

Final Technical Report

FSP Project Y103187

**Evaluation of the Complex Stand Simulation Model SORTIE-ND for Timber Supply Review
in Sub-Boreal Forests of Northern BC**

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1 Abstract

A sensitivity analysis was performed to evaluate general model dynamics and model predictions were compared to independent datasets from forests of northwestern BC. Estimated parameters from selected behaviours were systematically varied to better understand model dynamics. The model is evaluated in terms of its logic and conceptual structure to ensure realistic representations of forest stands. We provide graphic description and summary statistics on the ranges of accuracy and precision of individual tree and stand level predictions. We document the effects of different types of calibration with the intent of making model predictions better align with independent data. To resolve the parameterization and calibration issues around model development we will maintain two versions of parameter files that drive the model: a research parameter file based on parameterization of field data and a management parameter file that will undergo calibration based on comparing model predictions to independent data.

2 Introduction

The purpose of this study was to investigate the capabilities and short comings of SORTIE-ND as a predictive model for growth and stand dynamics in forests of central and northwest BC, especially those impacted by the Mountain Pine Beetle (MPB) epidemic. This project started in April 2007 under Project number Y081187. It is a three year project and finished March 31, 2010. This report represents accomplishments during the three years of the project.

SORTIE-ND is an individual tree, spatially explicit model of stand dynamics that originated from the small scale disturbance model SORTIE developed and tested in the mid 1990's for transitional oak-northern hardwood forests in the northeastern US (Pacala et al. 1996). SORTIE was designed to extrapolate fine-scale/short-term field measurements to large-scale, long-term forest dynamics. In recent years SORTIE was parameterized for mixed forests in northwestern British Columbia and modified to be better suited for dealing with management issues (SORTIE/BC) (Coates et al. 2003). SORTIE/BC has recently been restructured and reprogrammed in C++. The result is SORTIE-ND (www.sortie-nd.org) where ND signifies the model's focus on local neighbourhood dynamics.

Forest dynamics is the change of forest composition and structure over time. The spatio-temporal development of forests may be described as changes of tree populations due to birth and colonization, growth and death of trees. SORTIE-ND uses a combination of empirical and mechanistic sub-models to predict forest dynamics based on field experiments that measure fine-scale and short-term interactions among individual trees. SORTIE-ND is designed to provide growth predictions for individual trees in multi-species complex structured stands. The model is especially well suited for growth predictions in stands impacted by the MPB epidemic.

In order to practice sustainable forest management, it is a necessity to have growth models that can project future growth of stand types, including complex structured stands. A given growth model can never be good at predicting growth under all the different stand conditions found throughout BC in natural and managed stands. Thus, it is important to have a host of models that each have strengths and weaknesses but can be utilized under the conditions where they are most suitable. In this way, SORTIE-ND would provide a good addition to the models that currently are most frequently used for timber supply analysis in BC.

For a model to be used in timber supply analysis it is important that the model is evaluated and that efforts are made to obtain unbiased model predictions. Evaluation is defined as a process in which a model's conceptual structure and predictions are described and assessed with regard to a specific purpose, for example, individual tree or stand-level growth attributes. This definition encompasses what is often referred to as validation and verification in the modeling community. SORTIE-ND has been parameterized based on field experiments. Parameterization is the process in which the parameters in an equation are fitted to a dataset. The model has not been calibrated to

independent data. Calibration is the processes in which the predictions from a model are compared with observations and afterwards one or more parameters in the model are changed to produce predictions that match the observations. The intent of this project is to evaluate overall model performance and determine if calibration of SORTIE-ND is desirable from the perspective of supporting timber supply analysis.

The long-term objectives of the project were to: (1) compare model predictions to independent observations of growth from permanent sample plots or other sources of long-term data; (2) provide users with information on model performance and model developers with knowledge on where to concentrate further model development; (3) demonstrate how SORTIE-ND can be used for planning silvicultural treatments including their impacts on Timber Supply Review. The emphasis of this project was on using the model in complex structured stands resulting from the MPB epidemic, especially for prediction of mid-term timber supply opportunities; and (4) calibrate SORTIE-ND, if necessary, for use in the timber supply analysis.

2. Methods

The SORTIE-ND research programme in northern British Columbia aims to improve our understanding of important processes that control forest dynamics in natural and managed forests. Our approach is to study ecosystem processes that affect fine-scale and short-term interactions among individual trees to provide insight into long-term forest response to natural and managed disturbances. We believe that linking empirical studies to models is the best approach for answering the many questions foresters and ecologists have regarding site, stand and landscape conditions in future forested landscapes.

Forest ecosystems are fundamentally a network of interacting elements. In SORTIE-ND we try to understand and represent the important elements (termed behaviours in the model) of the forest ecosystems that affect tree recruitment, growth and mortality. The interactions among individual trees and their spatially heterogeneous environment are inherently local in nature acting at a neighbourhood scale over restricted distances. Unfortunately, traditional growth and yield models that are deterministic and non-spatial are not very useful in this context. Models that use trees as individual modeling agents and are spatially explicit represent a significant advancement.

In SORTIE-ND, the forest is represented by a large collection of interacting trees that are followed both in time (in steps of at least one year) and space. Those trees are currently divided among seedlings, saplings, adult trees and snags. Population-level dynamics are simulated by summing the collective activities of numerous individuals. Each tree is a discrete object that is described with various attributes (size, growth rate, age, crown morphology, and so on). Each tree's (individual) behaviour is modeled with rules that describe the interactions with other individuals (e.g., effect of species and distance of neighbours on growth of individual trees) or its environment (e.g., growth of seedlings in relation to available light levels).

There are many tests designed for model validation (Yang et al. 2004). Most tests are designed to compare model predictions with independent observations. Since we know a priori that a model is false it makes little sense to test that the two are the same (Reynolds and Chung 1986). Statistical tests will have a limited role in our evaluation. The alternative to statistical tests is statistical estimation and description. Statistical description can be more informative than statistical tests and it leaves the choice of acceptability up to the individual user. We will use different forms of statistical and graphic description to characterize how the SORTIE-ND model predictions conform to independent data. The evaluation proposed in this study will not result in a simple "yes or no" answer.

We will evaluate the model in terms of its logic and conceptual structure to ensure realistic representations of forest stands. This will be done by identifying model structures that result in

counterintuitive growth patterns. Model predictions will be compared to general expectations for the stand development in sub-boreal spruce forests. This will be done to identify if obvious structural limitations exist in the model.

A sensitivity analysis will also be performed. Sensitivity analysis is an important part of model evaluation (Vanclay and Skovsgaard 1997). This will provide information on the model's sensitivity to uncertainty about the parameter estimates and will indicate the parameters with greatest influence on predictions. The sensitivity analysis will be performed with a Monte Carlo approach where all parameters are varied simultaneously and the parameter value for each model run is determined by a random draw from a distribution (e.g. Lexer and Hönninger 2004). The span of predicted values following a Monte Carlo style sensitivity analysis gives an indication of the error in the model predictions created due to uncertainty about the input parameters, however, this result does not directly yield a ranking of the importance of input parameters. To get at this issue, we will use regression analysis to identify and rank the most important parameters following a Monte Carlo type sensitivity analysis. The results from the sensitivity analysis will be assessed in two steps. First, an analysis will assess the amplitude of variability caused by uncertainty in parameter estimates. This will be performed through visual assessment of species-specific plot results (e.g., basal area, stems/ha). The second step of the analysis will rank the relative importance of parameters on, for example, final basal area or stems/ha. Each of the output variables will be regressed against the predictor variables and the parameters ranked according to R².

We will compare model predictions with independent observations of growth from permanent sample plots (PSP) located in the sub-boreal spruce zone. This will provide graphic description and summary statistics on the ranges of accuracy and precision of individual tree and stand level predictions. We will use the BC Forest Service PSP database to find independent repeatedly measured plots to compare with SORTIE-ND predictions. Selected plots must: be located in the sub-boreal spruce zone; have data for at least 20-yr; be dominated by spruce, subalpine fir, lodgepole pine or aspen.

Lastly, we will perform mini-sensitivity analysis by altering key parameter values. This will allow us to document the effects of different types of calibration with the intent of making model predictions better align with independent data. Choice of parameters to be altered will be partly based on the sensitivity analysis and partly on knowledge of the model structure. For the calibrated model, we will calculate the summary statistics and redo the graphics that were produced for the non-calibrated model. The change in predictions due to calibration can then be assessed by comparison of summary statistics and graphical products.

Specifically, this report covers information on:

1. Sensitivity analysis of the model.
2. General test of model dynamics.
3. Comparisons of projected growth of single-species plantations of varying densities in SORTIE-ND compared to TIPSy projections.
4. Comparisons of projected growth and mortality in SORTIE-ND compared to independent Permanent Sample Plots (PSP)
 - a) stand level comparisons
 - b) individual tree level comparisons.
5. Mini-sensitivity analysis based on results from 1-5 above
 - a) competitive mortality
 - b) species-specific lambda
 - c) alpha
 - d) maximum growth.
6. Growth of young plantations.
7. Growth of aspen varying starting densities.
8. Development of a SORTIE-ND web site.

3. Results

We have prepared extensive in house reports documenting numerous model simulations and extensive graphical comparisons of results. These documents are available upon request. Here, we summarize the main results.

Sensitivity analysis of the model

The sensitivity analysis was carried out on two stand types. The first stand type is a mixed aspen-spruce stand with 7000 aspen with a mean dbh of 2cm and 1000 spruce seedlings between 35 and 50 cm tall. The second stand type is a pine-dominated stand with MPB attack. The MPB attack is assumed to kill all pine trees larger than 8 cm (dbh) in timestep 1. This corresponds to snag basal area of 26.3 m²/ha or 1550 trees per ha. The secondary structure is dominated by spruce and subalpine fir with minor components of pine and aspen. At the beginning of timestep1 there are 570 seedlings per ha (spruce = 266, pine = 9, subalpine fir = 284, aspen = 14). This corresponds to a sapling basal area of 0.085 m²/ha. There is a total of 650 adults per ha (spruce = 300 (BA = 2.85), pine = 50 (BA = 0.22), subalpine fir = 300 (BA = 2.77), Aspen = 0) with a total basal area of 5.86 m²/ha.

