per ha and the number of residual trees per ha varied between 924 and 7106 stems per ha. The pre-harvest residual basal area and stems per ha of the five plots chosen from the IDFdm2 ranged from 21.3 to 42.7 m^2 per ha and from 993 to 6207 stems per ha, respectively.

The 10-year projections for each of the 10 plots indicated that the increase in basal area per ha was within expected ranges, except for the 5th plot of IDFdk1 (Tables 8 and 9). In that plot, a very small tree representing a large number of stems per ha was projected to have a large increase in diameter, resulting in a very large increase in plot basal area following partial cutting.

In the MSN analysis to estimate the regenerated stems per ha, stand variables by shade tolerance groups were used. These variables were computed from the 10-year projected, post-harvest treelists for the reference plots. For IDFdk1, all five target plots were matched with reference plots from the same subzone (Table 8). There was only one case in which a zonal site was used as the MSN for a drier site. All the selected reference plots for the IDFdm2 target plots were from the IDFdk variants (dk1, dk2, and dk3), but there were some site series disagreements between target and reference data (Table 9). In some cases, zonal sites (site series 01) were selected for drier sites (site series 02 and 03). The time since disturbance of all target plots were in close agreement (within 10 years or less) with their selected most similar neighbours. Also, there were good agreements on crown competition factor, except for IDFdk1, Plot 1, where the CCF for the selected plots from the Prognosis^{BC} database was 0.00 for 5 and 10 m^2/ha, indicating possible errors in the database. Comparing the basal area per ha between the target and reference plots, most showed good agreement, within 10 m^2/ha. On the other hand, the number of trees per ha for the majority of target plots were consistently higher than their selected reference plots (nearest neighbours). In both variants, there were nearly perfect matches of species composition between two target plots and their respective reference plots, except for minor species.

Table 8. Comparison of residual stand variables (TPH, BA, CCF, QMD), time since disturbance (Yrsince), species composition, site series, and BEC subzone/variant between target (T) and reference (R) plots for the three partial cutting intensities of the IDFdk1. Statistics for target plots are projections for 10 years after partial cutting; statistics for reference plots are compiled on measured data stored in the Prognosis^{BC} database.

Plot Number	**BEC Subzone/ variant**	**Planned Residual BA (m^2/ha)**	**BEC**	**BA**		**TPH**		**CCF**		**QMD**		**Yrsince**		**Species Composition**[a]	
			R	**T**	**R**	**T**	**R**	**T**	**R**	**T**	**R**	**T**	**R**	**T**	**R**
1	IDFdk1/05	5	IDFdk1/01	9.20	7.00	2417	550	53.00	0.00[b]	6.90	25.70	10	20	FD, PL	PL, SX*
		10	IDFdk1/01	14.90	7.00	2896	550	83.00	0.00[b]	8.10	18.80	10	20	FD, PL	PL, SX*
		20	IDFdk1/01	25.70	7.00	3400	550	134.00	3.00[b]	9.80	8.00	10	20	PL, FD	PL, SX*
2	IDFdk1/05	5	IDFdk3/01	14.20	20.00	6400	1073	83.00	75.80	5.30	59.80	10	4	FD, SE, PL*	FD
		10	IDFdk1/05	18.80	18.90	6580	926	105.00	86.10	6.00	16.10	10	19	FD, SE, PL*	SX, FD
		20	IDFdk2/05	25.00	23.90	6689	725	125.00	108.30	6.90	20.50	10	4	FD, SE, PL*	SX, FD, BL
3	IDFdk1/01	5	IDFdk1/01	8.00	10.50	2493	450	56.00	54.70	6.40	17.30	10	13	FD, PL	PL, FD
		10	IDFdk1/01	13.50	10.50	2617	450	81.00	54.70	8.10	17.30	10	13	FD, PL	PL, FD
		20	IDFdk2/04	23.40	4.80	2691	1110	119.00	24.00	10.50	14.30	10	12	FD, PL	PL, FD
4	IDFdk1/04	5	IDFdk3/02	9.40	10.00	610	445	61.00	59.20	14.00	17.60	10	5	FD	FD
		10	IDFdk1/04	15.80	17.80	786	575	97.00	93.90	16.00	19.80	10	12	FD	FD
		20	IDFdk2/04	22.70	36.10	882	550	129.00	151.00	18.10	28.90	10	5	FD	FD
5	IDFdk1/05	5	IDFdk3/01	30.10[c]	15.00	3351	1931	129.00	65.30	10.70	10.50	10	12	SX, HW, PL*	SX
		10	IDFdk1/05	25.90[c]	18.90	3467	926	114.00	86.10	9.80	16.10	10	19	SX, HW, PL*	SX,FD
		20	IDFdk3/07	31.20	10.00	3578	19	135.00	29.70	10.50	83.00	10	5	SX, PL, HW	FD

a Planned Residual BA= residual basal area per ha for simulated disturbances, values at the time of disturbance; FD= Douglas-fir; PL=lodgepole pine; SX= hybrid spruce; SE= Engelmann spruce; HW= western hemlock; BL= alpine fir * indicates that this was a minor species components

b CCF values as extracted from the PrognosisBC database.

c Large increases in basal area per ha over the 10 year period are attributed to ingrowth trees.

Table 9. Comparison of residual stand variables (TPH, BA, CCF, QMD), time since disturbance, species composition, site series, and BEC subzone/variant between target (T) and reference (R) plots for the three partial cutting intensities of the IDFdm2. Statistics for target plots are projections for 10 years after cutting.

Plot #	BEC Subzone/ variant	Planned Residual BA (m^2/ha)	BEC	BA		TPH		CCF		QMD		Yrsince		Species Composition[a]	
			R	T	R	T	R	T	R	T	R	T	R	T	R
1	IDFdm2/01	5	IDFdk3/02	7.1	10.0	729.0	445.0	38.0	59.2	11.2	17.6	10	5	FD	PL, FD
		10	IDFdk3/01	12.9	30.0	801.0	656.0	65.0	149.8	14.3	35.6	10	5	FD	FD
		20	IDFdk2/03	23.0	23.7	892.0	525.0	107.0	103.1	18.1	24.0	10	19	FD	FD
2	IDFdm2/03	5	IDFdk2/04	6.9	18.4	3408.0	150.0	35	73.2	5.1	39.5	10	11	FD	FD
		10	IDFdk2/03	12.4	19.8	3420.0	200.0	53	82.2	6.8	35.5	10	18	FD	FD
		20	IDFdk3/01	22.5	10	3437.0	60.0	84	37.5	9.1	52.4	10	4	FD	FD
3	IDFdm2/04	5	IDFdk1/04	6	5.2	3912	375	34	33.2	4.4	13.2	10	10	FD, HW	FD
		10	IDFdk3/01	11.7	20	3998	1100	57	122.1	6.1	17.6	10	11	LW, FD	FD
		20	IDFdk2/04	22.5	32	4085	600	101	129.4	8.4	26.1	10	0	LW, FD,	FD, EP
4	IDFdm2/01	5	IDFdk1/01	13.8	17	2150	425	90	78.7	9	22.5	10	7	FD, SX	SX,FD
		10	IDFdk1/01	17.7	17	2456	425	112	78.7	9.6	22.5	10	7	FD, PL, SE, BL	SX,FD
		20	IDFdk1/05	26.2	17	2691	275	153	74.4	11.1	28	10	7	FD, PL, SE, BL	FD,SX
5	IDFdm2/01	5	IDFdk1/01	9.6	21.2	5673	475	75	95.6	26.2	9.6	10	9	FD, OC	PL,FD
		10	IDFdk1/03	15.2	7.5	5797	375	100	41	15.2	24.8	10	14	FD, OC*	FD,PL
		20	IDFdk1/04	24.8	21.7	5812	600	138	108.8	7.4	21.5	10	19	FD, OC*	FD,SX*

a Planned Residual BA= residual basal area per ha for simulated disturbances, values at the time of disturbance; FD= Douglas-fir; PL=lodgepole pine; SX= hybrid spruce; SE= Engelmann spruce; HW= western hemlock; EP= paper birch * indicates that this was a minor species components

By the end of the 60-year projection period (10-year initial projection, regeneration imputation, and 50-year additional projection), the average number of trees per ha was lower for the 20 m^2/ha residual basal area, and there were no noticeable differences in the basal area among the three treatments, as expected (Table 10). The yields (standing merchantable volume plus cut merchantable volume) were greater for the greater basal area removals, since the harvest volumes were greater. Total volumes achieved in the IDFdk1 were commonly higher than in the IDFdm2, as might be expected

The imputed natural regeneration mostly increased with decreasing residual basal area, as would be expected. The average regeneration established ranged from 2614.8 to 1434.6 seedlings per ha for IDFdk1 and from 1075.6 to 1960.8 seedlings per ha for IDFdm2. The highest regeneration was estimated for stands that were heavily disturbed (Table 10).

Table 10. Summary of stems per ha, basal area, total and merchantable volumes, total and merchantable yield, and the amount of imputed regeneration averaged over the five plots in the IDFdk1 and in the IDFdm2 BEC subzones.

Site	**Planned Residual BA**	**TPH**	**BA m^2/ha**	**Vol. T m^3/ha**	**Merch. Vol. m^3/ha**	**MV. Rem m^3/ha**	**Merch. Yield m^3/ha**	**Regen at Year 10 SPH**
IDFdk1	5	3231	46.96	329.4	219.9	194.0	414.0	2615
	10	2914	46.62	346.3	240.0	181.5	421.6	1575
	20	2942	47.38	376.0	255.1	123.1	378.2	1435
IDFdm2	5	3486	36.00	242.4	178.6	217.7	396.3	1961
	10	3285	37.72	271.6	206.7	188.9	395.6	1076
	20	2935	40.46	336.1	286.0	111.2	397.2	1248

Planned Residual BA= simulated disturbance; BA= basal area at the end of the projection; TPH =trees per ha a the end of the projections (large trees); Vol.T, Merch. V = total and merchantable volume, respectively, at the end of the projection; MV. Rem= Merchantable volume removed at the beginning of the projection; M. Yield = Harvested volume + volume at the end of the projection.

