An Evaluation of the FORECAST model for projecting the temporal patterns in the development of old-growth structural attributes in second-growth stands

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In the previous chapter I succeeded to segregate structural attributes that correlate with stand age. To be valid FORECAST model should show similar temporal trends. If we want to use FORECAST as a tool to simulate forest management, we first want it to simulate proper dynamics of the forest. For example, suppose we want to see what will happen to forest, if it is partially harvested at age 150. That means that the model should properly simulate the forest state at year 150 and also the proper dynamics of the forest after partial cut.

In our case, I used the comparison of the field data to the model. That in order to see if the model can produce the curves for the attributes that will be similar to the field data curves. Similar curves will support the validity of the model. However, there were two site specific parameters that did not allow such comparison:

1. The amount of seedlings at the stand initiation phase
2. The amount of trees eliminated per each disturbance event.

Those two parameters are highly variable from site to site. The fitted curves of the field data do average the dynamics of the forest. Consequently, if we want to evaluate the model against field data, we need to enter in the model some average numbers for seedlings and eliminated trees. Once the model can show that it can produce averaged curves, it will be more trustable to be accurate for non-averaged behavior.

So basically, the idea is to calibrate the model for some average number of seedlings and eliminated trees. In the same time we want to evaluate the model performance. The field data can be used to calibrate those two variables and to evaluate its modeling capabilities in the same time. This is done by separation of the model into two parts: A and B. Part A consists from variables for amount of seedlings and for trees killed by disturbance. Part B of the model is all the other algorithms and variables of the model. Part B was already calibrated and needs to be only evaluated against the regional field data. The process of FORECAST calibration is explained in {{68 Blanco,J.A.}}.

Now, let us suppose that part B was not calibrated properly. Consequently, we probably would not be able to calibrate part A, because the model would not produce proper curves anyway. Therefore, if we do succeed to calibrate part A, it will support part B validity.

After model description I show the outcomes of evaluation run with averaged refined numbers for part A.

FORECAST model description

FORECAST (Kimmins et al. 1999) is a stand level model that simulates forest growth on an area of one hectare. It also allows the user to apply different management techniques on the simulated forest. The model is non-spatial and hence can work only with processes and entities that are evenly distributed through the area. The simulation is on individual tree level and also includes soil based processes. This method of simulation allows the model to predict competition for nutrients and light among the trees.

FORECAST is a hybrid model which combines the historical bioassay data with process based simulation. The increase in biomass is calculated on stand level. It is based on the amount of foliage. By knowing the foliage biomass it is possible to calculate the net primary production due to photosynthesis. The primary production is then distributed to an individual tree based on its size. The historical data plays important role in calibration of the model.

The growth is reduced or enhanced due to actual availability of light and nutrients during the simulation process. To calculate the needs for light and nutrients the model simulates growth of individual trees. This simulation includes stem, foliage and roots growth. Biomass loss due to foliage, bark and root turnover is also accounted for. As the biomass for individual tree is known, the model can calculate the amount of nutrients and light needed to sustain the biomass and to increase the biomass for the next year. Those calculations determine the actual growth of the trees and their mortality.

The mortality in the model composed from two parts. First, the model follows the curve of stem density based on the data from self thinning stands. FORECAST eliminates trees that have the lowest nutrients or light amounts to survive. Second, the user can define additional mortality due to disturbance events or management.

Shrubs are simulated in similar way; however the shrubs are simulated as one entity and not as separate bushes.

The canopy in the model is separated into horizontal layers. Each layer is evenly distributed and can shade the trees beneath it. The amount of shade is calculated from the amount of foliage biomass in each layer. It is important to note that because the canopy representation in FORECAST is evenly distributed its shading effect is different on small trees and shrubs comparing to old-growth stand. In old-growth stand there are canopy gaps and hence the light is distributed unevenly in the lower levels of the forest. Those differences and their outcome to simulation will be discussed later on.

All the biomass that is lost from trees or shrubs is going to the forest floor where its decomposition and subsequent nutrient release is simulated. Once the trees die, their decomposition is also simulated as snags or logs. The snags and logs are represented as individual entities.

Living trees, dead wood and shrubs are represented by species. For each species the parameters of growth and decay rates are different.

FORECAST is deterministic model. Consequently, stochastic events should be averaged or the model should run several times with randomized parameters. For example, windthrow events can be simulated with average time intervals or the user can run the model several times with events coming in random drawn times. The last option allows the user to simulate events that have low probability of occurring, but may be important to explore for management risk.

<u>The use of the model involves several stages:</u>

1. Calibration - calibration input has a long list of parameters. Several examples are: photosynthetic light saturation curve, biomass of various tree parts, nutrient concentration in those tree parts, tree size distribution in a cohort, stand age at canopy closure, parameters for foliage shading. The data is taken from regional research and surveys. It determines the mathematical curves for process based part of the model.

2. Initial run – its purpose is to activate the model. As we come to measure things in the forest, we do not come to an empty system. The ecosystem has heritage from previous years. That includes living trees and plants on the site, as well as accumulated dead wood, soil properties that developed through years and previous disturbance outcomes. Consequently, the model should grow several stands on the site to accumulate similar heritage.

3. Evaluation run and site specific calibration - it is needed to define initial conditions and disturbance regime in the model. This is done by comparison of the model to the field data. The starting parameters and disturbance regime are changed to see if the model can produce curves which are similar to the field data. For example, in current project we measured chronosequence of already mature stands and hence we do not know how many seedlings regenerate at the stand initiation phase. Nevertheless, the user can try to run the model with different amount of seedlings and then compare the output of the model to the field data. During the evaluation the user can see whether he should take some average of seedling numbers or if he should identify the need to run the model several times with different range of parameters.

4. Actual run - it is performed based on the disturbance regime and initial conditions determined in the evaluation run. During the actual run the user defines what management regime will be imposed on the stand. For example, the user may define to log the forest at certain age or thin out some trees. Model run shows the prediction that is done by the model for the management regime.

5. Output data - includes graphs and files. Some example of plot information include:

a. Individual trees: DBH, height, biomass, volume.
b. Dead stems and logs: diameter, length, biomass, proportion of biomass decayed since death.
c. Shrub biomass, light availability, nutrient competition, litterfall, mortality rates.
d. Data regarding soil nutrients, humus layer, moisture dynamics.

Evaluation process

FORECAST was already calibrated for the CWHvm subzone. To continue with initial run I needed first to determine the average site index (SI at age 50) for Tsuga heterophylla (Western Hemlock). FORECAST needs the input for SI to determine the growth of vegetation during the runs and Hemlock is a relative species in CWH dataset. To determine SI for each site I used leading Hemlock trees on each site and the TIPSY site index calculator. {{56 Research Branch, Ministry of Forests 2007}}

To calculate the index I used eight CWHvm1 sites that are younger than 100 years. This is due to the fact that trees accumulate damage with age and hence the site may diverge from the SI fitting curve. Also, SI fitting equations in British Columbia are more reliable for sites between ages 20-120 years.{{55 Marshall, P.L. 2005}} The average site index from field data is 30.1±1.5. This is comparable to reports from Ministry of Forests SI=27.7±0.1 for Hemlock in CWHvm1 on zonal site in Vancouver region {{57 Forest Science Program, Ministry of Forests and Range 2008}}. Surprisingly, the four young CWHvh1 sites have SI=29.5±2.4. This number is much higher than SI=16(error is not reported) that is presented in the ministry report for vh1 variant. The measurement of high SI for vh1 variant supports my decision to clump together the data for vh1 and vm1 variants.

During the modeling runs FORECAST showed difficulty to grow big diameter trees quick enough. This was due to the fact that the amount of available nutrients goes sharply down between the ages 40 and 100 years. Thus, I decided to raise the SI in the model to be 32 to compensate on the decline.

Once, proper SI was chosen I ran the model for 10 cycles of 250 years each. During each cycle I grew Hemlock trees and burned them in the end. This was done to increase the humus mass and to stabilize its dynamics. Once the stability was reached I grew a “pre-disturbance” stand of Hemlock for 250 years with clearcut at the end. Clearcut was done do have a fresh start on the site without veteran trees or residual snags and logs. Moreover, during the 250 years run I introduced small mortality events to enhance the productivity of the site. However, I stopped the mortality events 60 years before the clearcut to allow full decay of most residual logs and snags. (FORECAST version that I used did not have the option to remove dead wood during clearcut)

Evaluation run

Based on the above explanation the evaluation run starts without significant amount of residual dead wood or veteran trees. Due to the fact that most of the trees on our sites were Hemlock, I decided to use only this tree species for evaluation run to simplify the modeling. For the same reason I chose only Vaccinium genus shrubs to be simulated.