The sensitivity analysis was carried out with research parameter file version 1.0. The parameter file was modified so that spruce growth maximum growth was reduced to 1.090125 which is a 15% reduction from the original parameter value. This modification was done due to the know overestimation of spruce growth (Astrup 2006). For each stand type 1000 simulations were completed. In each simulation, all the selected parameters were randomly drawn from a uniform distribution bounded at plus minus 10% of the original value. In the aspen-spruce scenario 29 parameters were varied for aspen and 28 parameters for spruce. In the mountain pine beetle scenario 41 parameters were varied for aspen, 39 parameters for spruce, 38 parameters for pine, and 39 parameters for subalpine fir.

The sensitivity analysis illustrates that with the large number of parameters in the model, relatively small levels of uncertainty about parameter estimates can lead to very large levels of variation in the predictions, however, it was noted that 50% of the data is within a relatively narrow range while the full range of variation is wide (Figs. 1-4).

The parameters that have the largest effect on the outcome as ranked by R² were the adult NCI growth parameters (especially alpha) and the allometry parameters.

General test of model dynamics

Multiple sets of model runs were completed using various densities and combinations (monocultures and mixed species) of subalpine fir, interior spruce, lodgepole pine and trembling aspen. In these simulations we looked carefully at 3 stages of stand development: a) early growth in young stand, up to 40 years old; b) intermediate stage, 40-100 yrs; and c) older stands, 100 yrs +. We varied initial densities (800 to 7200 sph) and species composition. We found undesirable model behaviour in mixed stands at higher densities where spruce and/or pine in combination with subalpine fir experienced considerably higher than expected mortality rates resulting in unusual successional dynamics (Fig 5.). This dynamic was easily fixed with a minor adjustment to the adult competitive mortality function.

Comparisons of projected growth of single-species plantations of varying densities in SORTIE-ND compared to TIPSy projections.

Various SORTIE-ND parameter files were compared to TIPSy runs for Interior Spruce (Sx), Lodgepole Pine (Pl) and Subalpine Fir (Bl). All runs were for 100 years, 300m x 300m plot size,

starting density in stems per hectare 500, 800, 1000, 1500, 2000, 2500, 3000 and 4000. Initial seedling height varied from 16-26 cm. Stand-level growth of lodgepole pine, interior spruce and subalpine fir in SORTIE-ND were consistent with projections by TIPSy. Growth projections were very similar at intermediate densities (1000-2000 sph). The greatest variation occurred at lower or higher densities than 1000-2000 sph.

Comparisons of projected growth and mortality in SORTIE-ND compared to independent Permanent Sample Plots (PSP)

A total of 54 PSP plots that were situated in (or compatible with) the SBSmc2 subzone variant were selected. The PSP plots were previously measured at approximately 10 years interval for a period of 30 years. The initial conditions for each plot were replicated in SORTIE-ND and the model was run for 30 year in each case and the model outputs values were compared with the PSP results.

a) stand level comparisons

We assessed model capabilities at stand level with comparisons of diameter distributions (for example, see Fig. 6). Stand level comparison of SORTIE-ND growth and mortality to that observed in PSP resulted in the following general observations.

- pine mortality rates were much higher in PSP than SORTIE-ND.
- stand-level basal area values where pine makes up a lot of the plot don't mean much.
- spruce, subalpine fir and aspen mortality rates were fairly similar between SORTIE-ND and the PSP.
- pine growth in SORTIE-ND was very consistent with PSP data when stands were dominated by pine
- pine growth in SORTIE-ND maybe a little too slow when mixed with lots of spruce
- if aspen is mixed with the spruce, then pine growth is about right
- spruce growth seems to vary depending on species composition:
 - a) spruce growth looks pretty good when spruce dominates the composition
 - b) spruce growth seems high with lots of pine
 - c) spruce growth seems pretty good when some aspen is mixed in with the pine
 - d) spruce growth seems high with lots of aspen
 - e) spruce growth seems pretty good
- aspen growth in SORTIE-ND was good or high when mixed in plots dominated by pine
- aspen growth in SORTIE-ND was reasonable in mixed pine-spruce plots
- aspen growth in SORTIE-ND was reasonable when mixed with plots dominated by spruce
- we have very little data on subalpine fir from the PSP.

Based on these results we looked more carefully at individual tree growth to try and better understand growth dynamics in SORTIE-ND.

b) individual tree level comparisons

We selected 12 representative PSP plots for detailed analysis. The model outputs were used to calculate the diameter growth increment per 2 cm diameter classes for each species. Results from this analysis supported those of the stand-level analysis and provided additional useful information. For example, small aspen trees generally grew much faster in SORTIE-ND than in the PSP, however, growth of larger aspen trees were similar in SORTIE-ND and the PSP (Fig. 7).

Results from these and earlier tests resulted in our undertaking targeted mini-sensitivity analysis of specific behaviours and parameter values. For example, in many cases either the species-specific competitive parameter λ or the maximum growth parameter in the adult tree growth behaviour can be changed to influence growth rates of a tree species.

Mini-sensitivity analysis

Here, we systematically changed the values of one parameter at a time to determine the influence of the parameter on the variable of interest.

a) competitive mortality

The competitive mortality function that can be applied to adult trees was found to be extremely sensitive especially in higher density stands. The function is sensitive to the estimated radial growth rate of individual trees based on the adult tree growth behaviour. Hence, as crowding increases and individual tree growth decreases, high mortality rates can occur depending on parameters values. Rates of mortality can far exceed those observed in actual stands. Very small changes in parameter values can result in highly variable mortality estimates depending on species composition and density. This can result in unstable model dynamics (e.g., Fig. 5).

b) species-specific lambda

In general, we found adjusting the lambda parameter (the species-specific competition index that ranges from 0 to 1) to be an effective way of altering individual tree growth of a specific species while minimizing impacts on other species. To illustrate, we started individual species simulations at 1800 stems per hectare (all trees in 8-10 cm diameter class) for subalpine fir (Bl), trembling aspen (At), lodgepole pine (Pl) and interior spruce (Sx) using Research Parameter File 1.6, No Regeneration, Snags and running for 60 years. Lambda values for each species were set at 0, 0.2, 0.4, 0.6, 0.8 and 1.0. The 20, 40 and 60 year average dbh growth increments were graphed to compare tree growth for each of the different monoculture lambda values (Fig 8a, b, c, d).

Similar tests were conducted for all possible pair-wise comparisons (16 combinations) with lambda values set at 0, 0.2, 0.4, 0.6, 0.8 and 1.0 (hence, 96 simulations).

c) alpha

In the overall model sensitivity analysis alpha (the shape of the effect of neighbour dbh) was identified as one of the parameters that have the largest effect on the outcome of a simulation. Hence, we conducted systematic tests of alpha similar to those conducted for lambda. For this mini sensitivity analysis current NCI alpha values for subalpine fir (Bl), trembling aspen (At), lodgepole pine (Pl) and interior spruce (Sx) were varied +5%, +10%, -5% and -10% from their current value in Research Parameter File 1.6, no regeneration, snags as illustrated in the table below.

NCI Alpha values used in mini sensitivity analysis

	-10%	-5%	RPF 1.6 NCI Alpha	+5%	+10%
Bl	2.26943595	2.395516	2.521596	2.647675275	2.773755
At	1.253367	1.322999	1.39263	1.4622615	1.531893
Pl	1.39580163	1.473346	1.550891	1.628435235	1.70598
Sx	1.316637	1.389784	1.46293	1.5360765	1.609223

An example of the results is provided for lodgepole pine with initial starting densities of 1800 stems per hectare and a simulation time of 60 years (Fig 9). The average 20, 40 and 60 year diameter at breast height growth increments were used to evaluate tree growth.

d) maximum growth.

Maximum growth in SORTIE-ND is estimated using a lognormal function that estimates the dbh at which maximum growth occurs and the shape of the function. By varying the estimated parameter

values it is possible to, for example, make either small trees grow faster, large tree grow slower, small trees grow slower, large trees grow faster, or increase or reduce growth of all trees. When comparing growth of individual trees in SORTIE-ND to growth of individual trees in PSP we found differences between model simulations and real field data, especially in growth rates of small and big trees. However, these results often varied depending on species composition and size hierarchy in the stand making simple adjustments to the maximum growth function complex. Changing this function has multiple cascading effects in the model that can be difficult to fully understand.

Growth of young plantations

During the summer of 2009 temporary sampling plots were located in plantations varying in age from 10-40 years old. Our intent was to obtain a dataset of young plantation growth that could be compared to model simulations. We obtained a dataset of diameter at breast height (cm) for 10-40 year old Lodgepole Pine (Pl) and Interior Spruce (Sx) plantations. Diameter at breast height (cm) was taken, and the trees were aged using cores and harvest dates from the Canfor Forest Development Plan 2003-2007 and the Vegetation Resource Inventory. All trees within 5.64 m radius plot had their species and dbh recorded. It was decided in the field whether a tree was a planted tree or a natural (either advanced regeneration, natural after planting or residual). The dbh of individual trees (planted) were graphed against age to create a growth graph of open grown plantations. These graphs can be compared to SORTIE-ND young planted Sx and Pl stands (Figs. 10 and 11). These runs used Research Parameter File 1.6 Planted Trees, No Regeneration, Snags with planted trees 10-20cm tall and 1600 stems per hectare.