For individual plot projections, differences in the density (TPH) among the disturbance intensities were strongly related to the basal area (Tables 11 and 12). The reduction in stems per ha from prior to cutting (1999) to 60 years after cutting (2059) was about 16% for the IDFdm2 stands (Table 12).

For Plot 4 of IDFm2, the stems per ha were very similar across cutting intensities 10 years after harvest (2010B) and after imputation (2010A), resulting in very similar stems per ha for each 10-year projection (Figure 2). In Plot 3 of IDFdk1, the stems per ha were very similar after harvest (2009B), but the imputed regeneration was much larger for the 5 and 10 m^2/ha residual basal areas than for the 20 m^2/ha basal areas, resulting in quite different stems per ha after the 60-year projection (Figure 3). For these same plots, the basal area per ha trajectory indicates that the basal area per ha values approach the same value in the 60-year projections (Figures 4 and 5).

Table 11. Trees per ha (TPH), basal area per ha (BA), projected total (Vol. T.) and merchantable volumes (Merch V.), and total (TV. Rem) and merchantable (MV. Rem.) harvested volumes for the three partial cutting intensities in the IDFdk1.

Plot No.	Planned Residual BA	Year	TPH	BA	Vol. T	Merch V	TV. Rem	MV. Rem
1	5	1999	3966	31.9	206.2	78.4	158	78.4
		2009	4050	9.2	44.7	3.1	.	.
		2059	2906	46.6	324	135.3	.	.
	10	1999	3966	31.9	206.2	78.4	155.4	78.4
		2009	4529	14.9	86.5	0	.	.
		2059	3054	45.5	351.6	157.4	.	.
	20	1999	3966	31.9	206.2	78.4	88.2	77.3
		2009	5033	25.7	170.6	27.9	.	.
		2059	3235	47.5	400.7	197	.	.
2	5	1999	7102	48.7	402.4	347.8	384.6	347.8
		2009	10114	14.2	57.4	3.9	.	.
		2059	5234	54.9	403.8	301.7	.	.
	10	1999	7120	48.7	402.4	347.8	356.6	339.6
		2009	8364	18.8	92.1	35.8	.	.
		2059	4512	53.5	398.1	293.6	.	.
	20	1999	7102	48.7	402.4	347.8	268.3	258.1
		2009	8770	25	174.4	119.2	.	.
		2059	4831	51.7	381.9	246.8	.	.
3	5	1999	2837	35.8	321.3	286.5	301.2	286.5
		2009	5019	8	36.6	2.6	.	.
		2059	3600	43.8	265.1	161	.	.
	10	1999	2837	35.8	321.2	286.5	259.4	248.9
		2009	4994	13.5	86.3	50.4	.	.
		2059	3558	42.7	288.8	192.4	.	.
	20	1999	2837	35.8	321.2	286.5	154.8	149.2
		2009	3622	23.2	196.7	158.5	.	.
		2059	2501	45.2	354.8	252.5	.	.
4	5	1999	924	17.2	92.7	64	77.3	64
		2009	610	9.4	37	9.9	.	.
		2059	452	34.4	255.7	237.8	.	.
	10	1999	924	17.2	92.7	64	50.9	47.3
		2009	1082	15.8	77.5	44.4	.	.
		2059	783	37	279	252	.	.
	20	1999	924	17.2	92.7	64	0	0
		2009	1181	23.2	132.9	95	.	.
		2059	833	39.9	311.9	271.3	.	.
5	5	1999	3734	36	259.1	193.5	239.2	193.5
		2009	8552	30.1	124	20.2	.	.
		2059	3963	55.1	398.4	263.8	.	.
	10	1999	3734	36	259.1	193.5	211.7	193.5
		2009	5251	25.9	123.9	34	.	.
		2059	2661	54.4	414.2	304.7	.	.
	20	1999	3734	36	259.1	193.5	139.8	131.1
		2009	5807	31	190.7	107.1	.	.
		2059	3309	52.6	430.7	307.7	.	.

1999 – prior to disturbance; 2009 – 10-years after disturbance; 2059 – 60 years after disturbance.

Table 12. Trees per ha (TPH), basal area per ha (BA), projected total (Vol. T.) and merchantable volumes (Merch V.), and total (TV. Rem) and merchantable (MV. Rem.) harvested volumes for the three partial cutting intensities in the IDFdm2.

Plot No.	Planned Residual BA	Year	TPH	BA	Vol. T	Merch V	TV. Rem	MV. Rem
1	5	2001	993	32.6	265.8	248.1	234.8	223.2
		2011	729	7.1	49.1	42.8	.	.
		2060	591	25.7	230.1	198.2	.	.
	10	2001	993	32.6	265.8	248.1	197.2	188.3
		2011	3029	12.9	95.8	86.9	.	.
		2060	2212	36.7	278.1	209.7	.	.
	20	2001	993	32.6	265.8	248.1	113.2	108.7
		2011	1040	23	185.1	172.1	.	.
		2060	761	34.7	330.6	311.4	.	.
2	5	2001	3568	21.3	194	185	153.1	147.3
		2011	7865	6.9	55.4	48.8	.	.
		2060	5644	37.4	219.1	136.7	.	.
	10	2001	3568	21.3	194	185	104.4	100.4
		2011	3420	12.4	111.3	103.1	.	.
		2060	2476	34.9	252.4	189.3	.	.
	20	2001	3568	21.3	194	185	11.5	11.1
		2011	3437	22.5	210.5	199.4	.	.
		2060	2392	37.6	317.6	265.2	.	.
3	5	2001	4438	42.7	376.9	349.5	338.5	320.7
		2011	3912	6	48.6	41.6	.	.
		2060	3151	26.6	198.6	155.9	.	.
	10	2001	4438	42.7	376.9	349.5	295.1	280.4
		2011	3583	11.7	100.1	90.2	.	.
		2060	4050	34.4	267.3	212	.	.
	20	2001	4438	42.7	376.9	349.5	203.7	194.1
		2011	4085	22.5	202.7	187.7	.	.
		2060	2903	36.5	336.2	306.1	.	.
4	5	2001	3091	35.1	235	164.6	222.5	164.6
		2011	3190	13.8	47	5.8	.	.
		2060	1920	44.8	327.8	272.3	.	.
	10	2001	3091	35.1	235	164.6	193.9	164.6
		2011	3496	17.7	77.9	9.8	.	.
		2060	2194	42.7	310.4	237.5	.	.
	20	2001	3091	35.1	235	164.6	117.1	108.8
		2011	3731	26.2	157.4	84.2	.	.
		2060	1930	49.4	399.5	326.1	.	.
5	5	2001	6207	34.9	264.8	232.9	250.4	232.9
		2011	9980	9.6	33.7	8.6	.	.
		2060	6123	45.5	236.2	129.8	.	.
	10	2001	6207	34.9	264.8	232.9	221.2	211
		2011	8322	15.2	73.3	44.6	.	.
		2060	5493	39.9	249.6	184.8	.	.
	20	2001	6207	34.9	264.8	232.9	139	133.3
		2011	10865	25.3	164.1	209.1	.	.
		2060	6687	44.1	296.7	221.2	.	.

2001 – prior to disturbance; 2011 – 10-years after disturbance; 2060 – 60 years after disturbance.

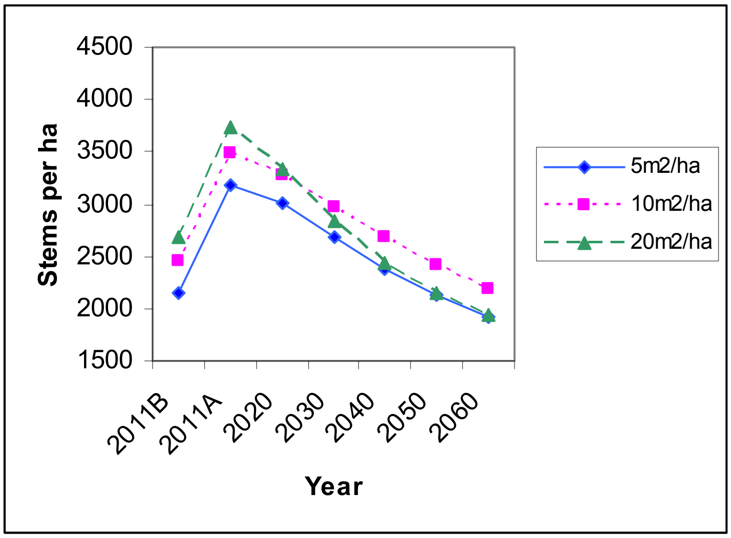

Figure 2. Projected stems per ha for Plot 4, IDFdm2 for 5, 10, and 20 m2/ha residual basal area and regeneration imputed from the PrognosisBC database. 2011B indicates plot before imputation; 2011A indicates plot after imputation.