Numerical characteristics of the model that determine the run were first established by estimates from the field work data or literature. They are presented in table-3.1. Then, I was able to refine the estimates based on the logic of the output and on how well the output followed the field data. Further, I tested the sensitivity of the model for change in important variables. At first I explain the logic behind the initial numbers.

Table 3.1 Model parameters for evaluation run

Model variable	Value	Remarks
Total evaluation time	300 years	
Vegetation simulated	Western Hemlock, Vaccinium genus	
Shrub regeneration at first years: percent of maximum occupation	20%	
Number of cohorts	5	3 regenerate in stand initiation phase, 1 in understory reinitiation and 1 in old-growth phase
Stems/ha regenerated	600, 400, 400, 400,400	For cohorts 1-5 respectively
Year of cohort establishment	1, 11, 21, 171, 211	For cohorts 1-5 respectively
Small impact disturbances	Uprooting and standing dead killing	
Uprooting	Each 40 years kills 10% of trees. The killing is once every 40 years.	Kills trees older than 40 years
Standing dead	Each 20 years kills 3% of trees. The killing occurs continuously within 20 years.	Kills trees older than 40 years.

One of the important parameters that influence initial tree growth is how many shrubs we have on the site. The amount of shrubs at the beginning was based on previous experience with the model. 20% of fully stocked site is sufficient to start shrub regeneration.

Hemlock trees being shade tolerant can successfully establish under older trees canopy. Due to that fact they can establish on a new site at different time. This means that I can not simulate establishment of all trees at the same year. Eventually, however, the canopy will become closed enough to exclude any potential germination. Hence, there is a window of time when the trees can establish on the site. In FORECAST the user defines how many trees to establish and at which time. Though it is possible to use many cohorts, practically more than several cohorts complicate the use of the model without adding additional accuracy to the output.

Running the model with only one cohort provides output which is not diverse enough by tree sizes. Hence, I decided to add more cohorts until I would get sufficient diversity. I found that three cohorts would be a good number. When I kept adding more cohorts, the later established trees became suppressed and did not grow.

The time between the cohorts establishment was based on previously mentioned graph-2.1. I suggest to look at sites that are less than 100 years old. This is because they have no understory trees that are big enough to reach the main canopy. Since the graph shows the difference between oldest and relatively young trees from the main canopy, we can assume that this is the maximum difference between tree regeneration times. The graph shows an average of 20 years of difference between oldest tree and a younger one. I used this number to establish the first cohort at year 1, second cohort at year 11 and third cohort at year 21. Thus, the difference between the oldest and the youngest trees is 20 years.

The next thing was to decide how many trees to grow in each cohort. It is logical to assume that more trees enter the site when it is still unoccupied by seedlings. Consequently, I decided to regenerate 600, 400 and 400 stems per hectare in first, second and third cohort respectively. Sensitivity of the model to the change of those numbers is described later on.

Once the trees are established, FORECAST user should define disturbance regime. The model can kill the trees while leaving them standing or it can uproot the trees. In nature most of the uprooting is done by the wind, whereas most of the snags are from decease agents (!!! Citation !!!). The snags that are created by wind breakage in real world are many times connected to a stem rot and hence in the model we can assume that wind is not the primer reason for snags.

If the model runs without any disturbance, the volume and amount of stems increase above the field data. Generally, FORECAST implements tree mortality by following the curves from self thinning stands data. Nonetheless, additional low impact disturbance regime is influential for the simulation. I assumed that the regime can be represented by cyclic events. To define the regime further we need to know the length of the cycle, the attributes of trees that are susceptible to the disturbance and what percent of them should be killed each time.

Both the length of the cycle and the mortality rates are difficult to establish. For example, precisely measured wind speed data does not go more than 100 years back in time. Also the location of the measurements are points of sensor towers and do not represent any spatial data on stand level. That is why the wind disturbance period for current simulation was estimated by an expert opinion. It was estimated to be 40 years (!!! Should I put the name of Steve Mitchell as the expert who gave the opinion? !!!) Similarly, I had a problem to establish mortality rates. I was not able to find a report regarding CWH zone mortality rates suitable for modeling use. For example, Wells does report mortality rates {{38 Wells,Ralph Walter 1996}}. His database was collected over a period of 40 years. However, the data analysis does not indicate the cause of the mortality. Hence, I can not separate wind caused mortality from self thinning processes which are automatically simulated in FORECAST.

Due to those problems I decided to introduce mortality rates based on best fitting of the model output to field data. That means that enough trees should die to follow the stems/ha, tree volume, CWD and snags data measured in current field work. To follow stems/ha and tree volume curves the sufficient mortality was found to be 15% of trees per 40 years. But I also needed to decide the proportion of standing dead trees to uprooted once. That in order to have enough logs and snags. That was done by referring to {{18 Lertzman,K.P. 1996}} article. Lertzman et al report that in small forest gaps the relation between the standing dead trees and uprooted/snapped trees is around 1:2 ratio (data for CWHvm1 variant on page 1261). FORECAST can not simulate snapped trees and that is why I added snapped and uprooted trees together. As standing dead trees are not killed by wind, I changed the disturbance cycle for standing dead trees to be more frequent and equal to 20 years. The percentage of trees killed standing each time was changed to 3% to keep the ratio of 1:2.

The disturbances eliminate trees that are older than 40 years, because otherwise the trees are too small and less affected by windthrow or stem rot. Enough of those small trees are killed by self thinning algorithm of the model.

FORECAST, as some other forest growth models, does not have an automatic regeneration of trees on the site. Consequently I needed to introduce additional two cohorts in older stage of the simulation. That in order to grow enough small and medium sized trees during understory reinitiation and old-growth phases.

Total evaluation time was set to be 300 years. After 300 years the modeling output becomes unstable, because the field data does not include proper measurements for regeneration of trees in old-growth forest. Hence, the model fails to simulate replacement of main canopy trees in more advanced years.

Evaluation techniques

To evaluate FORECAST performance I was considering the following steps:

First of all, the model should follow ecological sense. That means that the model should show ecologically reasonable results in most of the time steps and for most of the attributes. Moreover, its graph shapes should follow theoretical shapes discussed in a previous chapter. Deviation from this logic should be explained. Hence, further down I compare the shapes of the graphs to the actual field data and explain deviations of the model. Additionally, at some advanced point of time the model output for each attribute should enter an old-growth threshold for this attribute. Hence, it is important to see if the model does enter those thresholds for all attributes.

The next step would be to consider the accuracy of the model and to perform sensitivity analysis. Common accuracy indices for forest growth models are {{58 Vanclay,J.K. 1997}}:

Mean Biass = $\frac{1}{n}\sum_{i=1}^{n}(Y_i^{field} - Y_i^{forecast})$ (Equation 3.1)

Root mean square error (RMSE) = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i^{field} - Y_i^{forecast})^2}$ (Equation 3.2)

Modeling Efficiency (also called R^2) = $$1-\frac{\sum_{i=1}^{n}(Y_i^{field}-Y_i^{forecast})^2}{\sum_{i=1}^{n}(Y_i^{field}-Y_{average}^{field})^2} \qquad \text{(Equation 3.3)}$$

For sensitivity analysis I change some initial conditions and disturbance regimes. After model runs I compare the output to the field data to see if the model starts to show unstable or illogical behavior. I also compare the shapes of the model graphs to the field data.

It is important to notice that while the field data comes from a chronosequence, FORECAST simulates a growth of a single stand. The field data is highly variable due to do difference of disturbance history of the sites as well as of the differences in initial conditions, amount of regeneration and site attributes. No matter how good the model will be, it can not simulate all those trajectories of the stand dynamics at once. But, in order to simulate individual sites, we need first to evaluate the model against some data. In our case it will be an averaged trajectory from the chronosequence. Once the model evaluation is complete, the model will be able to predict individual trajectories.

Following the above logic I decided to compare the model first to the chronosequence data as it is. Secondly, I take each graph for the field data and fit it to theoretical regression. Those regressions are also being compared to the model. Obviously, the model follows better the regression lines than the actual data. This is because regressions represent averaged trends and hence smooth the effect of large variance between the sites.