Growth of aspen varying starting densities

To test aspen dynamics in SORTIE-ND we varied the starting density of trembling aspen from 2000 stems per hectare to 20,000 stems per hectare. Starting densities were split into 3 seedling classes; 1: upper height class 40 cm, 2: upper height class 80 cm, and 3: max seedling height 1.3m. 25% of seedlings went into class 1, 25% into class 2 and 50% into class 3 (see below). A total of 10 runs starting at a density of 2000 and by 2000 until 20,000 were run.

Starting seedling height and stems per hectare.

Initial Density (#/ha) - Seedling Height Class 1 (40cm)	Initial Density (#/ha) - Seedling Height Class 2 (80cm)	Initial Density (#/ha) - Seedling Height Class 3 (1.3m)	total stems per hectare
500	500	1000	2000
1000	1000	2000	4000
1500	1500	3000	6000
2000	2000	4000	8000
2500	2500	5000	10 000
3000	3000	6000	12 000
3500	3500	7000	14 000
4000	4000	8000	16 000
4500	4500	9000	18 000
5000	5000	10000	20 000

Density in stems per hectare and basal area in m²/ha for each timestep was taken from the SORTIE-ND output files and graphed (Figs. 12 and 13) to contrast trembling aspen growth at different starting densities.

Development of a SORTIE-ND web site

We have developed an extensive and comprehensive SORTIE-ND website that explains the development of the model, our modelling approach, model testing and calibration, with links to all related papers. The site is at <http://www.bvcentre.ca/sortie-nd>

5. Discussion

SORTIE-ND simulates changes in tree populations over time. The model uses a combination of empirical and mechanistic behaviours to predict forest dynamics based on field experiments that measure fine-scale and short-term interactions among individual trees. All field studies operate at the neighbourhood scale of forest dynamics. SORTIE-ND is designed to provide growth predictions for individual trees in multi-species complex structured stands. It has a much higher degree of flexibility in terms of which processes are set to act on a population of trees. SORTIE-ND encapsulates the emerging theory of neighbourhood dynamics, where interactions among individual trees and their spatially heterogeneous environment are inherently local in nature acting at a scale over restricted distances. All model behaviours and related parameters are user-specified and the model can be fitted to a wide range of specific conditions. SORTIE-ND has an intermediate position between purely empirical and process-based models.

Since the mid-2000s the focus of the SORTIE-ND research programme in northern BC shifted to issues around projecting stand dynamics after the massive Mountain Pine Beetle (MPB) epidemic in the sub-boreal spruce forests of central BC. This research programme has been undertaken by the Bulkley Valley Research Centre and the BC Forest Service and has included the establishment of a series of new experiments and large stem-mapped plots in sub-boreal forests.

Forest researchers and managers often have different requirements and expectations from forest simulation models which, in turn, can profoundly influence their thoughts on model development, testing and validation. There is considerable value to promoting a suite of models with different modeling approaches, structures, capabilities and strengths. We have specifically developed SORTIE-ND to be a research model that has considerable flexibility to incorporate new research finding. In this way the model can keep evolving as new research finding emerge. SORTIE-ND can be thought of as a modeling framework for research into neighbourhood dynamics. Our approach is very powerful from a research program and research model development perspective, but has limitations from a management applications perspective. To move from a research model emphasis to a management model emphasis requires extensive testing of model predictions. This must be done using a static version of the model. Adding a new behaviour, for example, in the middle of model testing is a nightmare. This is but one small example of the many issues that must be considered in model development, testing and validation.

Currently, SORTIE-ND is a parameterized model. Parameterization is the process in which the parameters in an equation are fitted to a dataset. Calibration is the processes in which the predictions from a model are compared with observations and afterwards one or more parameters in the model are changed to produce predictions that match the observations. Most traditional growth and yield models have some kind of calibration performed in order to make the predictions realistic. Calibration, however, goes against the basic ideals of a research model. The danger with calibration is that you will not necessarily allocate the changes to the correct processes. A calibrated model is not a research model. For example, if a research model under predicts growth of one tree species, then this suggests there may be a factor controlling growth of that species that is not understood or for that particular species you have an inadequate dataset, or some combination of the two. Further

experimentation or sampling may solve the problem and lead to a better understanding of forest dynamics. Calibration to solve the problem may lead to little understanding.

Based on the sensitivity analysis, the test of general model dynamics and comparisons with TIPSy and PSP datasets we identified the adult competitive mortality behaviour and components of the neighbourhood adult tree growth behaviour as the most likely behaviours for calibration in SORTIE-ND. The adult competitive mortality behaviour is directly linked to the growth behaviour – slow growing trees are more likely to die. The neighbourhood adult tree growth behaviour is a complex function with many components. In particular, we focused on the lambda function and the size function. Mini-sensitivity analysis of these behaviours suggested ways to better align SORTIE-ND growth predictions with actual growth from independent field data.

6. Conclusion and Management Implications

To resolve the parameterization and calibration issues around model development we will maintain two versions of parameter files that drive the model: a research parameter file based on parameterization of field data and a management parameter file that will undergo calibration based on comparing model predictions to independent data, for example re-measured permanent sample plots (PSP). For predicting growth for timber supply analysis the calibration of SORTIE-ND is appealing since it could reduce biases in critical predictions, for example, individual tree and stand growth development over time.

7. Literature Cited

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List of Figures

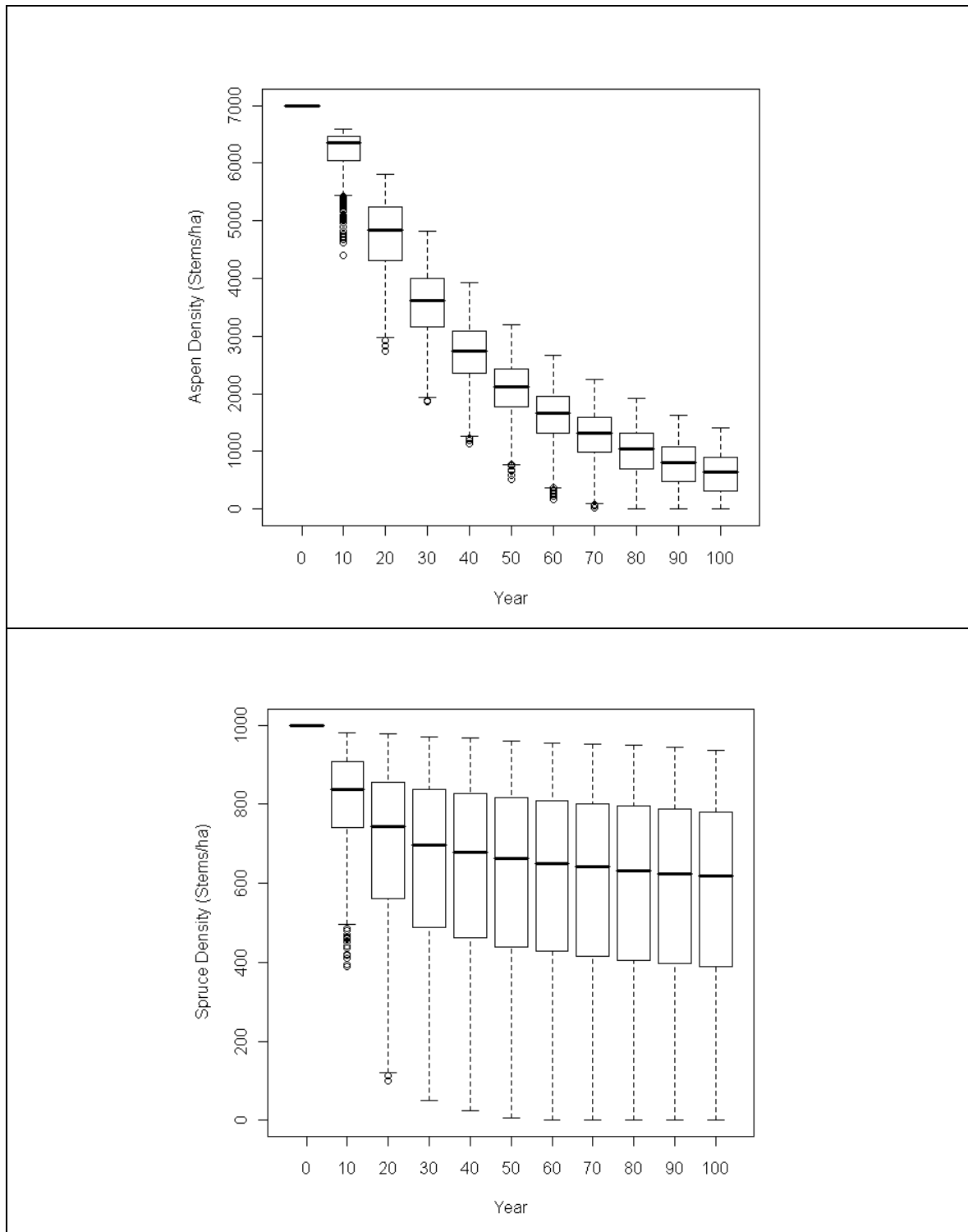


Fig. 1. Box plots of the 1000 simulations for density in the aspen-spruce scenario. The line illustrates the median, the box illustrates the 25th and 75th quintiles, the bars illustrate the max and min while individual circles illustrate outliers.