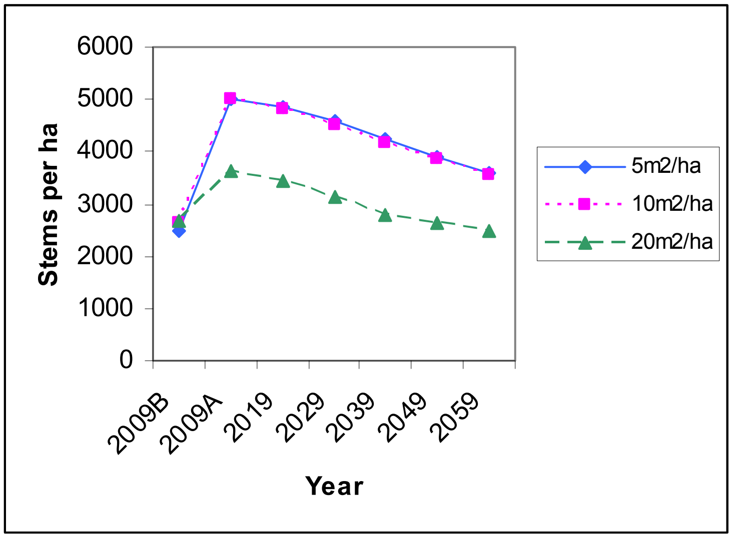

Figure 3. Projected stems per ha for Plot 3, IDFdk1 for 5, 10, and 20 m2/ha residual basal area and regeneration imputed from the PrognosisBC database. 2009B indicates plot before imputation; 2011A indicates plot after imputation**.**

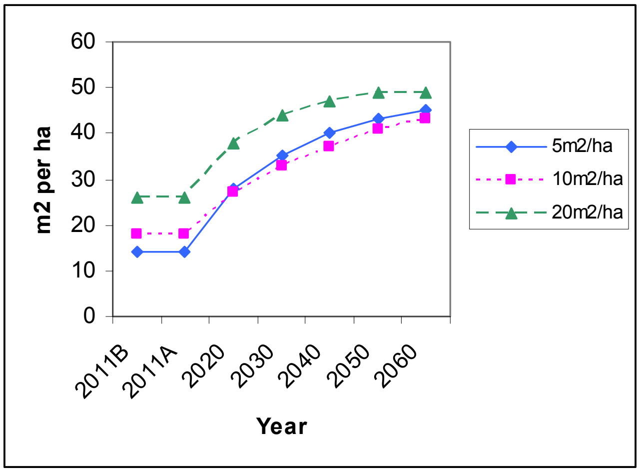

Figure 4. Projected basal area per ha for Plot 4, IDFdm2 for 5, 10, and 20 m^2/ha residual basal area and regeneration imputed from the Prognosis^{BC} database. 2011B indicates plot before imputation; 2011A indicates plot after imputation.

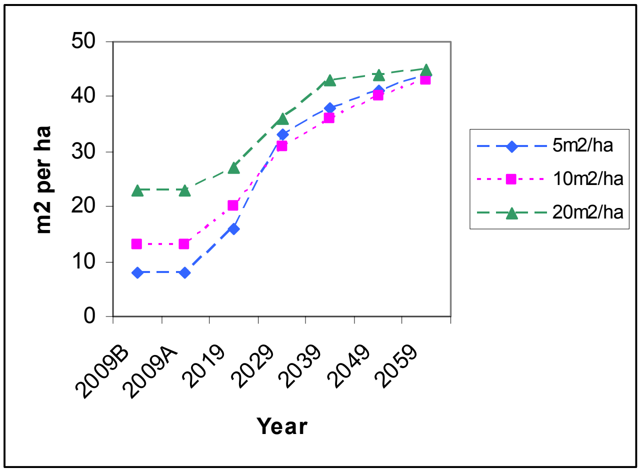

Figure 5. Projected basal area per ha for Plot 3, IDFdk1 for 5, 10, and 20 m2/ha residual basal area and regeneration imputed from the PrognosisBC database. 2009B indicates plot before imputation; 2009A indicates plot after imputation**.**

In terms of species composition, the amount of partial cutting and the use of imputation following cutting resulted in large changes in species composition by stems per ha (Figure 6), using Prognosis^{BC}. For the lowest cutting intensity, many of the imputed regenerated trees were spruce, resulting in a high proportion of spruce relative to Douglas fir following imputation. Since Douglas-fir is semi-shade intolerant, the more shade tolerant spruce might be expected to be regenerated following low intensity removals. However, more examination of these results of imputation is needed.

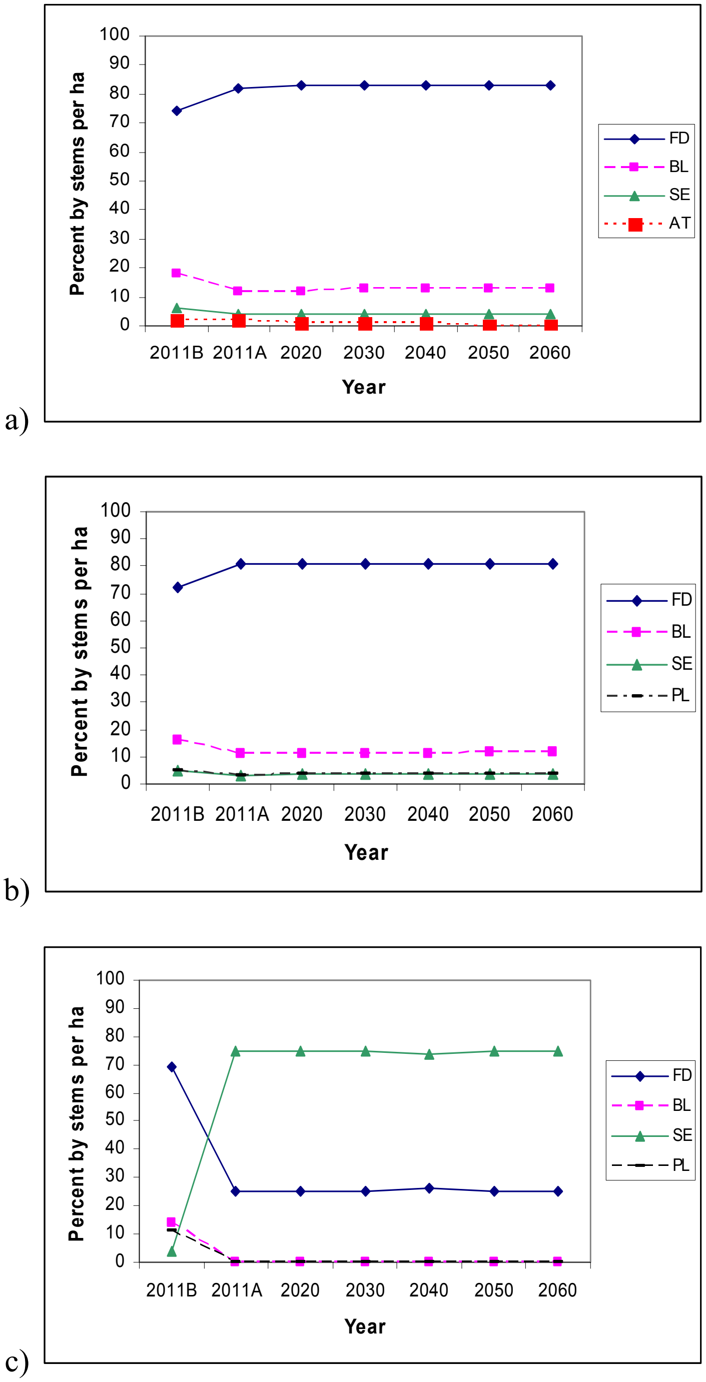

Figure 6. Species composition by stems per ha for a) 5 m^2/ha; b) 10 m^2/ha; and c) 20 m^2/ha for Plot 4 of IDFdm2.

DISCUSSION

An imputation-based Prognosis^{BC} regeneration model was developed and calibrated for predicting natural regeneration following partial harvesting disturbances. However, further testing of this approach to estimating regeneration is presented in this report. In particular, the use of the regeneration component model for MPB-affected stands was investigated, and the use for long-term projections of partially cut stands was further examined.

Regeneration Imputation in MPB-Affected Stands

Using any model outside the range of conditions for which it was developed could result in inaccurate predictions. The MSN approach to imputation selects the closest (most similar) neighbour plot (stand) from the available reference plots (stands) based on correlations among the set of variables used in the model. The use of MSN with overstory and site variables to predict regeneration has been used on partially cut stands, based on statistics for live residual trees. When used to predict natural regeneration following MPB disturbances, the model (MSN plus site variables and live overstory variables) consistently underestimated regeneration of the shade intolerant species, even when data from MPB-affected stands was used in the imputations. These results could be due to: 1) the sparseness of available MPB-affected stand data; and/or 2) need for other variables for imputing regeneration in MPB-affected stands.

To obtain good results for estimating regeneration in MPB-affected stands, data from affected stands are needed. The MPB-affected stand data used in this study represented very few plots. Predictions produced by the MSN models that used the MPB-affected plot data alone or in combination with the existing model database were more accurate than those produced by the model that used the existing model database alone. Data in the existing Prognosis^{BC} regenerated stands database show Douglas-fir as the leading species, whereas MPB-affected stands are predominately lodgepole pine. When both datasets were used, estimates were less biased than using the MPB data alone. An examination of the selected neighbours indicated that 75% of the target plots were matched with reference plots from the existing partial harvesting database. Likely this was due to the low range of stand conditions represented in the MPB-affected stand data, as few data were available.