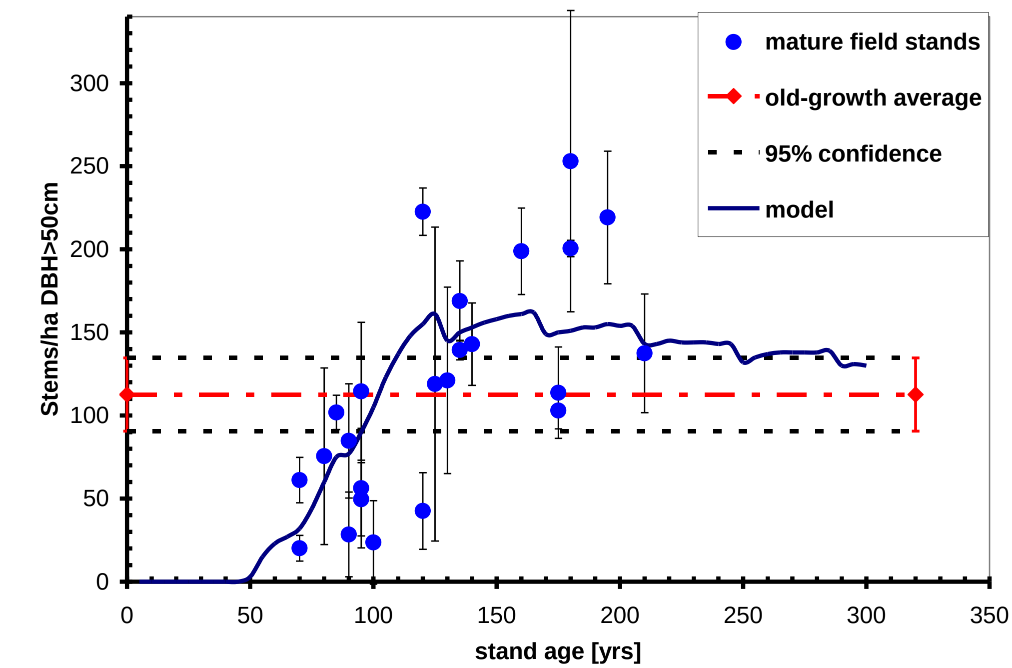
Graphs 3.1−3.14 display the comparison between the model and the actual field data. Tables 3.2−3.3 summarize the comparison of accuracy. It is important to pay attention to the fact that the trends near age 300 of the model can not be extrapolated to forecast trends for older years. This is due to the fact that the dynamic changes of the stand in the model are not gradual. The wind disturbance and changes of tree sizes can cause disrupt changes in curve tendencies. Since the model did not run further than 300 years, it is impossible to predict model behavior in more advanced years.

The graph for CWD goes in proximity of most field points. The trend of the field data is not obvious, because each stand was hit in different times by small disturbances with different severity level. Hence, accuracy indices were not calculated for dead logs. That is why both field and model data were fitted by theoretical function and then accuracy indices were calculated (CWD graph 3.14 and table 3.3).

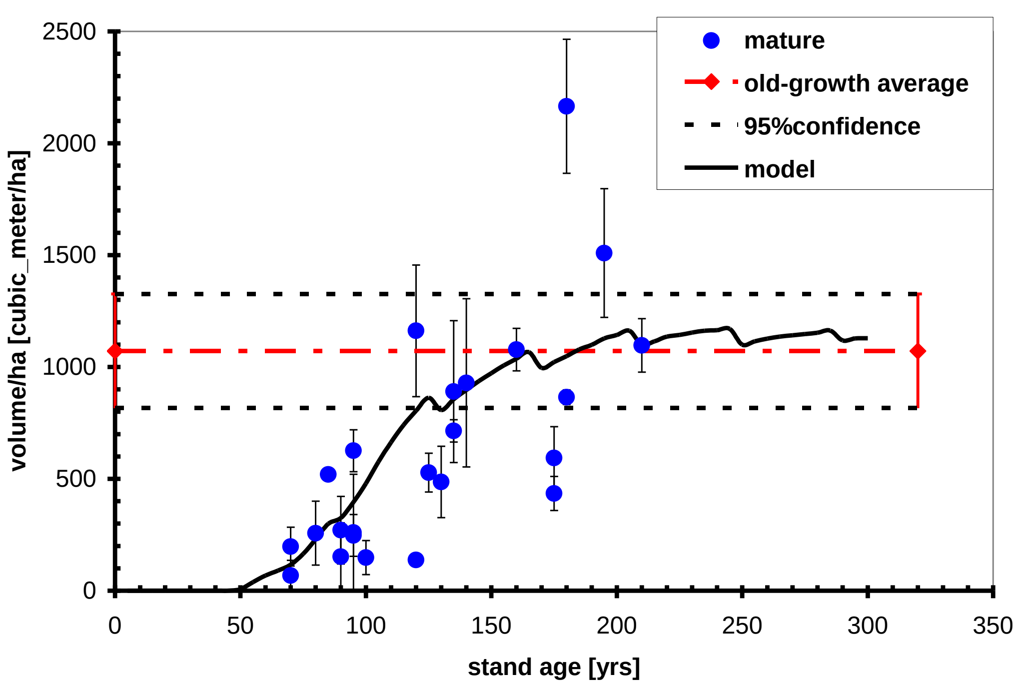
The comparison for snags between the model and the field data involved snags with DBH>50cm, because only those snag sizes from the field data showed significant change with time. For other tree sizes the field data had insufficient information. The comparison of those big snags was problematic, because the field data for snags was highly variable (graph 2.1). That was why I created age classes for field data and averaged the amount of snags for each age class. The error bars were calculated using the equation Error= $\frac{\sigma}{\sqrt{N}}$, where σ is the standard deviation and N is the number of sites in age class. Since that kind of data is not continuous on the axis of time, the best comparison is to check whether the curve of the model passes close to the averages of the field data within error bars.

The shrub percentage cover in the model is significantly lower than the field data (graph 3.9). One of the reasons for that is because the model does not allow to calculate percentage cover of its small trees which grow in the shrub layer. Nonetheless, even when the understory trees are excluded from the field data, the shrub cover of the model is much lower. The reason for that is the small amount of light that reaches the shrub layer in the model. FORECAST represents the canopy as a uniform layer. In real forest however spatial position of the shrubs relative to canopy openings is important.

The biggest living tree DBH that the model reached after 300 years was 126cm. The old-growth sites had on average 9 trees/ha with much bigger sizes up to 310cm DBH for the largest tree that we measured. Those huge trees probably grew much longer than 300 years. We also should take into account that more than half of those huge trees were Western Cedars (Thuja plicata). The site index of Cedar is reported to be lower by 5 points than the SI of Hemlock on CWHvm1 zonal sites {{57 Forest Science Program, Ministry of Forests and Range 2008}}. That means that those Cedars needed even more time to grow than Hemlock. Although it is also true that the site index probably changed through such a long period of time.