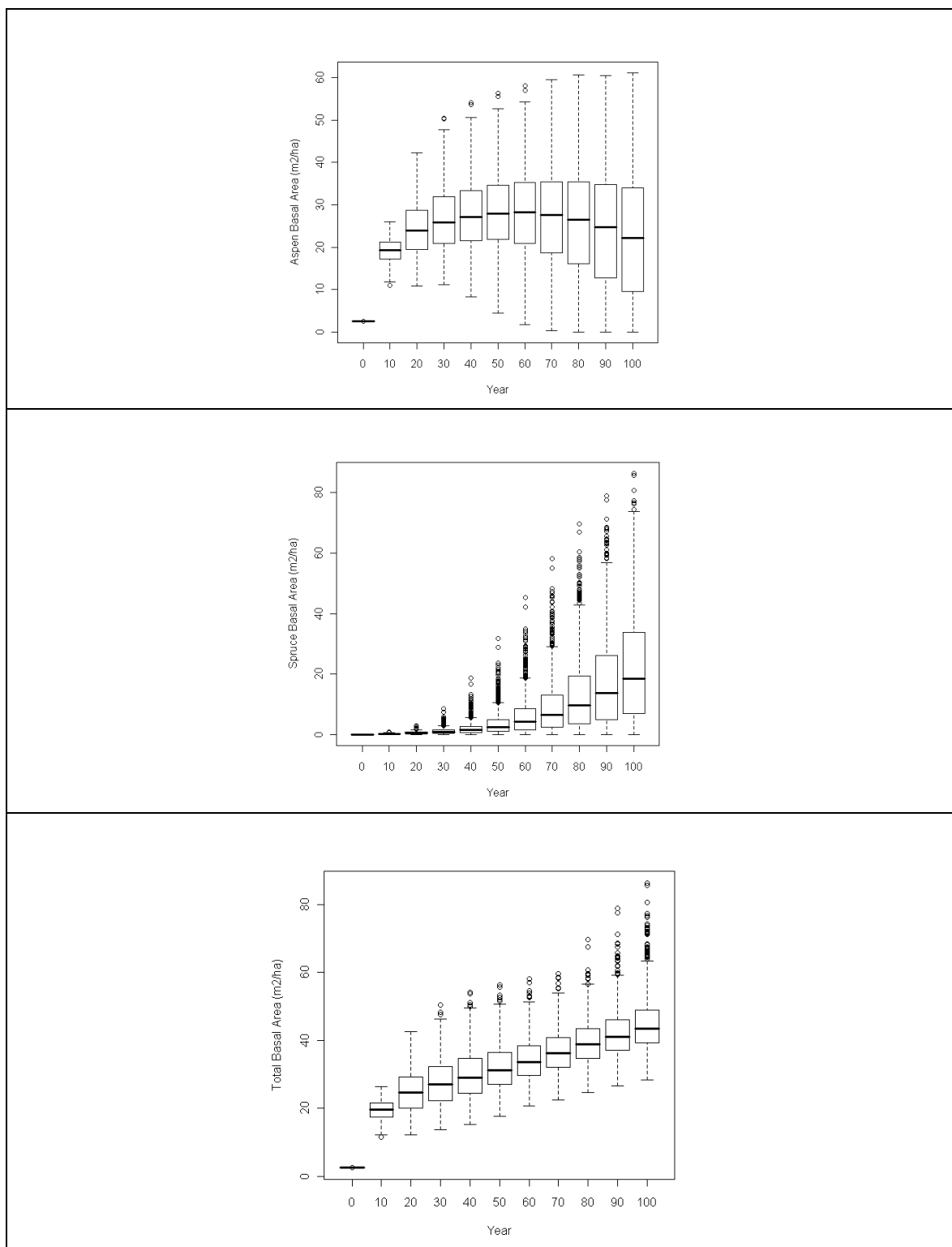


Fig. 2. Box plots of the 1000 simulations for basal area in the aspen-spruce scenario. The line illustrates the median, the box illustrates the 25th and 75th quintiles, the bars illustrate the max and min while individual circles illustrate outliers.

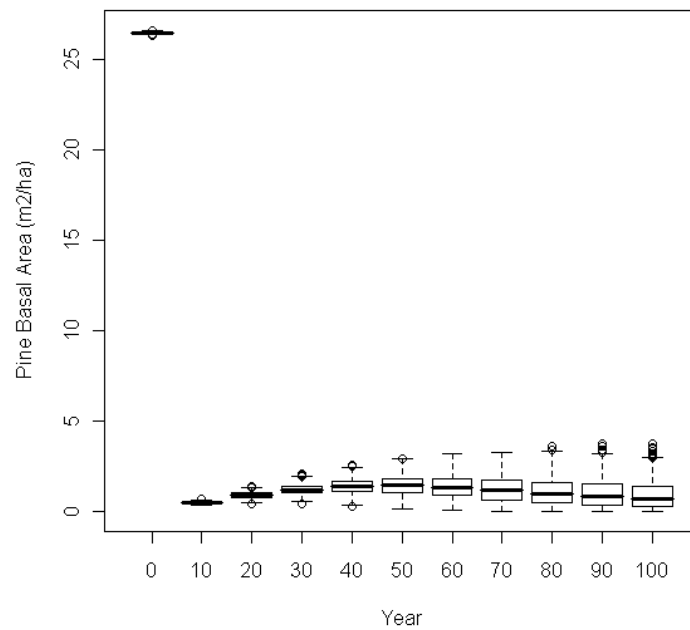
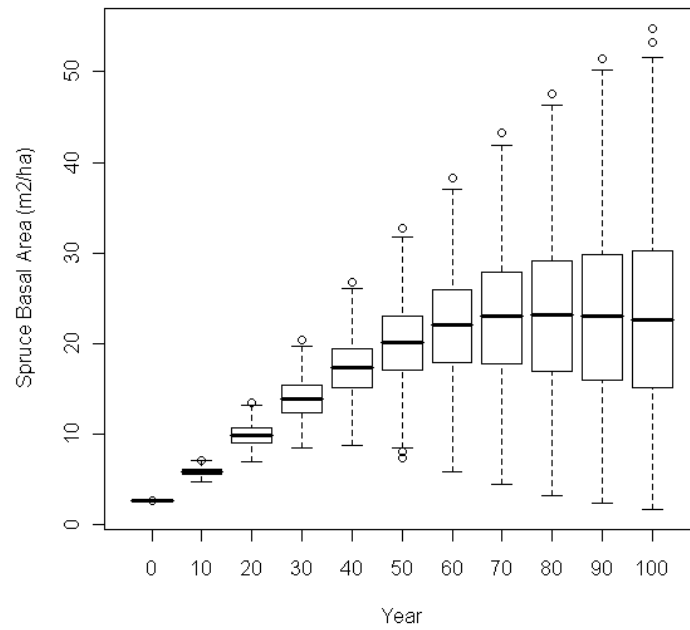


Fig. 3. Box plots of the 1000 simulations for spruce and pine basal area in the mountain pine beetle scenario. The line illustrates the median, the box illustrates the 25th and 75th quintiles, the bars illustrate the max and min while individual circles illustrate outliers.

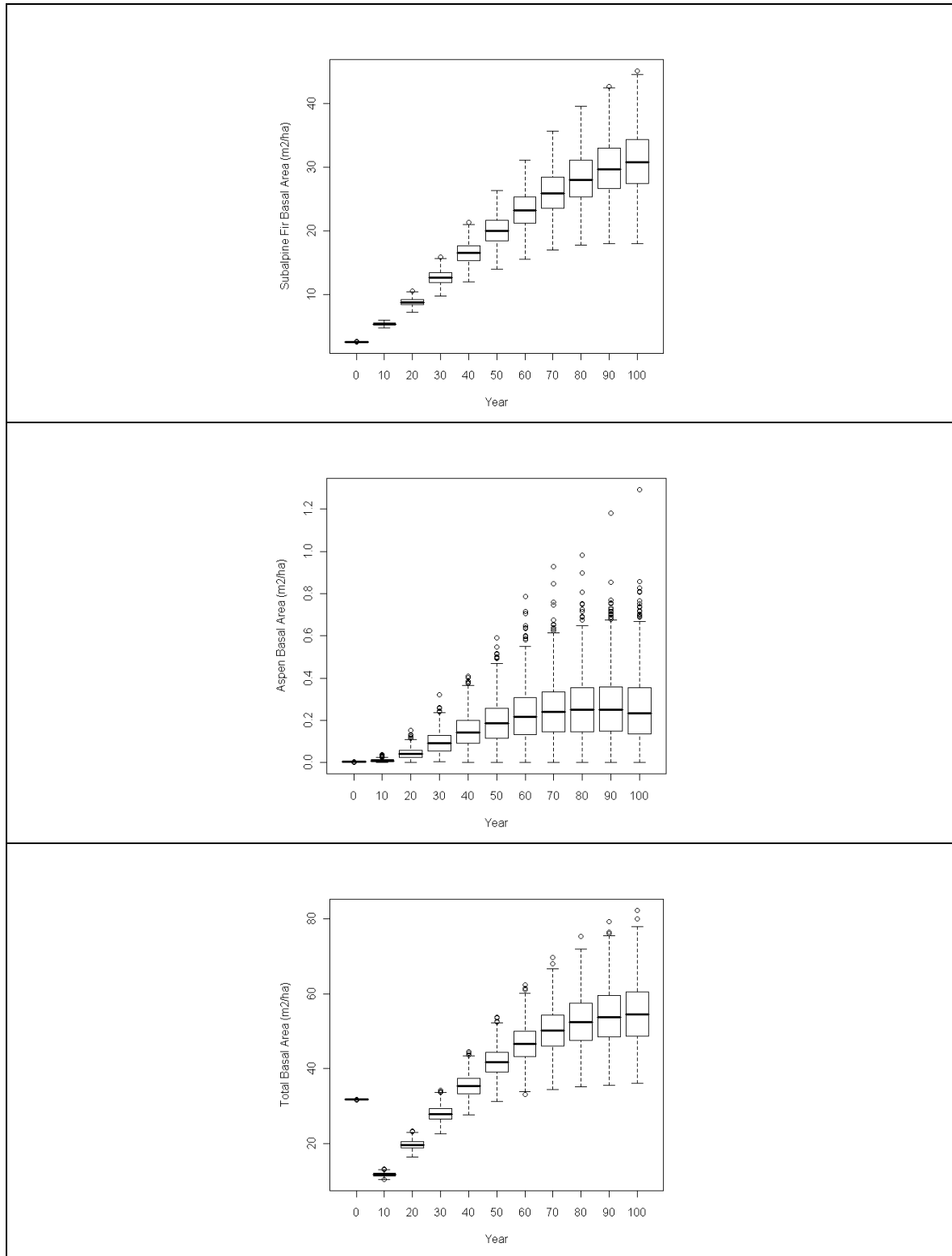


Fig. 4. Box plots of the 1000 simulations for subalpine fir, aspen and total basal area in the mountain pine beetle scenario. The line illustrates the median, the box illustrates the 25th and 75th quintiles, the bars illustrate the max and min while individual circles illustrate outliers.