As well as the problem with little data and limited ranges of variables represented in the MPB-affected plot data, the poor performance of the Prognosis^{BC} regeneration model could be attributed to the exclusion of the variables that best describe stand dynamics of MPB-affected stands and to the absence of some site variables in the MPB data. Stands could be at different stages of development following MPB- infestation and yet have the same basal area or number of live trees. For example, given two stands with the same residual density of standing live trees, one stand could be more occupied due to a high density of snags, thus limiting the establishment of regeneration, whereas the other stand with the same standing live trees could have few standing dead trees and more coarse woody debris (fallen trees). Changes in stand structure are expected as a result of beetle infestation (Amman and Baker 1972; Mitchell and Preisler 1991) and inclusion of information on mortality, survivor growth, ingrowth, snag decay and fall rates and coarse wood debris in MPB-affected stands would have undoubtedly provided better estimates and enhanced the performance and the stability of Prognosis^{BC} regeneration model predictions. The use of other site variables, such as aspect, could potentially improve the selection of the most similar neighbour stands. Aspect has been cited as a crucial variable for the MPB attack, with more severe in the warmer south-facing aspects.

Since the established regeneration found in these zones appears to be dominated by shade intolerant species, changes to the regeneration imputation model (approaches and variables used) are needed, in order to make long-term projections in MPB-affected stands. Linking a model that could simulate the impact of MPB and subsequent development of the affected stands to Prognosis^{BC} would provide estimates of the variables that describe the pine beetle population dynamics.

Effects of Varying Levels of Partial Cutting on Long-term Prognosis^{BC} Model Projections

Partial harvesting is generally used to stimulate the growth of the residual stands, maintain species and structural diversities, improve stand health, and generate financial return. The intensity of partial cutting and the subsequent natural regeneration establishment are keys to achieving desirable outcomes. Three different intensities of partial cutting were simulated and results investigated for validity. The level of removal was defined by setting the residual plot basal area, and cutting from above (larger diameters first).

In estimating regeneration in these partially cut stands, the number of years since disturbance, residual basal area, and crown competition factor were often used in finding a match in the reference dataset. In all the scenarios simulated, the number of residual trees per ha and the quadratic mean diameter of the stand were often not used. Other studies have indicated similar results in estimating natural regeneration (e.g., Martin *et al.* 2002, Hassani *et al.* 2004).

The 60-year projections following each of the three simulated partial cutting intensities mostly followed expected trends. The average number of trees per ha over the five plots in each subzone was lower for the 20 m^2/ha residual basal area, and there were no noticeable differences in the basal area among the three treatments. The yields (standing merchantable volume plus cut merchantable volume) were greater for the greater basal area removals, since the harvest volumes were greater. Total volumes achieved in the IDFdk1 were commonly higher than in the IDFdm2, as might be expected. Also, the imputed natural regeneration mostly increased with decreasing residual basal area, as would be expected.

However, species composition was quite different among the three cutting intensities, given that the same pre-cutting plot data were used. Although regeneration is expected to be higher for tolerant species following lower intensity removals, more examination of species changes with regeneration for varying partial cutting intensities is needed.

Some issues with projection of very small trees were also noted in the simulations. These trees represent a high number of stems per ha, and any problems with estimation can result in large differences in projections over long periods. Further validation of estimating DBH from height for very small trees, and small tree mortality is needed. Also, the diameter limit used in defining overstory trees needs to be further examined, in order to be certain that there is no overlaps with imputed regeneration causing overestimates of stems per ha.

CONCLUSIONS

Forests of southeastern and central BC are complex and have been originated via a variety of natural and managed disturbances. Partial cutting has been employed to preserve species and structural complexities. These forests have also been undergoing a catastrophic MPB outbreak. The use of models, such as Prognosis^{BC}, have potential for simulating long-term impacts of these disturbances. However, models need to be calibrated and validated in order to provide logical and accurate projections.

Due to limitations in the available MPB-affected plot data used for this project, a reduced set of overstory and site variables were used in the Prognosis^{BC} natural regeneration sub-model to estimate natural regeneration following MPB disturbances. Even when thse data were augmented by existing regeneration data for partially cut stands, regeneration was often underestimated. Other variables more relevant for predicting natural regeneration in MPB-affected stands should be tested; a larger MPB-affected plot database would improve imputation results.

The effect of varying degrees of degrees of partial cutting on long-term residual stand variables, merchantable yield, species composition, and the regeneration followed mostly expected trends. However, further investigation in species distributions for different cut levels is warranted as results were quite different among intensities simulated. Also, the DBH from height estimation model for very small trees should be examined for accuracy, and the DBH limit used to define overstory trees in estimating regeneration should be reconsidered.

REFERENCES CITED

Amman, G.D., and B.H. Baker. 1972. Mountain pine beetle influence on lodegepole pine stand structure. J. Forestry. 70: 240-209.

Beukema, S.J. and D.C.E. Robinson. 2004. Modelling mountain pine beetle in the Cholcotin using the Westwide pine beetle model. Prepared by ESSA Technologies Ltd., Vancouver, BC for the Canadian Forest Service, Victoria, BC. 21 pp.

Boisvenue, C. 1999. Early height growth and regeneration: applicability of Prognosis components to the southern interior of British Columbia. M.Sc. Thesis, University of British Columbia, Vancouver, BC, Canada.

Braumandl, T.F. and M.P. Curran. 1992. A field guide for site identification in the Nelson Forest Region. Ministry of Forests, Nelson. 311 pp.

British Columbia Ministry of Forests. 2003. Timber supply and the mountain pine beetle infestation in British Columbia. Forest Analysis Branch. Victoria, B.C.

Carroll, A.L., S. W. Taylor, J. Régnière. 2004. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Report prepared for the BC Ministry of Water, Land and Air Pollution.

Carroll, A.L., S.W. Taylor, J. Régnière, L. Safranyik. 2003. Effects of climate change on range expansion by the mountain pine beetle in British Columbia. Pages 223-232 in T.L. Shore, J.E. Brooks, and J.E. Stone, editors. Mountain Pine Beetle Symposium: Challenges and Solutions, October 30-31, 2003, Kelowna, BC. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, British Columbia, Information Report BC-X-399. 298 p.

Crookston, N.L. and A.R. Stage. 1991. User's guide to the Parallel Processing Extension of the Prognosis Model. USDA Forest Service Gen. Tech. Rep. INT-281. 88 pp.

Crookston, N.L., M. Moeur, and D. Renner. 2002. Users guide to the most similar neighbor imputation program Version 2. Gen. Tech. Rep. RMRS-GTR-96. UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 35 p.

Delong, D.L. 1997. Overview of silvicultural systems research in the Nelson Forest Region. In. Jull, M., D. Coxon, S. Stevenson, D. Lousier, and M. Walters (editors). 1997. Ecosystem dynamics and silvicultural systems in Iterior Wet-belt ESSF and ICH forests: Workshop Proceedings, June 10-12, 1997, University of Northern British Columbia, Prince George, B.C.

Fall, A., M. Eng, T. Shore, L. Safranyik, B. Riel, and D. Sachs. 2001. Mountain pine beetle audit project: Kamloops Forest District Landscape model. Final documentation. B.C. Ministry of Forests internal report.

Froese, K.L, V. LeMay, P. Marshall, and A-A. Zumrawi. 2003. Regeneration imputation models for PrognosisBC: IDFdm2 subzone variant, Invermere Forest District Report prepared for the Forestry Innovation Investment. Ref. No. R02-07, 67 pp. http://www.forestry.ubc.ca/prognosis/extension.html

Hassani, B.T., V. LeMay, P.L. Marshall, and A-A Zumrawi. 2002. Regeneration under partial cutting for Prognosis^{BC}, MSdk, Cranbrook Forest District. Report for Forestry

Innovative Investment, Ref. No. R02-07. 10 pp. (http://www.forestry.ubc.ca/prognosis).

Hassani, B.T., V. LeMay, P. Marshall, and A-A. Zumrawi. 2003. Regeneration under partial cutting for PrognosisBC, MSdk, Cranbrook Forest District. Report prepared for the Forestry Innovation Investment. Ref. No. R02-07, 30 pp. http://www.forestry.ubc.ca/prognosis/extension.html

Hassani, B.T. , V. LeMay, P. L. Marshall, H. Temesgen, and A-A Zumrawi. 2004 Regeneration imputation models for complex stands of Southeastern British Columbia. For. Chron. 80 (2): 271-278.

Hawkes, B, Taylor, S., Stockdale, C., and T. Shore. 2002. Impacts of mountain pine beetle attack on stand and ecosystem dynamics. Canadian Forest Service, Victoria BC. FRBC Reference # PAR 022003-06. Reporting period: April 1, 2001-March 31, 2002.

Heath, R. and R.I. Alfaro. 1990. Growth response in a Douglas-fir/lodgepole pine stand after thinninh of lodgepole pine by the mountain pine beetle: A case study. J. Entomol. Soc. B.C. 87.

Hope, G.D., W.R. Mitchell, D.A. Lloyd, W.R. Erickson, W.L. Harper, and B.M. Wilkeem. 1991. Interior Douglas-fir zone. Ecosystems of British Columbia. D. Meidinger and J. Pojar (Eds). Victoria, Research Bramch Ministry of Forests: 153-166.

J.S. Thrower and Associates. 1995. Incorporating impacts of partial cutting in timber supply analyses. Report prepared for the B.C. Ministry of Forests, Forest Practices Branch.

Ketcheson, M.V., T.F. Braumandl, D. Meidinger, G. Utzig, D.A. Demarchi, B.M. Wikeen. 1991. Interior Cedar-Hemlock Zone. *In*: Ecosystems of British Columbia. Special Report Series # 6. B.C. Ministry of Forests, Victoria.

Lencar, C. 2003. Prognosis^{BC} Database Consolidation. Report prepared for the Forestry Innovation Investment. Ref. No. HQ03-199, 28 pp.

Martin, R.A., B. Hassani, V.LeMay, P.Marshall, H. Temesgen, and C.Lencar. 2002. Development of regeneration imputation models for the IDF dk2, dk2, and dk3 subzone variants of the Kamloops and Cariboo Forest Regions. Report prepared for Forest Renewal BC. PAR02002, Activity Location 724187, 20 pp plus Appendices. http://www.forestry.ubc.ca/prognosis/extension.html

Meidinger, D. and J. Pojar. 1991. Ecosystems of British Columbia. B.C. Ministry of Forests, Victoria. B.C.