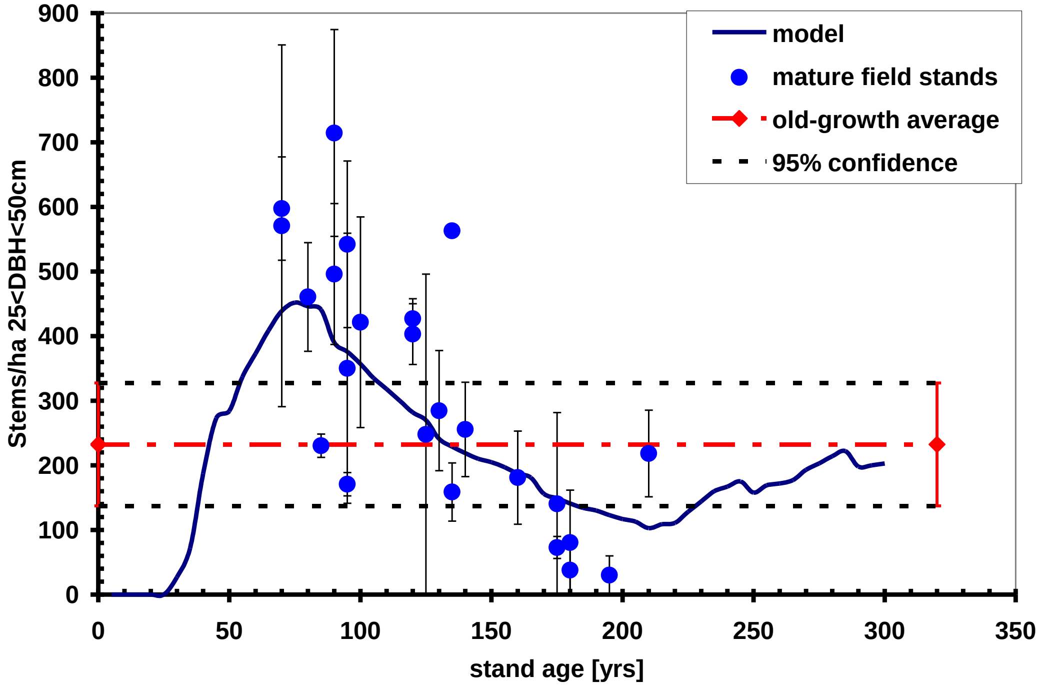


Graph 3.1

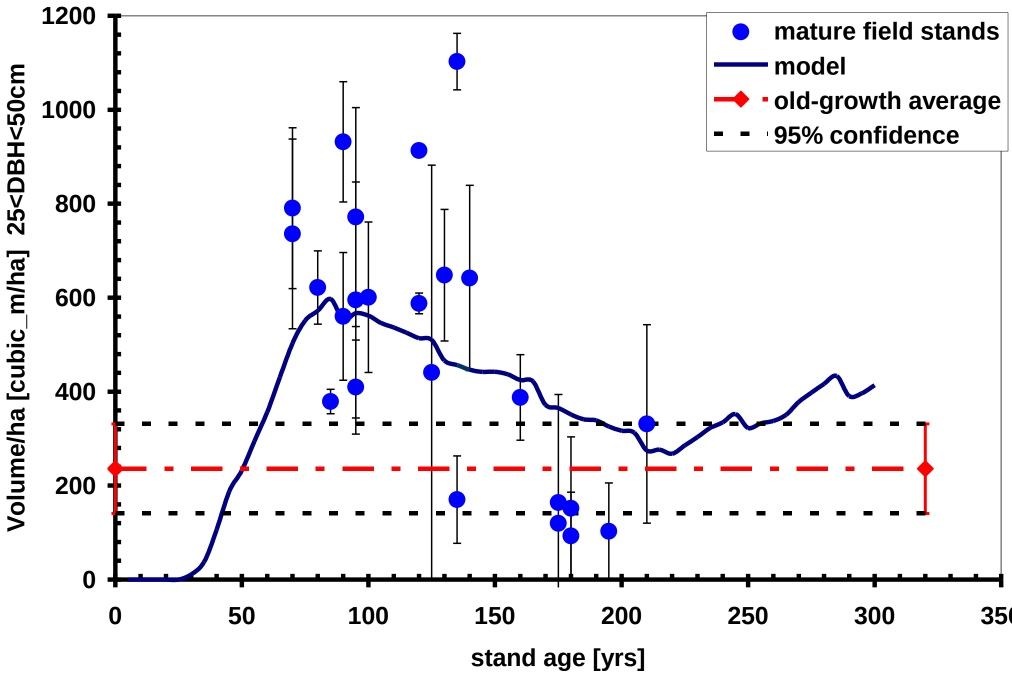


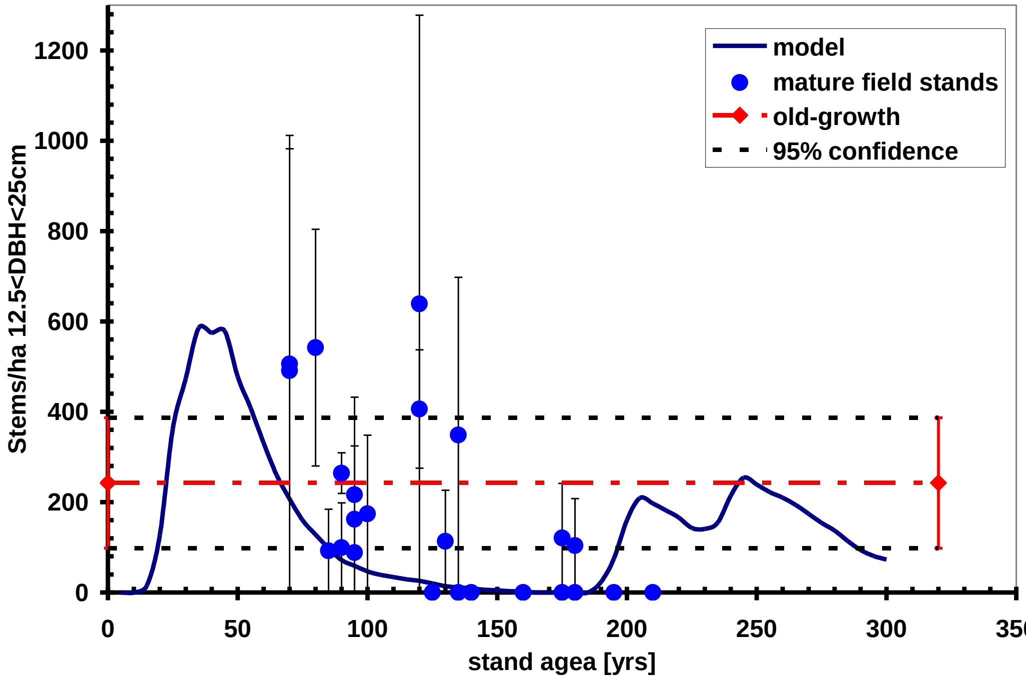
Graph 3.2

Graph 3.3

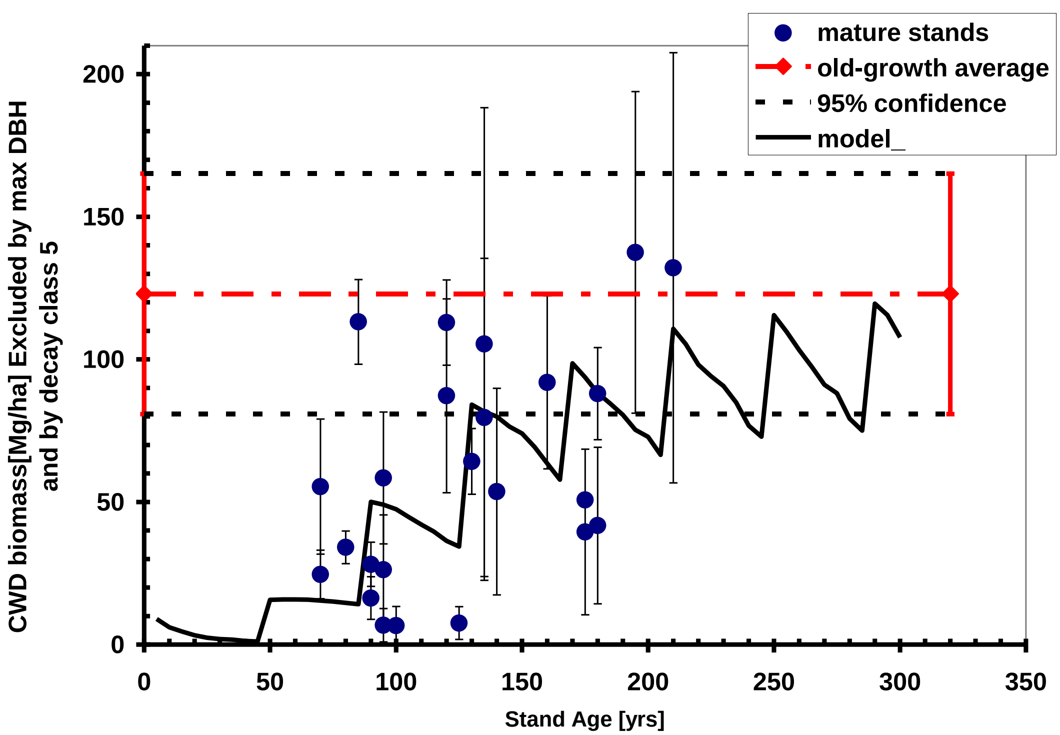


Graph 3.4

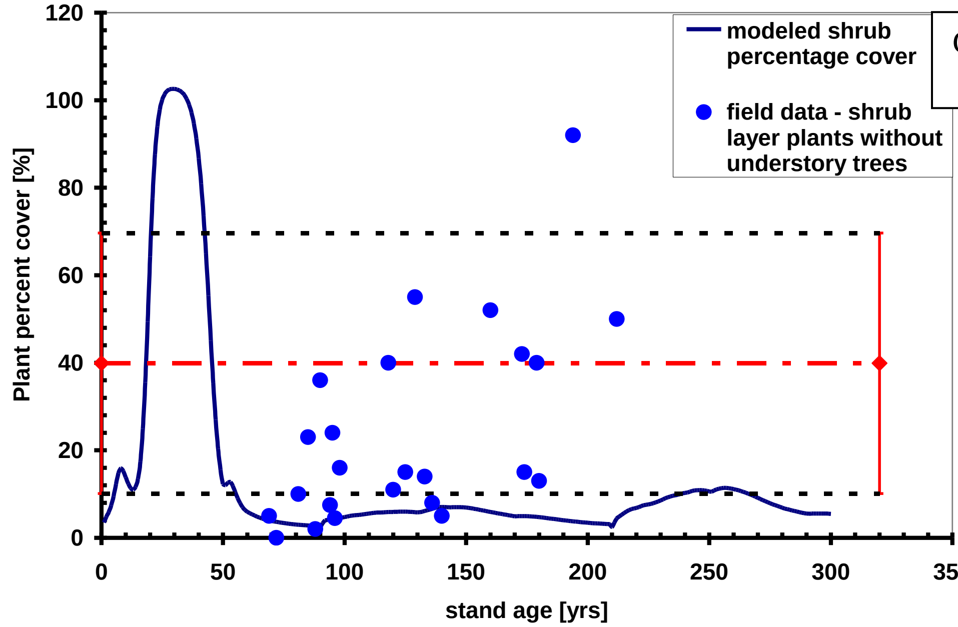




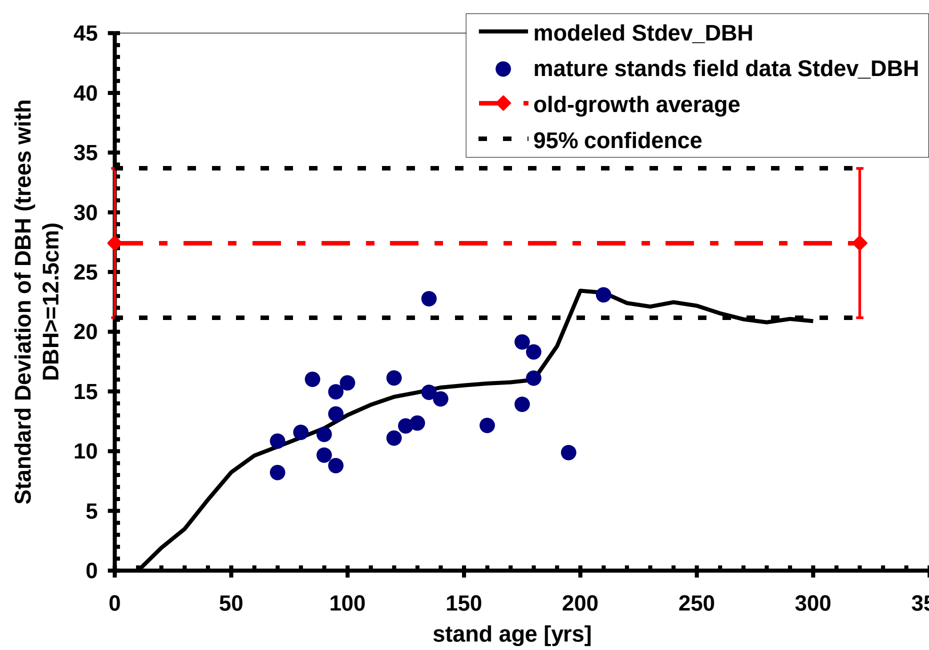
Graph 3.5



Graph 3.7



Graph 3.9



Graph 3.10
No error bars for mature sites

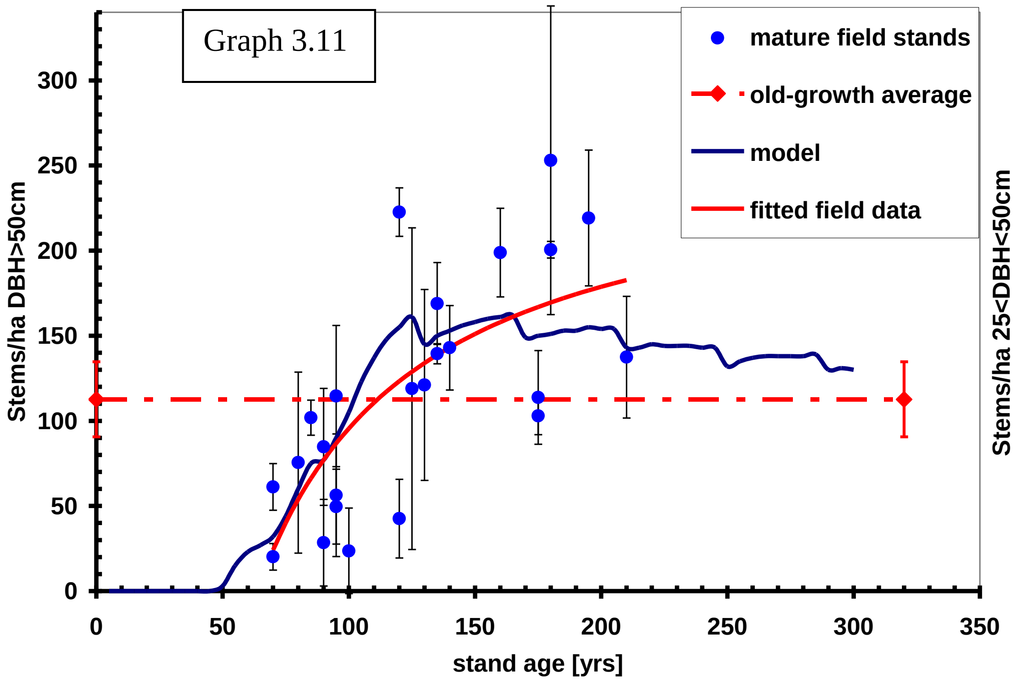
Table 3.2 − comparison between the field data and the model

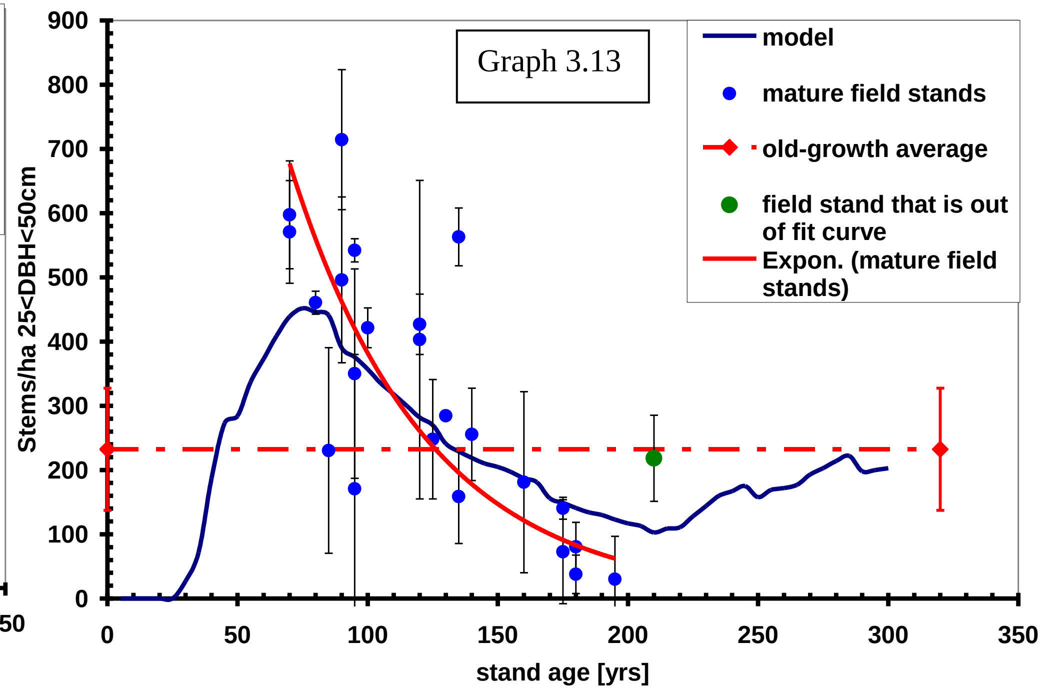
Graph	**Logical shape of the model curve**	**Mean Bias**	**RMSE**	**Model Efficiency (R^2)**	**Model reached old-growth 95% CI at year 300**
Stems/ha DBH>50cm	Yes	-2.49 stems/ha	48.51 stems/ha	0.46	Yes
Volume/ha DBH>50cm	Yes	-43.37 m^3/ha	357 m^3/ha	0.48	Yes
Stems/ha 25<DBH<50cm	Yes	34.54 stems/ha	136 stems/ha	0.5	Yes
Volume/ha 25<DBH<50cm	Yes	35.1 m^3/ha	239 m^3/ha	0.28	Slight overshoot
Stems/ha 12.5<DBH<25cm	Yes, but the model graph runs left of field points	NA	NA	NA	Slightly bellow the threshold
Volume/ha 12.5<DBH<25cm	Yes, but the model graph runs left of field points	NA	NA	NA	Yes
CWD Biomass	Yes	NA	NA	NA	Yes
Snags/ha, DBH>50cm	Fails to increase the amount of snags in old-growth age	NA	NA	NA	No
Plant percent cover	Fails to represent proper dynamics in stands older than 80 years	NA	NA	NA	No
Standard Deviation of DBH	Yes	-0.39	3.56	0.16	Yes