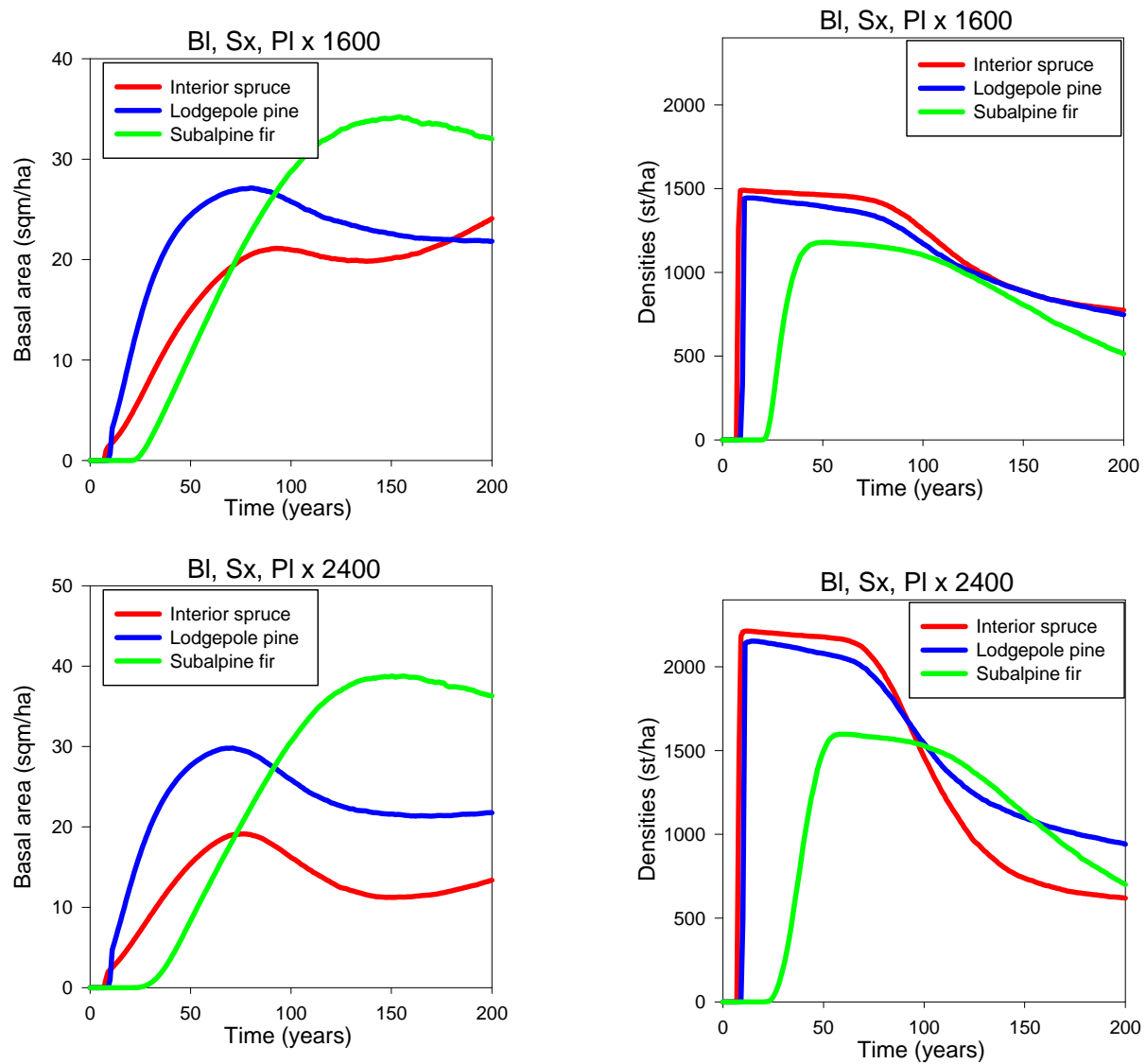


Fig 5. SORTIE outputs of Basal area (left) and densities (right) for the selected species as high density indicating unexpected dynamics.

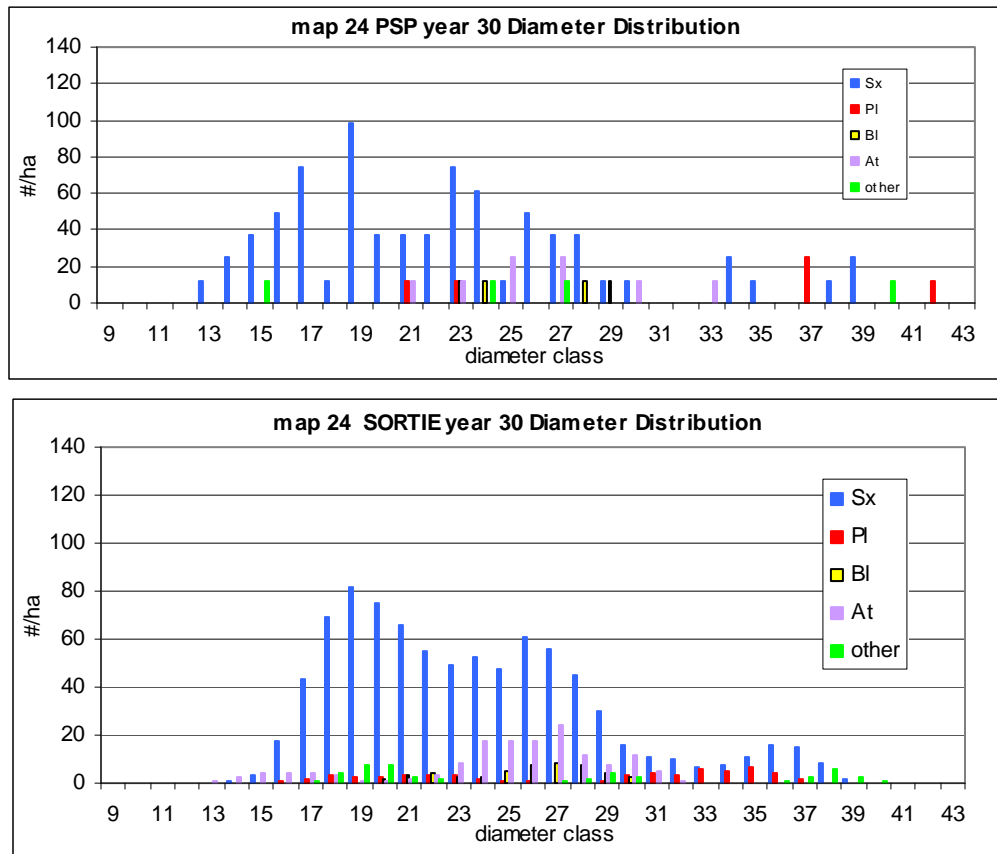


Fig. 6. Diameter distributions comparison by species in PSP plot (map) 24 and SORTIE output at year 30.