Mitchell, J.L. 1994. Commercial thinning of mature lodgepole pine to reduce susceptibility to mountain pine beetle. Forest Engineering Research Institute of Canada, Vancouver, BC. FERIC Special Report N0. SR-94. 20 p.

Mitchell, R.G., and H.K. Preisler. 1991. Analysis of spatial patterns of lodgepole pine attacked by outbreak populations of the mountain pine beetle. For. Sci. 37: 1390-1408.

Parminter, J. 1998. Natural disturbance ecology. *In* Conservation biology principles for forested landscapes. J.Voller and S. Harrison (editors). UBC Press, Vancouver, B.C., pp. 3-41.

Robinson, D.E. 1997. Prognosis Southern Interior (SI. 0g) Geographic Variant Description. Report to the Ministry of Forests. 178 pp.

Roth, M. Rossetto, P. Jackson. 2004. Effects of topography upon mountain pine beetle (*Dendroctonus ponderosae*) transport and dosperson as indicated by mesosclae meteorological models. Conference Proceddings. Preprints, 16th Conference on Biometeorology and Aerobiology. American Meteorological Society, Vancouver. August 22-26.

Safranyik L., H. Barclay, A. Thompson., and W.G. Riel. 1999. A population dynamics model for the mountain pine beetle, *Dendroctonus ponderosae* Hopk. (Cleoptera: Scolytidae). Natural Resouces Canada, Can. For. Serv. Inf. Rep. BC-X-386. 35 pp.

Shore, T. and L. Safranyik. 1996. The impact of the mountain pine beetle, Dendroctonus ponderosae on lodgepole pine stands in British Columbia, Canada. In: Korpilahti, E, Salonen, T., S. Ojal (eds). Caring for the forests: research in a changing world: abstract of invited papers, IUFRO XX World Congress, 6-12 August 1995. Tampere, Finland.

Snee, R.D. 1977. Validation of regression models: methods and examples. Technometrics. 19: 415 – 428.

Stage, A.R. 1973. Prognosis model for stand development. Res. Pap. Int – 137. USDA Forest Service, Intermt. For. And Range Exp. Stn., Ogden, UT. 32 pp.

Statistical Analysis Systems Institute, Inc., 2001. SAS Language: Reference, Version 8.2, second edition. SAS Institute, INC., Cary, NC.

Steen, O. and D.A. Demarchi. 1991. Chap. 13: Sub-boreal Pine-Spruce zone. *In* Ecosystems of British Columbia. D. Meidinger and J. Pojar (editors). B.C. Min. For., Victoria, B.C.

Steen, O. and D.A. Demarchi. 1991. Sub-Boreal Pine-Spruce zone. *In* Ecosystems of British Columbia. D. Meidinger and J. Pojar (editors). Research Branch, B.C. Minstry of Forests, Victoria, B.C. Special Report Series No. 6. pp. 196-207

Steen, O. and R.A. Coupe 1997. A field guide to forest site identification and interpretation for the Cariboo Forest Region. B.C. Ministry For., Victoria, B.C. Land Manage. Handb. No. 39.

Stone, W.E., and M.L. Wolfe. 1996. Response of understory vegetation to variable tree mortality following a mountain pine beetle epidemic in lodgepole pine stands in northern Utah. Vegetatio 122: 1-12.

Temesgen, H. and V. LeMay. 2000. Re-fitting the mortality model of PrognosisBC for both conifers and hardwoods in the Nelson and Kamloops forest regions. Report to the Ministry of Forests. 23 pp.

Wong, C. 2001. Towards ataxonomy of natural disturbances in British Columbia. Prepared for B.C. Min. For., Res. Br., Victoria, B.C.

Wong, C., B. Dorner, and H. Sandmann. 2003. Estimating historical variability of natural disturbances in British Columbia. B.C. Min. For., Res. Br., B.C. Min. Sustain. Resource. Manage., Resource Plan. Br., Victoria, B.C. Land Manage. Handb. No. 53. www.for.gov.bc.ca/hdf/pubs/Docs/Lmh/Lmh53.htm.

Wood, C.S. and L. Unger. 1996. Mountain Pine Beetle- A history of outbreaks in pine forests in British Columbia, 1910 to 1995. Canadian Forest Service, Natural Resources Canada.

Zumrawi, A., A. Stage, and B. Snowdon. 2002. Stand level scaling of a single distance independent diameter growth model: Interim calibration of Prognosis in the southeastern interior of British Columbia. *In:* Crooston, Nicholas L.; Havis, Robert N. comps. 2002. Second Forest Vegetation Similator (FVS) Conference; February 12-14, 2002, Fort Collins, CO. Proceedings RMRS-P-000. Ogden, UT: US. Department, Forest Service, Rocky Mountain Research Station.

Zumrawi, A. A., V. LeMay, P. Marshall, B. Hassani., and C. Lencar. 2003. Natural regeneration and juvenile height growth models for partially cut complex stands of Southeastern and Central BC. Presented at the Regeneration Issues in Partial Cutting Workshop, October 28, 2003, Kelowna, BC.

A Regeneration Model for Prognosis^{BC}

BC Ministry of Forests

A Regeneration Model for Prognosis^{BC}

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Acknowledgements

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1.0 Introduction

The Prognosis^{BC} regeneration system links a stand growth model and its initial inventory, observations of regeneration found at many sites, and statistical methods to infer the specific regeneration that is most likely to be found on a simulated site. The design, database and user interface are now complete and the system is available for testing in the IDF zone (the source of most of the regeneration data).

The system combines these key elements:

(iv) Prognosis^{BC} – a growth model calibrated for the IDF, ICH and SBS biogeoclimatic zones;

(v) MSN – a statistical programme that uses a multivariate database of regeneration observations to match an empirical observation from the database to the stand where regeneration is being simulated (Moeur and Stage 1995; Crookston et al. 2002, Hassani et al. 2004);

(vi) a stand-alone computer programme to coordinate formatting output from Prognosis^{BC}, querying the database and returning results back to Prognosis^{BC};

(vii) methods to constrain the data that are chosen by the similarity matching; and

(viii) an interface to simplify its use.

The first two components of this system are available and are not part of the deliverables for the project. The last three components have been completed under this project, resulting in a user interface to the database and statistical methodology. This report describes the approaches taken for the interface. Sample screen captures are included in the appendix.

A graphical view of the system's operation is shown below in Figure 1.1 (updated from Robinson 2003).

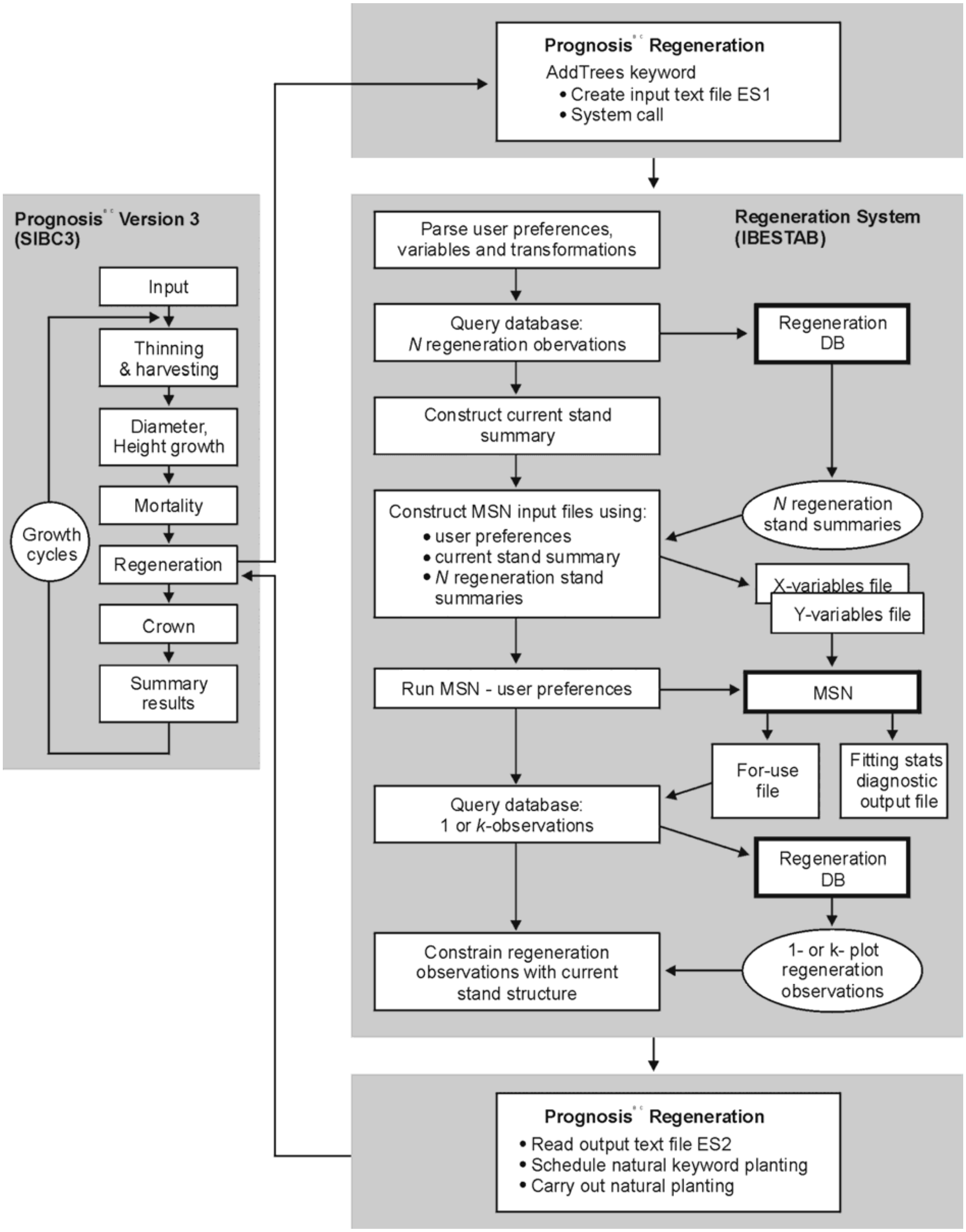


Figure 1.1: The regeneration system – IBESTAB – is linked to the SIBC3 growth model using the programme flow shown here.