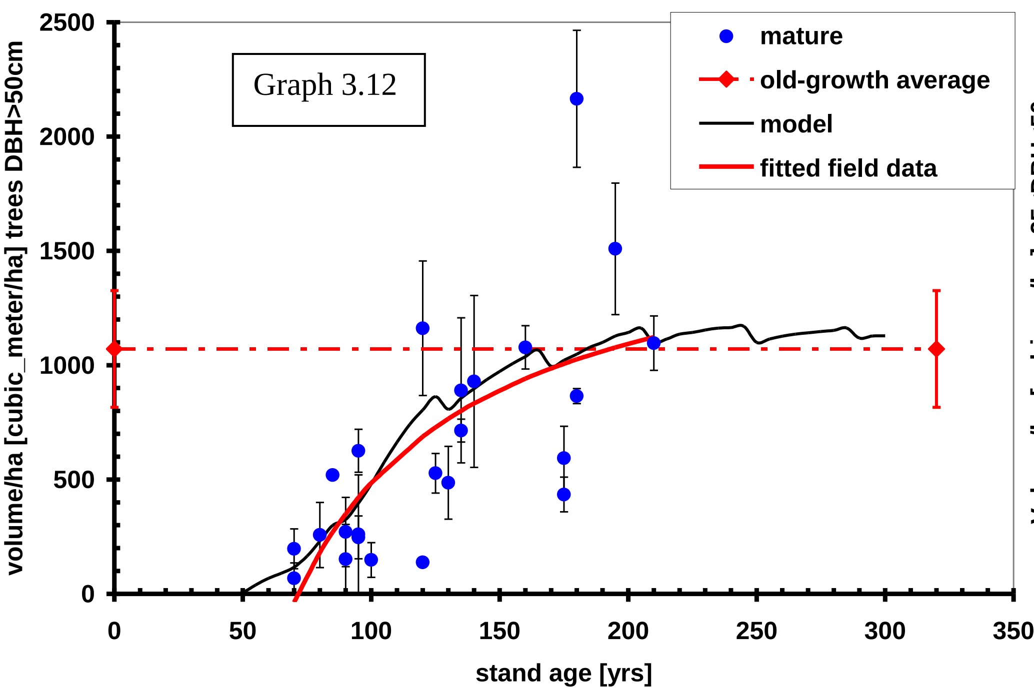
As was explained previously I also fit the field data by theoretical regressions. The theoretical equation for increasing curves is Y=a+b/X. This is due to the fact that the tree volume and stems/ha of big trees increase until the age of old-growth, where theoretically it suppose to stabilize. The increase slows down as the age of the stand approaches the old-growth age. Similar theoretical assumption is valid for CWD biomass. The CWD data from the model is also highly variable due to sensitivity to disturbance. Each 40 years there is a jump on the graph due to wind disturbance. Those jumps do not allow proper comparison of the model to average trends, because sometimes the model is far above the theoretical curve and sometimes is far bellow. Therefore, the CWD data from the model was also fit by theoretical curve

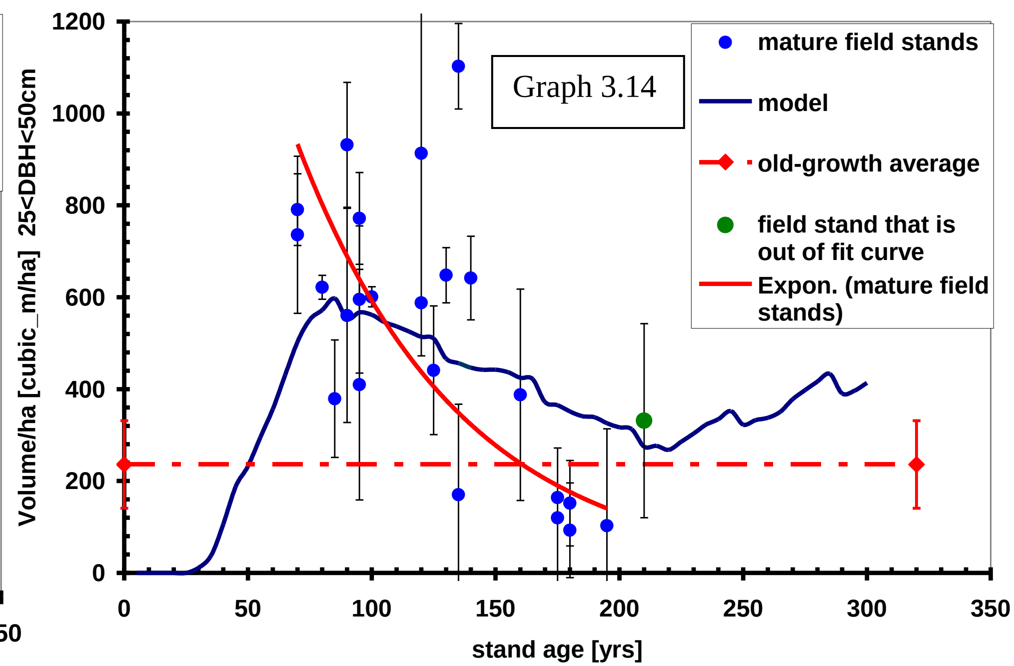
The equation that was fitted for decreasing curves is $Y=a\cdot\exp(-b\cdot X)$. Theoretically, the medium trees amount should decrease gradually from young to mature stages of the forest. This is because the trees become bigger and hence switch to a different size group. As trees become bigger, there are no small trees to enter the medium size group, because there is no regeneration during stem exclusion phase. Only since Understory Reinitiation phase trees start to regenerate. However, it looks from the field data that those trees do not grow bigger than 25cm DBH up until age 200. Therefore, we can fit sites that are younger than 200 to exponentially decreasing curve.

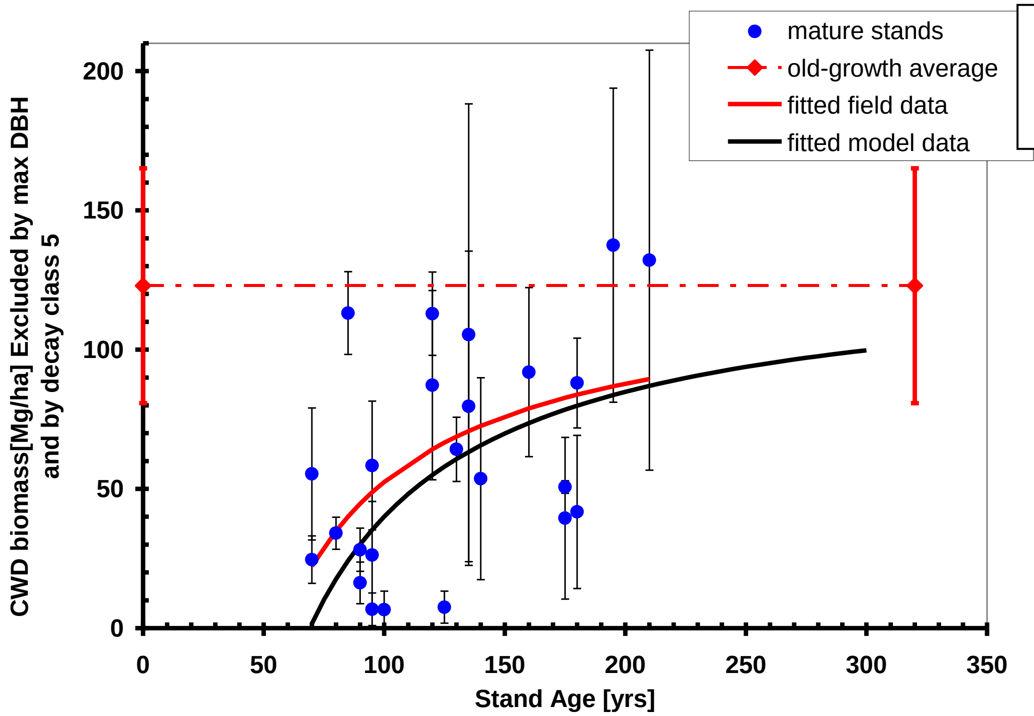
Since snags and shrub cover data is problematic, I did not fit any curves for those attributes.