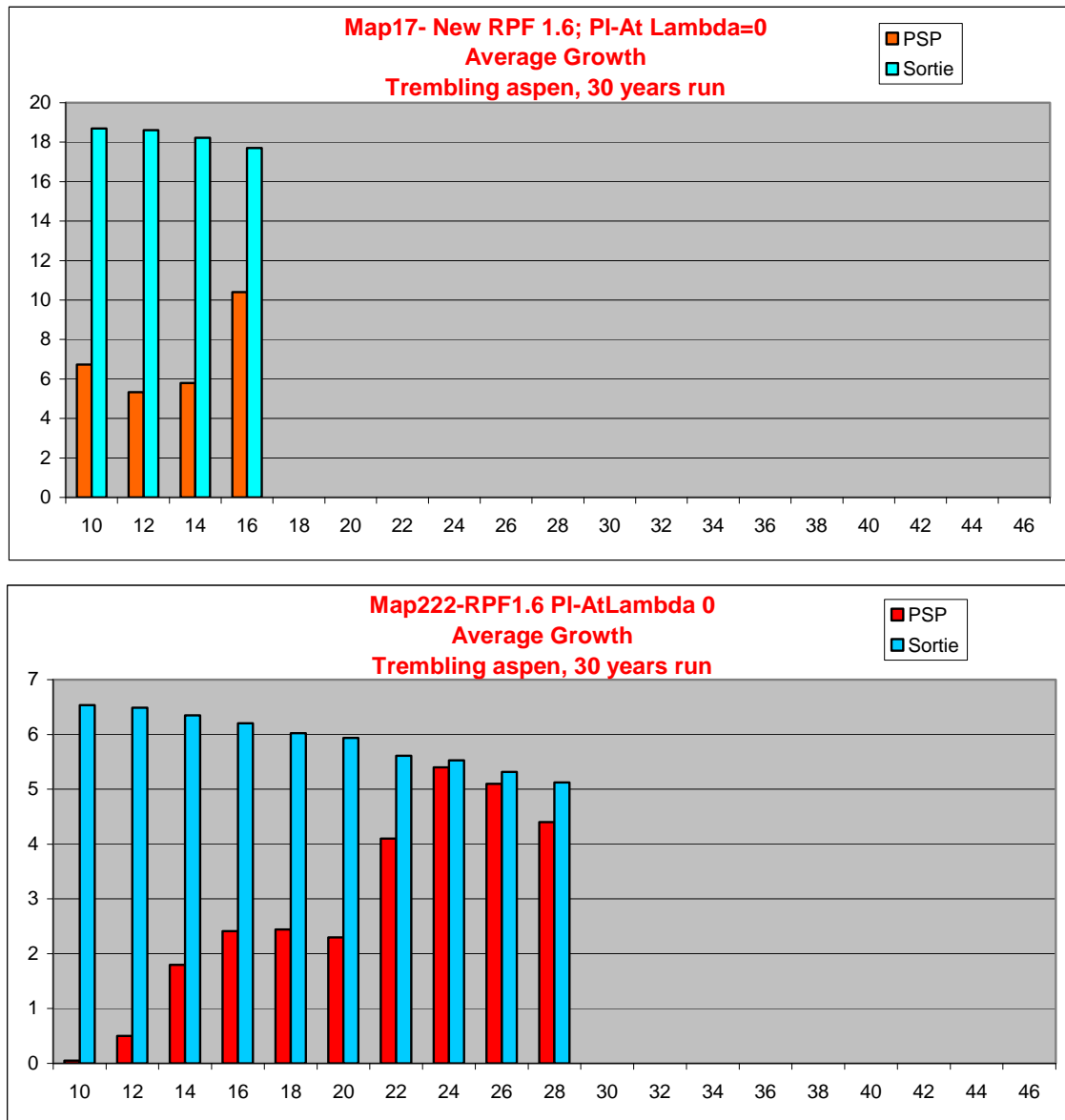


Fig. 7. Comparison between PSP and SORTIE outputs of growth behaviour over 30 year run for aspen in plot (maps) 17 and 222.

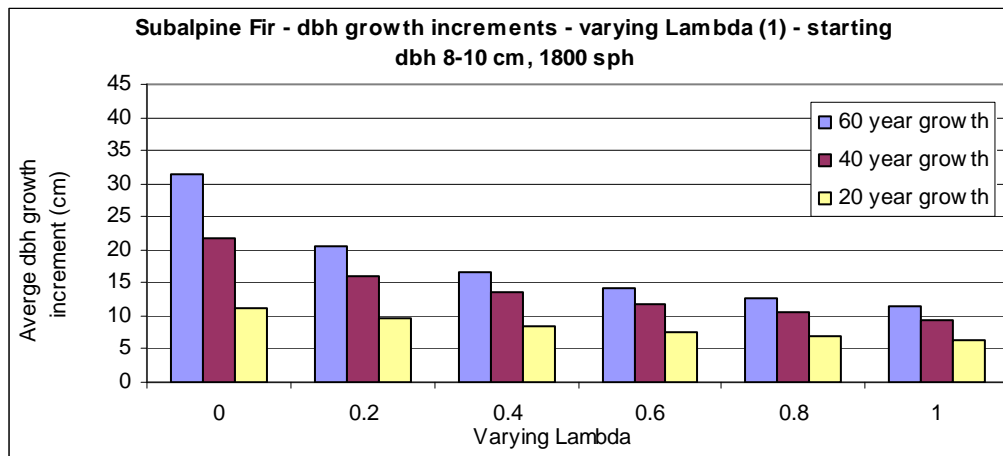


Fig. 8a. Subalpine Fir varying lambda 20, 40 60 year growth increments. Starting 8-10cm dbh, 1800 stems per hectare.

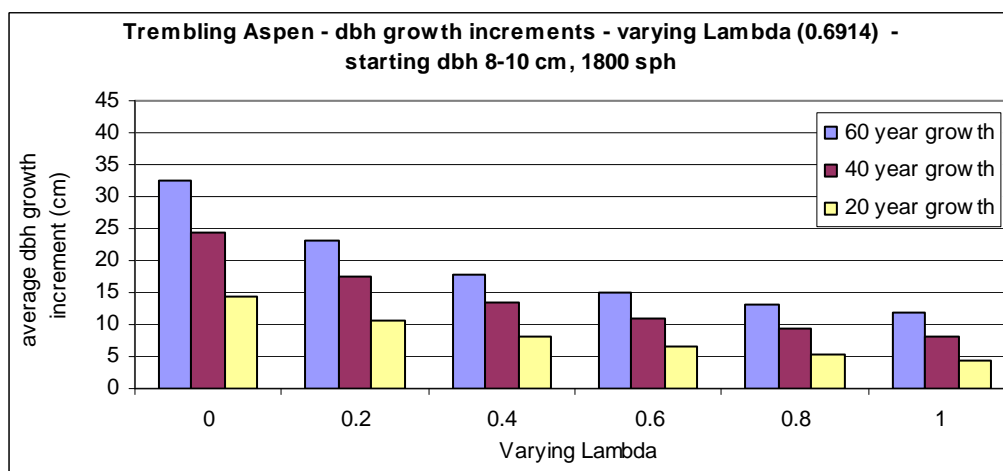


Fig. 8b. Trembling Aspen varying lambda 20, 40 60 year growth increments. Starting 8-10cm dbh, 1800 stems per hectare.

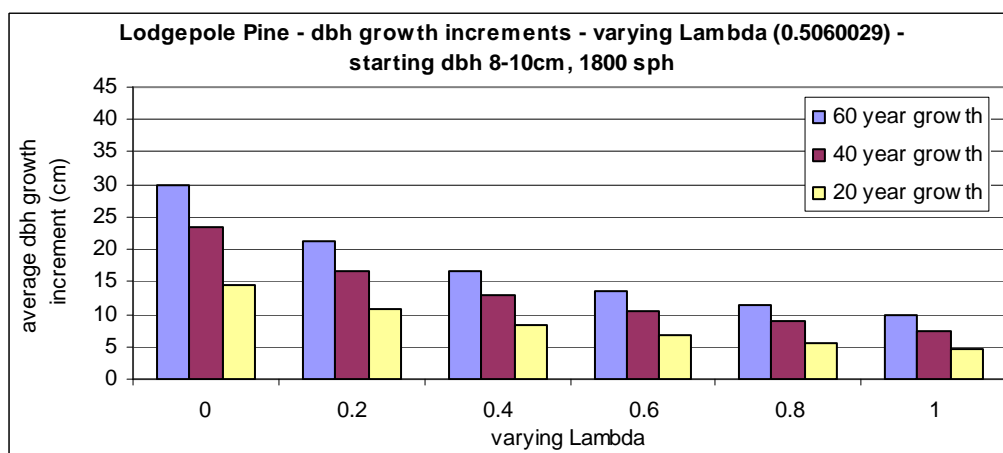


Fig. 8c. Lodgepole Pine varying lambda 20, 40 60 year growth increments. Starting 8-10cm dbh, 1800 stems per hectare.

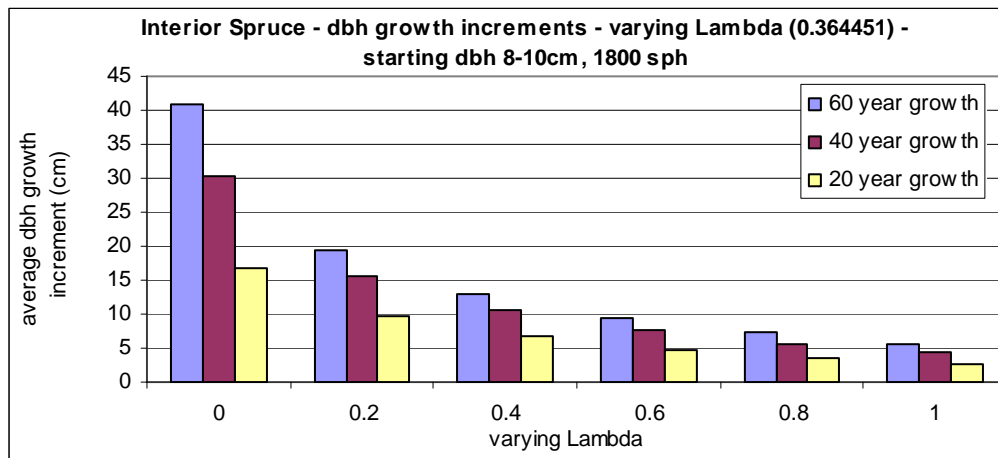


Fig. 8d. Interior Spruce varying lambda 20, 40 60 year growth increments. Starting 8-10cm dbh, 1800 stems per hectare.