2.0 System Design

2.1 Component Software

The regeneration system consists of 7 components:

- a host operating system;
- a graphical interface to simplify use;
- a stand-alone executable regeneration control programme;
- a regeneration database;
- methods for constraining the inclusion of selected regeneration trees;
- methods for selecting the most appropriate regeneration data; and
- a growth model.

The work covered by this report includes the development of the graphical interface, revisions to the regeneration database and methods for constraining the regeneration (components 2, 3, 4 and 5)

2.2 Operating Systems

The following Microsoft Windows operating systems are supported:

- Windows 2000; and
- Windows XP

With the exception of the Windows-based Prognosis^{BC} graphical interface (described below), the regeneration system should work on most other operating systems (OS) with additional development work. The key OS-dependent elements of the regeneration system are:

- support for querying the database. This is currently implemented with third party software from Canaima Software (http://www.canaimasoft.com);
- the ability to carry out a "System" call to the target OS from within the regeneration programme; and
- syntax differences among operating systems (e.g. the use of "\" to separate sub-directories on a DOS-derived OS; and "/" on a Unix-derived OS).

2.3 Graphical Interface

The Windows-based Prognosis^{BC} interface (a set of 3 linked VisualBasic 6 applications: DataProg, SimProg and ViewProg) provides model users with a simplified visual environment for making stand simulations. It is not supported on non-Windows operating systems, although the core growth model and regeneration model (both written in Fortran) could be ported to other system, providing database support was provided.

The SimProg interface has been modified to simplify the automatic selection of regeneration data. Design and implementation of the interface follow the development of the core functionality, and include the ability to schedule regeneration automatically or manually, depending on conditions specified by the user, followed by the automatic generation of keyword sets based on the user's selections. Example screen captures from SimProg are included in the Appendix.

2.4 Regeneration Control Programme

The purpose of the regeneration control program (IBESTAB.exe) is to prepare the information passed to it by the Prognosis^{BC} core growth model (SIBC3.exe) and format it for use by the Most Similar Neighbour (MSN) software. As well, information from the regeneration database is extracted and prepared for MSN. The two sets of information – simulation stand and database stands – are submitted to MSN and the best match is obtained. The match is constrained so that the most similar stand must be taken from the same BEC zone. Finally, the detailed regeneration information from the best match is extracted, formatted and placed in a text file for use by SIBC3.

The regeneration model was originally incorporated directly into the SIBC3 source code. One drawback of this design decision was that any researcher wishing to implement alternative regeneration rules would need to master a great deal of source code infrastructure before being able to implement the biological or geographic determinants of regeneration. To encourage the development of alternative regeneration models that could be developed and incorporated with a minimum of code change to the core model (subroutine esaddt), the design was altered, as shown in Figure 1.1 and Table 2.1, and described in detail below.

Table 2.1: Detail of steps taken by IBESTAB when called by Prognosis^{BC}. Italicised filenames show the subroutine names where the activities take place.

SIBC3

```
AddTrees is read and stored: – strp/src/esin.for
AddTrees is processed: – strp/src/esaddt.for
    Create and open file: Keyfile_StandID_year_IB.ES1
    Summarize necessary stand attributes: Stand ID, BEC, etc.
    Write stand attributes to ES1 file
    Close file
    Do System call: ibestab.exe <arguments> Keyfile_StandID_year_IB.ES1
```

IBESTAB

```
Run IBESTAB: – ibestab/src/main.for
    If IBESTAB.ini exists, open and read – ibestab/src/getini.for
        Keep-file flag
    Else
        Keep-file flag = false
    End
    If ES1 files exists
        Open and read stand attributes – ibestab/src/getprm.for
        Calculate predicted regeneration – ibestab/src/getstock.for
        Create output ES2 file – ibestab/src/setestb.for
            Write Keep-file flag
            Write Stand ID
            For each predicted regenerating species
                Natural keyword code – 431
                Calendar year to schedule activity
                6 (number of parameters)
                Numeric species code
                Trees/ha
                % survival
                age
                height
                shade code
            End
            Write ‘End’ terminating record
        Close
    End
    Close all open files
    Delete ES1 file if requested
End
```

SIBC3

```
Open ES2 file – strp/src/esaddt.for
Read Keep-file flag
Call OPRDAT to process remainder of file
Close ES2 file
Delete ES2 file if requested
Establishment Model keyword processing adds new trees to the simulation
```

2.4.1 Keyword Implementation

IBESTAB is run, either manually or through the SimProg interface, using SIBC3 and the Establishment Model’s AddTrees keyword[2] (see Tables 2.2 – 2.4). When a 1 is present in field 3 off AddTrees, a supplemental record containing the name of the executable file and its arguments must follow the record. As described in Section 2.4.4, SIBC3 uses unique runtime information (constructed from the keyword file prefix, Stand ID, year and variant abbreviation) to create a filename with the suffix ES1. Internally, SIBC3 appends this ES1 filename to the

---

[2] It is also possible to use IBESTAB independently of SIBC3 or Prognosis^{BC}; a useful feature when testing and developing new models.

name of the executable and its arguments, and submits the entire command line to the operating system for execution.

Table 2.2: Example of keyword set using AddTrees keyword with IBESTAB. When line 6 is passed to the operating system, the name of the ES1 file as appended to the end of the line. Note also that in this example, IBESTAB and the files referenced by its arguments are located in a different directory. Besides scheduling regeneration based on 'Condition', the example also shows a burning site preparation activity two years before regeneration.

```
Line                                  Column ruler
Nmbr  ----+----1----+----2----+----3----+----4----+----5----+----6----+----7
      Keyword      Field 1   Field 2   Field 3   Field 4   Field 5   Field 6
   1  If
   2  Condition
   3  Then
   4  Estab
   5  BurnPrep           0
   6  AddTrees           2         2         1
   7  .\Regen\ibestab.exe .\Regen\regen.mdb .\Regen\MSN.exe 1
   8  End
   9  Endif
```

Table 2.3: Fields of the AddTrees keyword.

Field	Example Value	Notes
1	2	Years after Condition is true that the AddTrees keyword is scheduled
2	2	Years after AddTrees is run to schedule a Natural planting; age to assign new trees
3	1	Method 1 signals Prognosis^{BC} to (1) read a supplemental record containing an executable filename (2) submit and run the record using a System call, appending a command line argument containing the ES1 filename; (3) read the ES2 output file created by IBESTAB; and (4) use the content of that file to schedule Natural keywords in Prognosis^{BC}.

Table 2.4: Fields of the record following the AddTrees keyword record.

Field	Example Value	Notes
1	.\Regen\ibestab.exe	location of the IBESTAB executable
2	.\Regen\regen.mdb	location of the regeneration database file
3	.\Regen\MSN.exe	Location of the MSN executable
4	1	MSN distance calculation method
5	NB: when the record is passed to the operating system for execution, the name of the ES1 file is appended as a 5th argument: e.g. rgntest_1-103_2016_IB.ES1	

2.4.2 Input and Output Files

A total of six files are using by the regeneration system. These are listed in Table 2.5 and described in subsequent sections. The second and third files – ES1 and ES2 – are dynamic data files automatically created (and possibly deleted) by SIBC3 and IBESTAB during a simulation run. The names ES1 and ES2 are filename suffixes only, and not complete filenames. When run from SIBC3, a unique filename prefix is created automatically, (see Section 2.4.4). The ibestab.ini, ES1 and ES2 files will (and must) all reside in the same directory as SIBC3. However, when run manually, the user can provide an alternative path for the ES1 file. Because of the way the ES1 filename is parsed, the output ES2 file will reside in the same location as the ES1 file.

Table 2.5: Files used by the Prognosis^{BC} regeneration system.

File	Notes
IBESTAB.exe	Regeneration model executable
ibestab.ini	Global parameters for regeneration system: save or delete intermediate files
ES1	File created by Prognosis^{BC} and used by IBESTAB
ES2	File created by IBESTAB and used by Prognosis^{BC}
MSN.exe	Most Similar Neighbour executable
regen.mdb	Prognosis^{BC} regeneration database

When run from the operating system command line (which is possible but will not usually be done outside of testing and development), IBESTAB is accompanied by a set of arguments (see Table 2.4) and then by the name of the ES1 input file. The input file need not be in the same directory as IBESTAB and need not have an ES1 suffix. The content of the ES1 file must exactly match the format described in Section 2.4.4.

2.4.3 ibestab.ini

This file contains the 1 line shown in Table 2.6 (additional default parameters may be added in the future). The line should be right justified to column 30, and text beyond column 30 is ignored. When the value of the line is non-zero, it instructs IBESTAB to keep the input file; otherwise it is deleted. If the ibstab.ini file cannot be found, the default shown in Table 2.6 is used.