Graph 3.11
mature field stands
old-growth average
model
fitted field data
Stems/ha DBH>50cm
stand age [yrs]
0
50
100
150
200
250
300
350

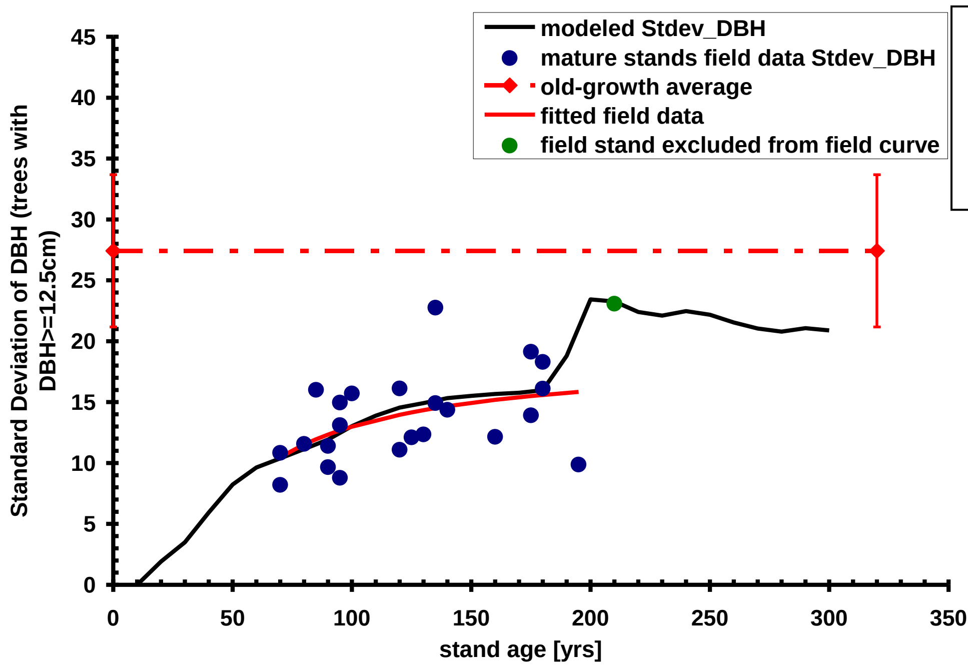

Graph 3.13
model
mature field stands
old-growth average
field stand that is out of fit curve
Expon. (mature field stands)
Stems/ha 25<DBH<50cm
stand age [yrs]
0
100
200
300
400
500
600
700
800
900


Graph 3.12
mature
old-growth average
model
fitted field data
volume/ha [cubic_meter/ha] trees DBH>50cm
stand age [yrs]
0
500
1000
1500
2000
2500


Graph 3.14
mature field stands
model
old-growth average
field stand that is out of fit curve
Expon. (mature field stands)
Volume/ha [cubic_m/ha] 25<DBH<50cm
stand age [yrs]
0
200
400
600
800
1000
1200



Graph 3.15



Graph 3.16
No error bars for mature sites.

Table 3.3 − comparison between the fitted field data and the model

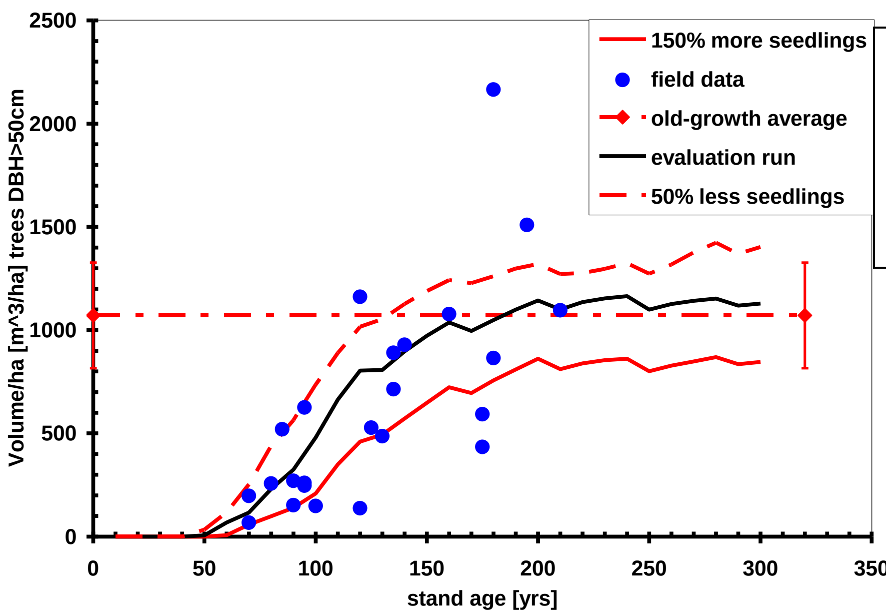
Graph	**R^2 field fitting**	**R^2 model fitting**	**Mean Bias**	**RMSE**	**Model Efficiency (R^2)**	**Model reached old-growth 95% CI at year 300**
Stems/ha DBH>50cm	0.5	No need to fit	-1.16 stems/ha	18.5 stems/ha	0.83	Yes
Volume/ha DBH>50cm	0.48	No need to fit	-54 m^3/ha	70 m^3/ha	0.95	Yes
Stems/ha 25<DBH<50cm	0.7	No need to fit	-9.61 Stems/ha	75 Stems/ha	0.83	Yes
Volume/ha 25<DBH<50cm	0.59	No need to fit	-61 m^3/ha	175 m^3/ha	0.47	Slight overshoot
CWD Biomass	0.21	0.76	8.47 Mg/ha	9.9 Mg/ha	0.72	Yes
Standard Deviation of DBH	0.22	No need to fit	-0.4 No units	1.18 No units	0.98 for years 70-180 comparison 0.46 for years 70-200 comparison	Yes

Site aged 210 years was excluded from curves of graphs 3.13, 3.14 and 3.16. This is due to the fact that the site has regenerated trees and hence is out of the declining trend for medium trees and also has higher standard deviation because of this regeneration.

Sensitivity analysis

The variables that were checked for sensitivity analysis: number of cohorts, total number of seedlings in stand initiation phase, timing of regeneration, percentage of trees killed by disturbance, disturbance period time.
Since the possibilities of changing those variables are endless, I decided to check only some changes that may be important. Moreover, to save space, I present only some of the graphs to represent the change.

1. **Number of cohorts:** I found that at least three cohorts in stand initiation phase are needed to represent proper stand dynamics. However, it is interesting to see if additional cohort will add more accuracy to the simulation. In the following run I use 4 cohorts with 7 years interval between them. To regenerate similar amounts of trees I regenerate 500, 400, 300, 300 stems/ha for respective cohort number. Theoretically, the last cohort should be suppressed and hence would not change much during the run.
   After the run I found that the cohorts 3rd and 4th had similar amount of biomass and similar amount of stems/ha. Addition of a cohort did not change significantly any graph of stand attributes presented during evaluation.
2. **Total number of seedlings in stand initiation phase:** I increased the total number of seedlings by 1.5 times comparing to evaluation run. Evaluation run had 600, 400, 400 stems/ha in respective cohorts. I increased it to be 900, 600, 600 respectively. I expected high competition between the trees and hence the trees will grow slower.
   After the run I found significant decrease in both volume and stems/ha of big trees (DBH>50cm) and significant increase in volume and stems/ha for medium and small size trees (DBH 25-50 and 12.5-25 cm) Since the trees were smaller, the CWD graph falls down more sharply between each wind event due to faster decomposition rates. The amount of big snags also decreased. Nonetheless, the shapes of the graphs followed similar trajectories. Graph 3.17 shows comparison of the evaluation run with the run of twice more seedlings and also with twice less seedlings.



Graph 3.17 Comparison of different initial seedlings amount

3. **Timing of regeneration:** Since Western Hemlock is a shade tolerant species it is interesting to check how long can be the difference of timing between the three regenerating cohorts. As mentioned above the decision regarding the cohort timing was

based on the ages of main canopy trees. I checked the sensitivity of the model to 5 year interval and 15 year interval between each cohort.

When I used 15 year interval between cohorts, the third cohort had more suppression comparing to evaluation run. Only minor changes were observed in graphs of medium and small size trees and snags. (DBH 25-50cm and DBH 12.5-25cm) Big trees and CWD graphs were not affected.