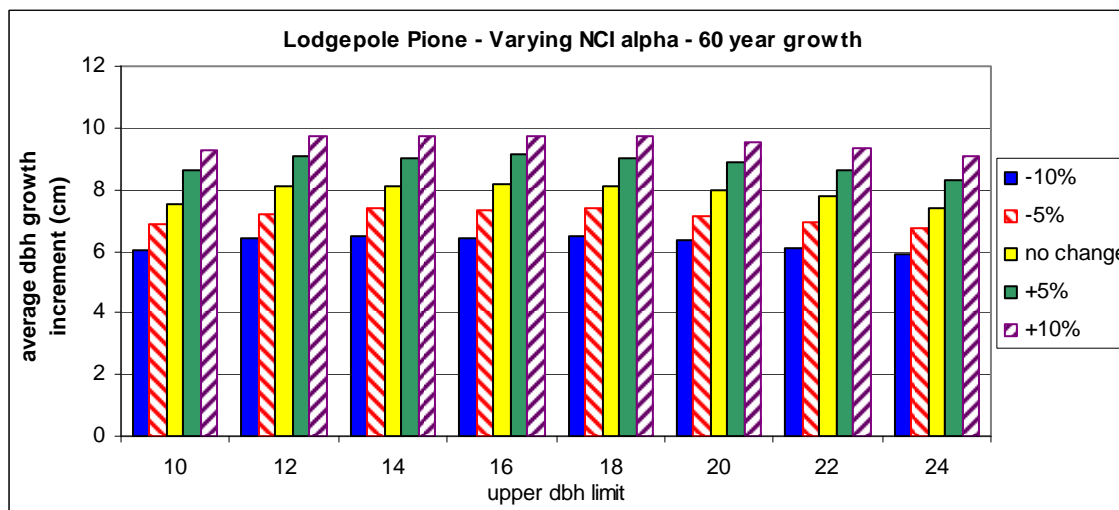
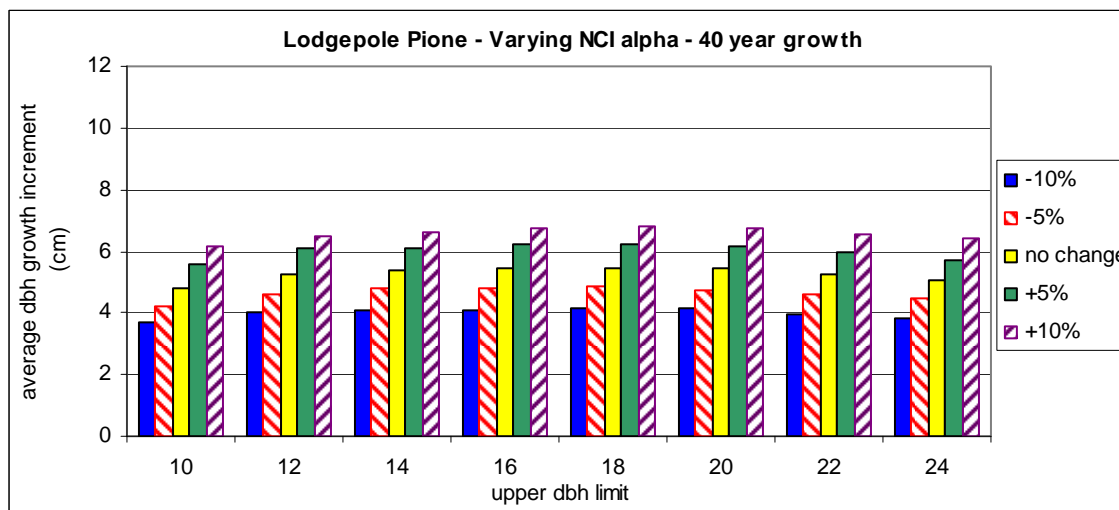
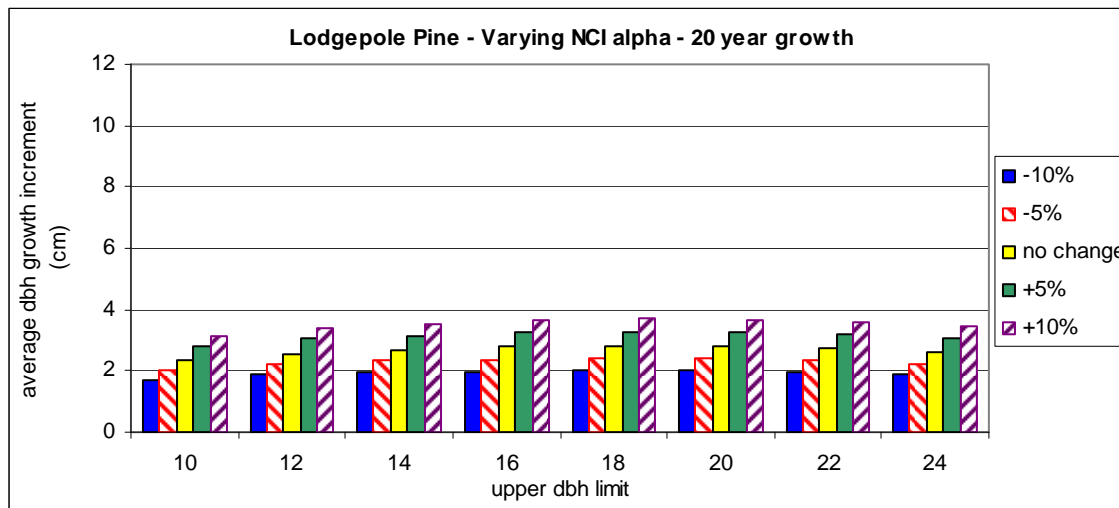


Fig. 9. Lodgepole Pine 20, 40 and 60 year dbh growth increment results using various NCI alpha values

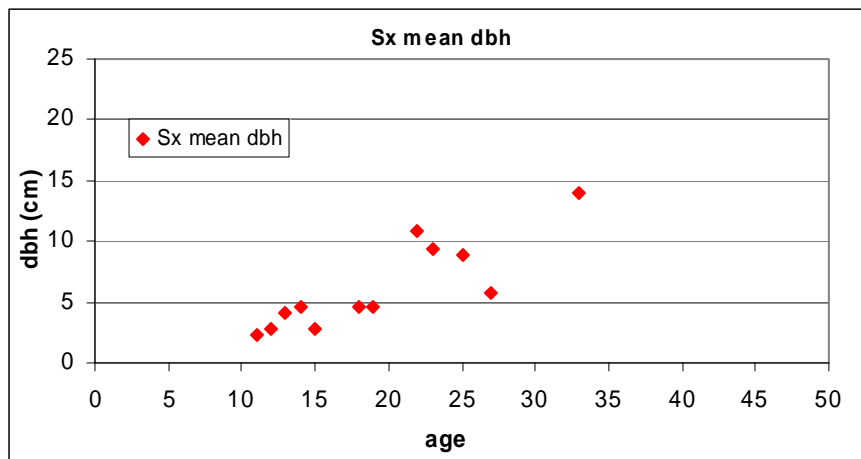


Fig. 10a. Interior Spruce diameter at breast height (cm) by age from plantation survey data.

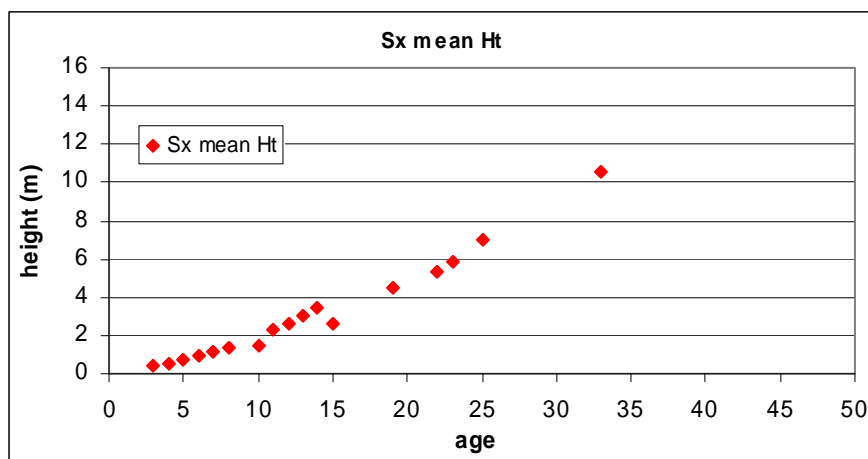


Fig. 10b. Interior Spruce average height (m) by age from plantation survey data.

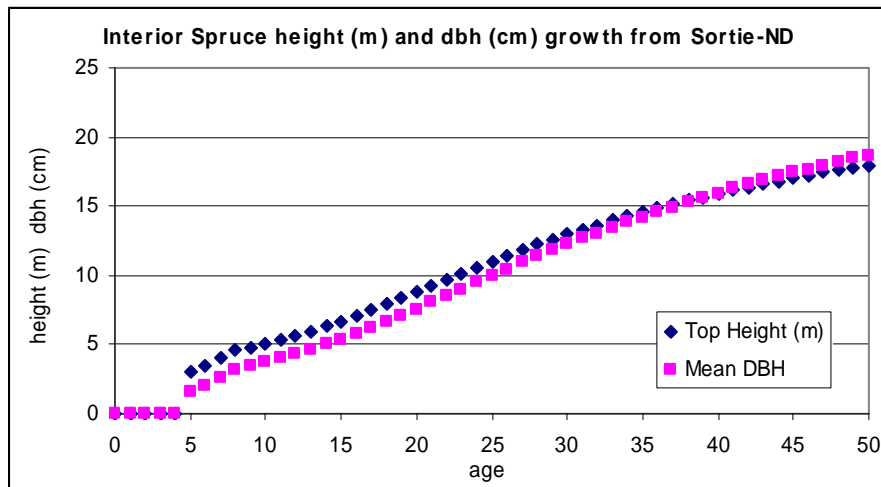


Fig. 10c. Interior Spruce height and diameter by age from Sortie-ND using Research Parameter File 1.6 Planted trees, No Regeneration, Snags.

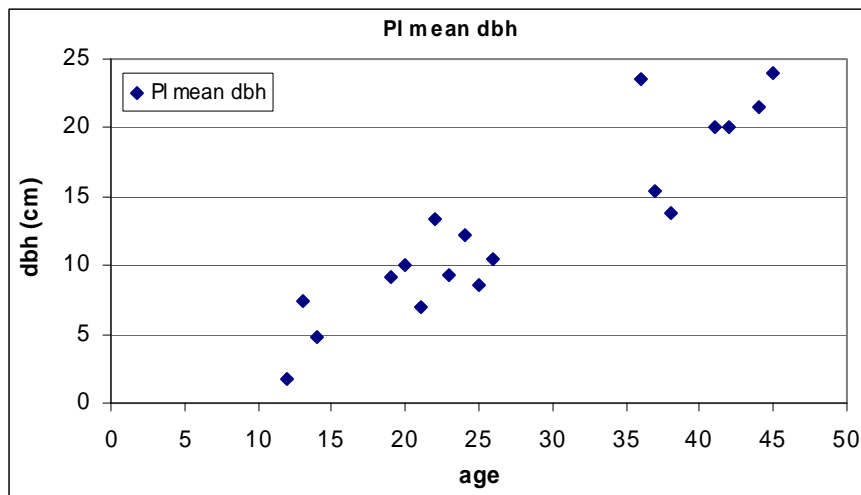


Fig. 11a. Lodgepole Pine diameter at breast height (cm) by age from plantation survey data.