Table 2.6: Records of the optional ibestab.ini file.

```
Line                  Column ruler
Nmbr  ----+----1----+----2----+----3----+----4----+----5----+----6----+

   1                               0  Keep: (default 1 = .TRUE.)
```

2.4.4 SIBC3 Output File ES1

When a simulation run uses the AddTrees keyword, SIBC3 creates a 17-record file having “ES1” as its suffix. All records in the file are right justified to column 30, and text beyond column 30 is ignored (Table2.7). The purpose of this file is to send runtime information to IBESTAB. The prefix of the filename is composed of the prefix of the keyword filename, the Stand Identifier name of the stand being processed, the year in which establishment is being predicted, and the 2-letter SIBC variant code “IB”. For example, given a keyword file “rgntest.key” containing a StdIdent keyword followed by “1-103” with IBESTAB scheduled for 2016, this filename would be created:

rgntest_1-103_2016_IB.ES1

The content of the ES1 file is tailored to the input requirements of IBESTAB, and only information required by IBESTAB is printed to this file. The fourth record of the input file passes to IBESTAB the value from field 2 of the AddTrees keyword.

Table 2.7: Example records of an ES1 file created by SIBC3.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+	
1	1-103	Stand ID
2	IDFdk4/01	BEC/site series
3	UPPER	slope position [1]
4	2016	planting year
5	3	years since disturbance
6	MIXED	site preparation [2]
7	274	aspect (degrees) [3]
8	31	slope (percent)
9	1120	elevation (m)
10	0.0	shade tolerant stems (ha^{-1})
11	12.6	shade semi-tolerant stems (ha^{-1})
12	5625.1	shade intolerant stems (ha^{-1})
13	0.0	shade tolerant basal area (m^2 ha^{-1})
14	0.0	shade semi-tolerant basal area (m^2 ha^{-1})
15	18.5	shade intolerant basal area (m^2 ha^{-1})
16	6.1	stand QMD (cm)
17	82.8	stand crown competition factor

[1] LOWER, MIDDLE, UPPER – Slope position is reduced from 5 possible levels in SIBC3 to 3 levels for use with the database.

[2] BURN, BRUSH, MECH, MIXED or NONE – Mixed defined as Burn and Brush within one year of each other; None defined as no site preparation within previous 10 years.

[3] Aspect 0 = North, aspect 90 = East, etc.

2.4.5 IBESTAB Output File ES2

IBESTAB creates a multiple record output file after it runs. The filename prefix of the ES1 input file is used as the prefix for the output ES2 filename. The total number of records in the ES2 file depends on the number of unique species and sizes to be planted, but at least three records are produced by every run (Table 2.8). The first record is right justified to column 10. Apart from the first line, records in the file need not be column formatted (to accommodate printing, blank spaces have been removed from the line 3 in the example shown in table 2.8). Since the purpose of this file is to send establishment information from IBESTAB to SIBC3, the content of the ES2 file is tailored to the generation of the Natural planting keywords that are part of the Prognosis^{BC} establishment model system.

Table 2.8: Example records of an ES2 file created by IBESTAB.

```
            Column ruler*
Line   --/--1--/--2--/--3--//--4--//--5--//--6--//--7--//--8--//--9
Nmbr

   1         1
   2   1-103
   3       431   2016     6      7  795.8     100      2   1.79      0
   4       431   2016     6      3  103.0     100      5   2.24      0
   5   End
```

* To accommodate printing on the page, blank spaces have been removed from the lines.

The simple example shown in table 6 contains only 4 records. The first record acts as a flag (just like the last record of ibestab.ini) passed back to SIBC3. If the value is non-zero the ES2 file is deleted after it is used; otherwise the ES2 file is kept. The following line contains the Stand ID (for possible future implementations where results for more than one stand are returned from a single run of IBESTAB). Subsequent lines contain regeneration predictions suitable for scheduling Natural planting keywords. The first field of the third and subsequent records (up to an ‘End’ record) gives an internal code used by SIBC3 for Natural plantings. The second field is the year in which to schedule the planting. The third field is the number of parameters (always 6) that will be used in the scheduling. The fourth field is the species code (7 in the table is the code value for lodgepole pine; 3 in the table is Douglas-fir); the fifth and subsequent fields are stems/ha, percent survival, age when ‘planted’, height and shade tolerance code. Finally, the regeneration records are terminated by an ‘End’ record. Further information about the Natural keyword may be found in the FVS keyword guide (van Dyck 2002).

2.5 Regeneration Database

The database is a single user Microsoft Access 97 file residing on a workstation on which Prognosis^{BC} has been installed and configured. Since all interaction with the database is done programmatically, users do not need to have Access installed to use the system. If the regeneration database grows to a large size (exceeding 1 GB), alternative database systems (for example, later versions of Access coupled with linked tables) could be employed. Currently, the key linkage to the standalone database is the existence of drivers to link the growth model with the database, and the use of SQL queries that work in all operating environments. With additional work the database could be hosted in a different format, or even hosted by an Internet-based SQL server, removing the need to issue database updates.

The regeneration database content has been developed by Cornel Lencar and Badre Hassani, Department of Forest Resources Management, UBC; with contributions and enhancements to the structure from Leonardo Frid and Sarah Beukema at ESSA. The original (2003) database was developed as number of Microsoft Excel spreadsheets, and has subsequently been imported to a Microsoft Access database and reformatted to accommodate efficient queries. The Access database is queried directly from the regeneration model using third-party software from Canaima software (http://www.canaimasoft.com).

The structure of the database tables and fields is shown below. Secondary tables are shown following each of the main tables.

2.5.1 Plot Information

The PlotInfo table and its related sub-tables (Table 2.9) contain topographical information and other information related to the location and history of the sample plots.

Table 2.9: Simplified table structure for plot information in the regeneration database.

PlotInfo

DBPlotID – key
RegionID
BECID
SiteSeriesID
SlopePositionID
DisturbanceID
SitePreparationID
SampleYear
YearsSinceDisturbance
Aspect
Elevation
Slope

Region

RegionID – key
RegionName

SkidRoad

SkidRoadID – key
SkidRoadPresence

BEC

BECID – key
BECAbbreviation
BECName

SiteSeries

SiteSeriesID – key
SiteSeriesName

SlopePosition

SlopePositionID – key
SlopePositionShortName
SlopePositionName

Disturbance

DisturbanceID – key
DisturbanceShortName
DisturbanceName

SitePreparation

SitePreparationID – key
SitePreparationShortName
SitePreparationName

2.5.2 Regeneration Information

The Regeneration table (Table 2.10) and its related sub-tables contain specific information for the regeneration observed in each plot.

Table 2.10: Simplified table structure for regeneration information in the regeneration database.

Regeneration

- DBPlotID – key
- SubPlotID – key
- Tree – key
- SampleTypeID
- SpeciesID
- Age
- AgeDescriptionID
- HeightClassID
- Height
- DBH
- RegenerationTypeID
- SkidRoadID
- ExpansionFactorID
- ExpansionFactor

SubPlot

- SubPlotID – key
- SubPlotAbbreviation
- SubPlotName

SampleType

- SampleTypeID – key
- SampleTypeName

Species

- SpeciesID – key
- SpeciesAbbreviation
- Species
- LatinName
- PrognosisCode
- TolId

AgeDescription

- AgeDescriptionID – key
- AgeDescriptionName
- Description

HeightClass

- HeightClassID – key
- HeightClassName
- AvgHeightM
- HeightRangeM
- LowRangeM
- HighRangeM

RegenerationType

- RegenerationTypeID – key
- RegenerationTypeName

ExpansionFactor

- ExpansionFactorID – key
- Radius
- Area
- ExpansionFactor

ShadeTolerance

- TolIID – key
- TolAbbrev
- TolName

2.5.3 Residual Tree Information

The SmallTrees and LargeTrees and tables (Table 2.11) contain information on the residual trees for each plot.

Table 2.11: Simplified table structure for residual trees information in the regeneration database.

SmallTrees		LargeTrees	
DBPlotID	– key	DBPlotID	– key
BlockID		TreeNo	– key
PlotID	– key	SpeciesID	
TreeNo	– key	DBH	
SpeciesID		Height	
DBH		ExpansionFactorID	
Height		ExpansionFactor	
ExpansionFactorID		BATree	
5YrIncrement		Age	
BATree			
Age			
Distance			
Bearing			
Notes			

Much of the information in the major tables is found through indirect references to sub-tables. There are good design reasons to use this structure, but it is not the fastest way to query the information. In particular, every time IBESTAB runs, it always obtains a summary of the entire database, and this summary is always the same, assuming the database content has not changed. To improve the speed of queries, a static copy of this summary information is made and stored in a table called ‘PlotInfo_Static.’ This table contains the results obtained through joining the plot information to the regeneration and residual large and small tree information.

2.6 Constraints on Regeneration Data

During the stand development of the modelled stand it is easy to imagine mismatches between current stand structure and the stand structures encountered in the regeneration data. These mismatches would result in “out-of-context” new trees ‘planted’ in the stand. In a separate white paper, Nicholas Crookston (pers. comm.) has identified a number of possible mismatch cases, particularly where the regeneration data themselves and time lags produce differences in the diameter distributions of the two stands. The general solution to these realistic but complex situations is to devise methods to constrain the regeneration data so that new trees are not out-of-context to the stand in which they are placed.

It is also possible to imagine stands in which *k* sample plots are present in the inventory. In such cases it may be appropriate to allow the user the option to select the *k* most similar matches, using those matches to impute different regeneration on the sample plots. The current regeneration system is unconstrained and returns the single most similar match within the BEC zone of the simulation stand. Constraint-methods have been discussed over the course of the project. As resources permit, these constraint methods will be implemented in subsequent releases.