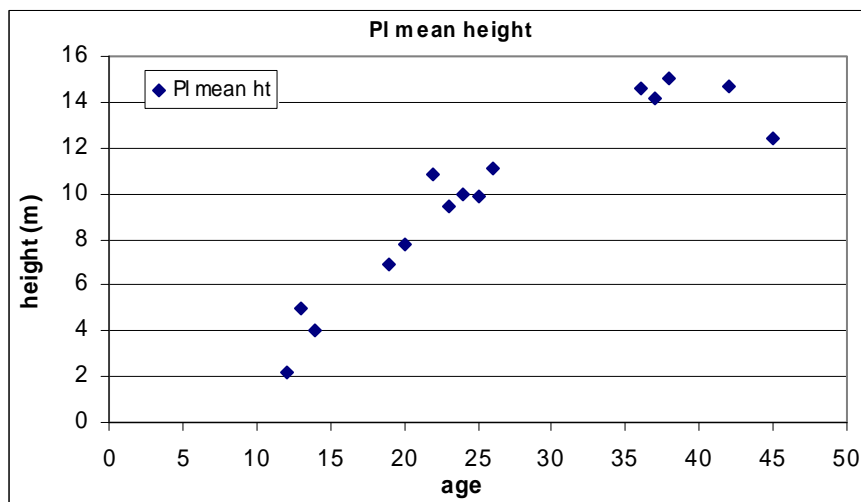


Fig. 11b. Lodgepole Pine average height (m) by age from plantation survey data.

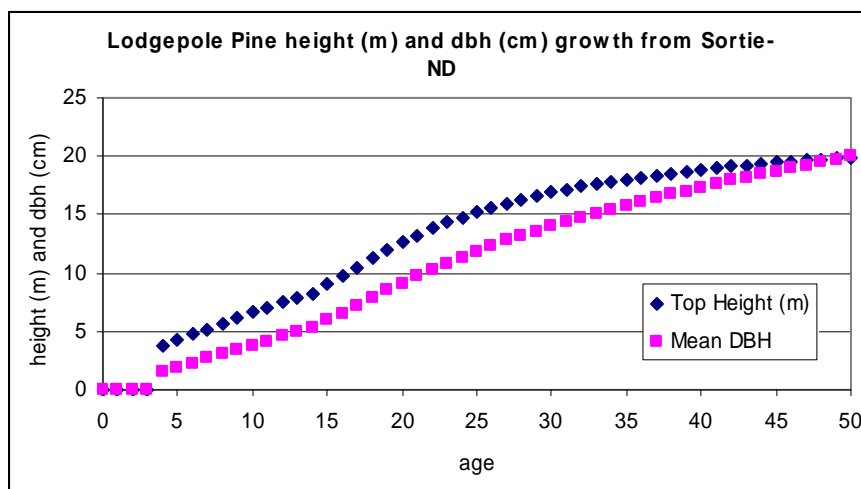


Fig. 11c. Lodgepole Pine height and diameter growth from SORTIE-ND using Research Parameter File 1.6 Planted trees, No Regeneration, Snags.

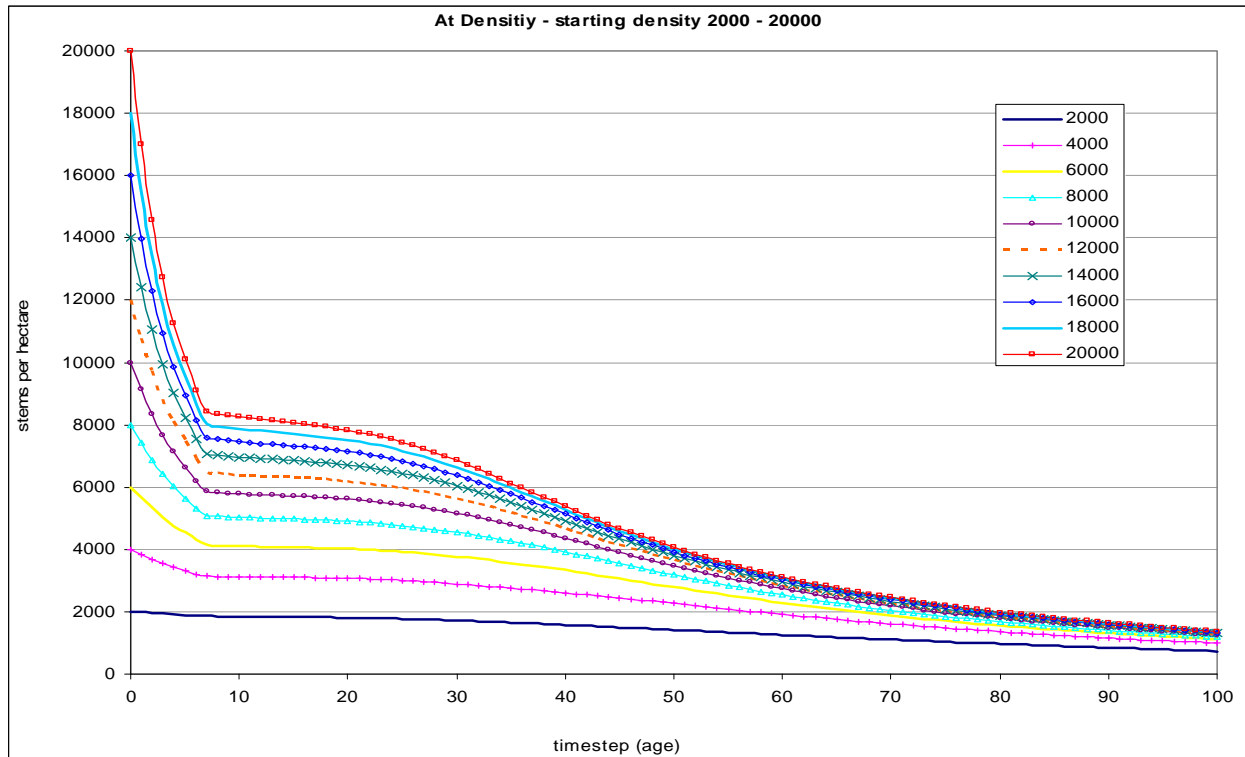


Fig. 12 Trembling Aspen density in stems per hectare over 100 years with starting densities of 2000 – 20,000 stems per hectare.

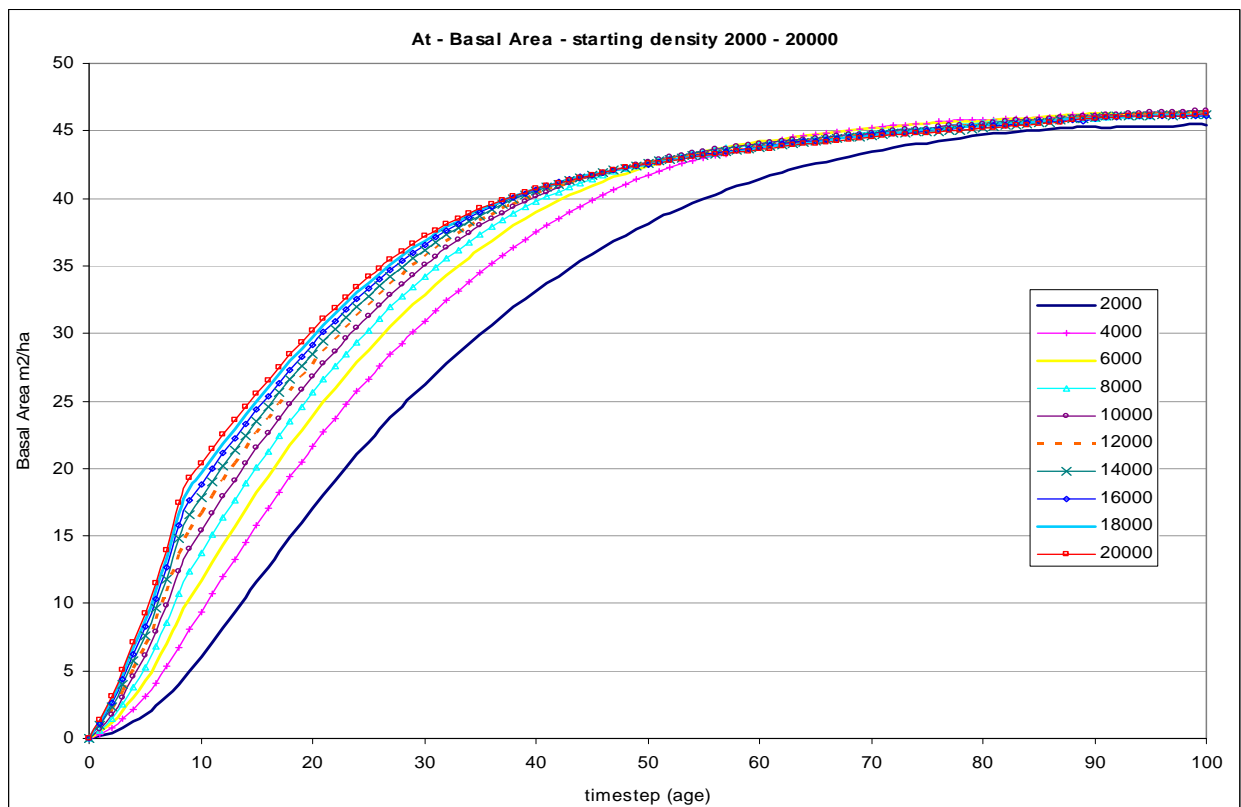


Fig. 13. Trembling Aspen basal area in m^2/ha over 100 years with starting densities of 2000 – 20,000 stems per hectare.