2.7 Imputation Methods

The regeneration system uses MSN software (Most Similar Neighbor Imputation Program Version 2 (Crookston et al. 2002)) to select most appropriate regeneration data (Hassani et al. 2004). The methodology is founded on the use of canonical correlation to find the best match (the minimum of a multivariate distance measure) between a collection of multivariate observations made from many stands, and a target stand. MSN provides five methods for computing the minimum distance, and users are able to select the MSN method they prefer.

Besides MSN's canonical correlation approach to measuring similarity, other approaches are also possible. Although these alternative statistical approaches (*e.g.* tabular or CART models) are not currently part of the system, the design of the linkage to the database has been made in a way that allows other regeneration models to be used as they are developed. The actual implementation of any new method will likely require a substantial effort.

2.8 Growth Model

The regeneration system is linked to the Southern Interior variant of Prognosis^{BC} (SIBC Version 3), and is applicable to current and future versions of the model. The existing 'STRP' ("stripped-down" Regeneration Model) suite of regeneration subroutines forms the basis for enhancements to the source code. The changes involve the following steps:

1. regeneration is scheduled with an AddTrees keyword invoked explicitly or through the Event Monitor (Crookston 1990);
2. the current stand structure is summarized based on user-specifications;
3. the database is queried for regeneration plot summaries;
4. MSN input files are constructed based on user-specifications, employing information from the current stand structure and from summaries extracted from the database;
5. the MSN programme is run with user-supplied options, optionally generating debug information;
6. MSN output is used to select the appropriate regeneration plot data;
7. the database is again queried to retrieve regeneration data;
8. data are constrained so that mismatches are reconciled; and
9. new trees are 'planted' in the simulation.

Since the STRP routines are used by all but two of the Prognosis variants (the exceptions are the Northern Idaho and Eastern Montana variants, which use Ferguson and Crookston's (1991) regeneration model), the changes made to develop this system are applicable to other variants besides Prognosis^{BC}: the enhancements made to develop this linkage are immediately transferable to the creation of regeneration models for any other variants of the Prognosis/FVS family that make use of the STRP routines.

3.0 Next Steps

Model development is a dynamic process, and a number of further development steps are possible. Some possible steps are described below:

1. Develop code to allow keyword control for constraining new trees, removing regeneration trees that are out-of-context for the current stand.
2. Streamline the SimProg interface to simplify simulation scenario definitions and better integrate regeneration options with the existing system.
3. With input from inventory specialists and commercial inventory companies, develop ways to harmonize field regeneration inventories with the database structure used by Prognosis^{BC}; a prototype data entry system has already been developed for this purpose.
4. Expand the regeneration inventory to include new BEC zones or more complete coverage of existing BEC zones, and to include better linkages between disturbances like fire and insects in both the database and Prognosis^{BC}.

4.0 References

Crookston, N.L. 1990. User's guide to the Event Monitor: part of the Prognosis version 6. Gen. Tech. Rep. INT-275. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 23 p. [http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/event_monitor.pdf]

Crookston, N.L., M. Moeur and D. Renner. 2002. User's guide to the Most Similar Neighbor Imputation Program Version 2. Gen. Tech. Rep. RMRS-GTR-96. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rock Mountain Research Station. 35p. [http://forest.moscowfsl.wsu.edu/gems/MSNUserGuide.pdf]

Ferguson, D.E. and N.L. Crookston. 1991. User's guide to version 2 of the Regeneration Establishment Model: part of the Prognosis Model. Gen. Tech. Rep. INT-279. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34 p. [http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/estab.pdf]

Hassani, B.T., V. LeMay, P. L. Marshall, H. Temesgen and A.-A. Zumrawi. 2004. Regeneration imputation models for complex stands of Southeastern British Columbia. Forestry Chronicle. 80:271-278.

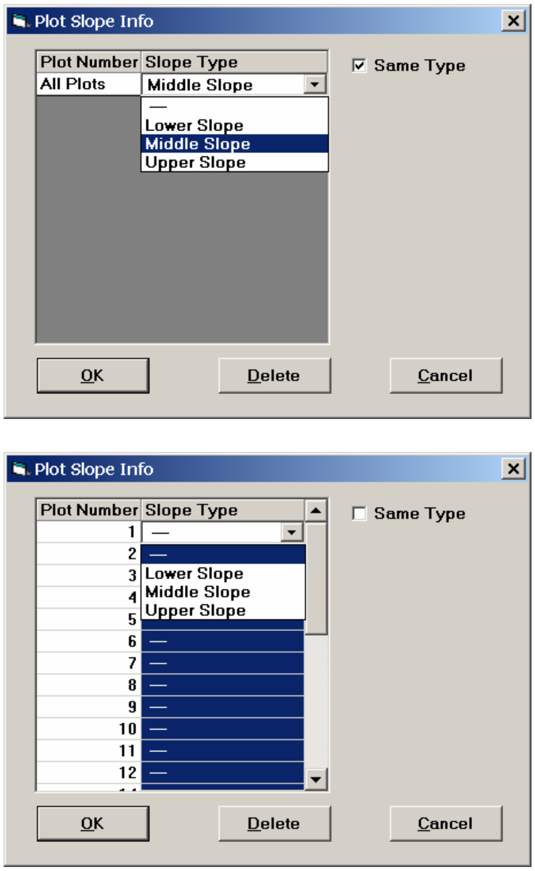
Moeur, M. and A.R. Stage. 1995. Most similar neighbor: an improved sampling inference procedure for natural resource planning. Forest Science 4:337-359.

Robinson, D.C.E. 2003. Development of a regeneration model for Prognosis^{BC} – design document. Prepared by ESSA Technologies Ltd. Vancouver, BC for BC Ministry of Forests, Victoria, BC. 9 pp.

Van Dyck, M.G. 2005. Keyword reference guide for the Forest Vegetation Simulator. USDA Forest Service, Forest Management Service Center, Fort Collins, Colorado. 122p. [http://ftp.fs.fed.us/pub/fmsc/ftp/fvs/docs/gtr/keyword.pdf]

Appendix

This appendix contains some example screen captures from the updated SimProg component of Prognosis^{BC}. Not all modified screens are shown here.



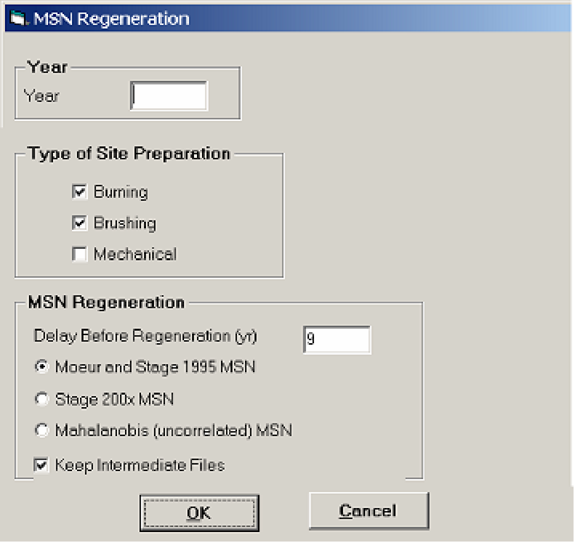
Plot Number	Slope Type
All Plots	Middle Slope

☑ Same Type

Plot Number	Slope Type
1	—
2	—
3	
4	
5	
6	—
7	—
8	—
9	—
10	—
11	—
12	—

☐ Same Type

Figure A.1: The regeneration system is sensitive to the slope position of the regenerating stand. This new information can be provided using a general (above) or specific assignment (below), based on the number of sample points in the simulated stand.



MSN Regeneration

Year

Year

Type of Site Preparation

☑ Burning

☑ Brushing

☐ Mechanical

MSN Regeneration

Delay Before Regeneration (yr) 9

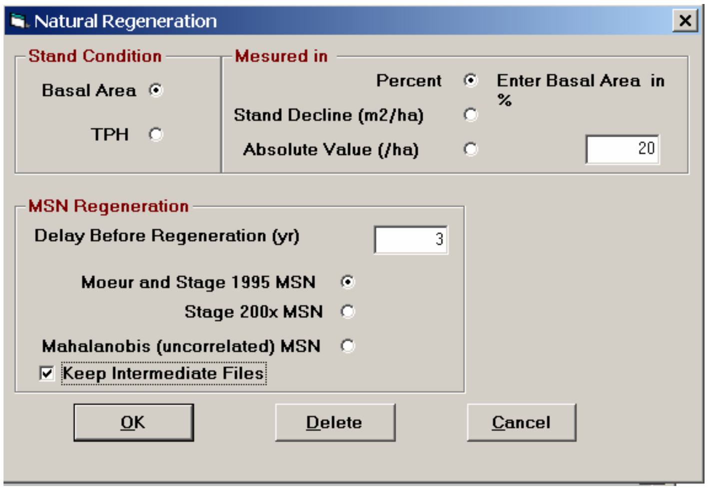
● Moeur and Stage 1995 MSN

○ Stage 200x MSN

○ Mahalanobis (uncorrelated) MSN

☑ Keep Intermediate Files

Figure A.2: In the simplest case, users schedule regeneration based on year and site preparation. This option also is coupled to existing screens available for each stand management activity (e.g. thinning from above or below).



Natural Regeneration

Stand Condition

Basal Area ●

TPH ○

Mesured in

Percent ● Enter Basal Area in %

Stand Decline (m2/ha) ○

Absolute Value (/ha) ○

20

MSN Regeneration

Delay Before Regeneration (yr) 3

Moeur and Stage 1995 MSN ●

Stage 200x MSN ○

Mahalanobis (uncorrelated) MSN ○

☑ Keep Intermediate Files

Figure A.3: Users may also schedule regeneration contingent on changes in basal area or stem density.