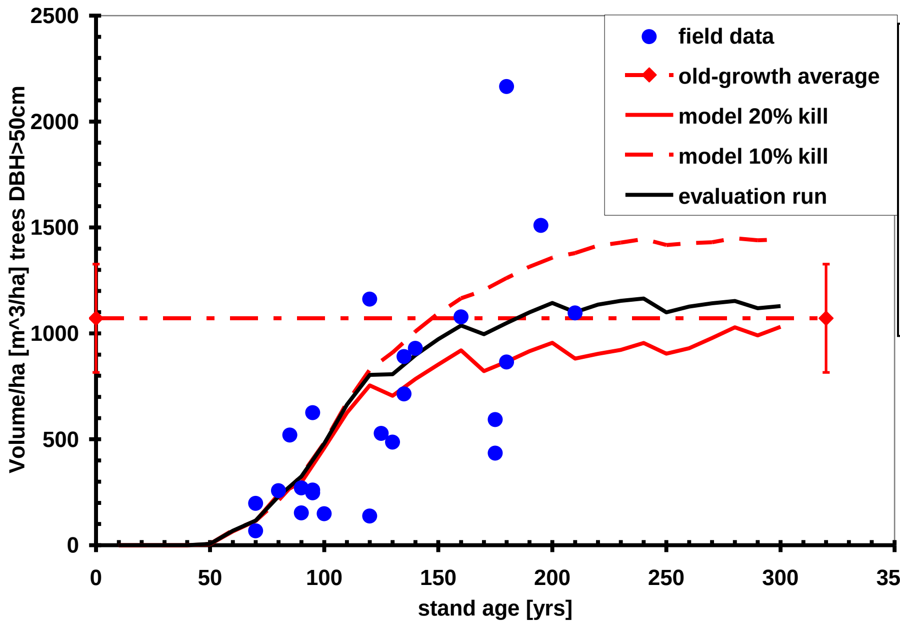
When 5 year difference was used, the second and the third cohort tree sizes had more similarity than during evaluation run. The changes for the stand level graphs were minor.

4. **Percentage of trees killed by disturbance:** As the sensitivity analysis for number of seedling showed differences in output, the number of trees in the model is influential. Dead wood graphs should be especially sensitive, because even small change in tree mortality may have large impact on dead wood biomass.

   I preferred to keep the relation between the amounts of trees killed by uprooting and the trees killed to become snags. The optimum evaluation run had 15% mortality due to disturbances in 40 years period. In sensitivity analysis I decided to check cases of 10% and 20% mortality.

   When I removed only 10% of trees, the graphs for big trees showed higher values. The dead wood graphs obviously significantly decreased.

   The opposite happened during increase of tree mortality to 20%. The graphs of big trees decreased and the dead wood graphs significantly increased. (example of the change on graph 3.18)



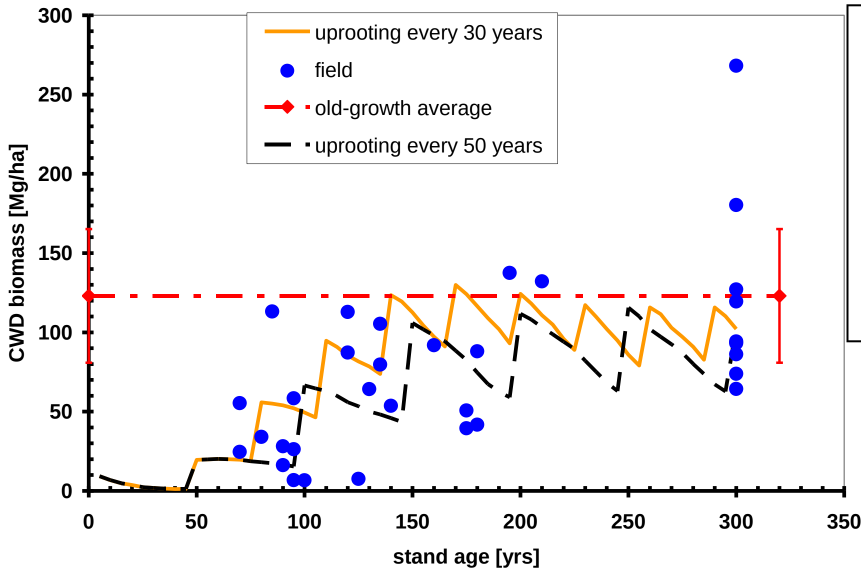
Graph 3.18 Comparison of large tree volume with different percentage of tree mortality

5. **Disturbance period change:** To simplify the analysis I checked only the change of uprooting disturbance. In optimum the disturbance happens every 40 years. I checked the changes in simulation if the disturbance period changes to 30 and to 50 years.

   Switch to 30 year cycle did not change significantly the graphs related to live tree volume or stems/ha. It did change slightly the CWD graph. The most important difference is that CWD has less time to decay between the uprooting events. However, because of more frequent death of the trees, the amount of CWD is higher by only 10[Mg/ha] relative to evaluation run.

Switch to 50 years cycle also mainly influenced the CWD graph with longer decay periods between uprooting events. The amount of CWD relative to the evaluation run decreased by only 10[Mg/ha].

Graph 3.19 presents the comparison of CWD biomass between 30 years and 50 years cycles.



Graph 3.19 Comparison between 30 years and 50 years disturbance cycle length

Discussion

Since the amount of trees in stand initiation phase is highly important, it is obvious that the model should have been adjusted to an average amount from the field data by trial and error method. The same is true for the percentage of trees killed by disturbance. Except those two variables other variables were not calibrated by the field data. Therefore, the evaluation run of the model can support the validity of non calibrated assumptions.

FORECAST graphs for living trees follow theoretical shapes. The graphs for big and medium trees (DBH>50cm and DBH 25-50cm) show high accuracy levels, whereas the graphs for small trees do not follow the timing and the amplitude of the field data. Visual comparison between graphs 3.12 and 3.14 shows that the model follows the trajectories for bigger trees better than for the medium once. Also, comparison between graphs 3.13 and 3.14 shows that in ages 120-200 the medium trees in the model have higher volume per tree than expected from the field data. Therefore, from year 120-200 the trees in the model grow faster. That may explain why the model does not show enough small trees in years just before this period. However, the small trees show faster decline in the graphs also due to tree mortality.

The graphs for the small trees (DBH 12.5-25cm) do keep the theoretical shape of the curve, but they are shifted left relative to the actual field points. This effect may have three possible explanations and their combination:

1. It may be that the model grows the trees too fast, especially the small once. In that case the shape of the curve runs left of the field points, because trees become larger than 25cm in DBH.
2. The model can overestimate tree mortality due to shading. It may be that small trees can persist in the field much longer.

3. Trees can regenerate in older ages and that is why we have small trees later on in the field data. That means that I should try to regenerate more trees in older cohorts or add additional cohort. However, it is unluckily, because not too many trees regenerate in shade.

The reader may be surprised to see an old-growth threshold for medium size trees. Other researchers do not usually refer to that size class while talking about old-growth. It is much more common to see reports about large size trees in old-growth. However, the dynamics of tree sizes is interdepended. Franklin and Spies {{69 Franklin,J.F. 1991}} note the importance of having certain amount of big trees per hectare as an indicator of old-growth. This amount of big trees obviously influences the amount of smaller trees in the area. The influence is caused by shading of lower trees as well as by competition for nutrients and moisture. Moreover, the large trees also reseed the area around them and hence cause regeneration of future trees. Additional important issue is that in order to keep certain amount of big trees in the area we need certain amount of smaller trees that can potentially grow and replace the larger ones after their death. That is why when we consider a certain size of trees we will have a certain threshold for their amount in the old-growth. For example, if we do not have enough medium trees in the area, we are not going to have enough big trees in the future. On the other hand, we can not have too many medium sized trees, because larger trees cause shading and competition for nutrients. Consequently the threshold for medium sized trees should have maximum and minimum values.

Standard deviation graph follows the predicted theoretical trend including the jump at years 180-200 due to appearance of regenerated trees that become wider than 12.5cm DBH at this time. The graph closely follows the field data trend with R^2=0.98 until year 180. However, the model starts to regenerate trees that reach DBH>12.5 at the same year. Hence the increase in modeled standard deviation that reaches proper value to pass near the field site aged 210. The modeled standard deviation also enters the old-growth confidence interval.

When we consider the comparison of the field data that was fitted by theoretical curves and the model, we get high numbers for model efficiency. Additionally, RMSE is low for big trees and CWD graphs, however it is pretty big for medium trees. This is another evidence to supports the fact that the modeling is more accurate for big trees.

It is important to notice that the indices of accuracy are pretty vague about their indication of actual accuracy of the model. The best example for indices limitation is the modeled standard deviation graph. It follows the field trend line until year 180, but it should increase afterward. The timing is important, because the model has to grow enough small trees to reach the value of the field site aged 210 years. The model fails to pass near the point of the field data at age 195 just because it is impossible to grow small trees and to keep low standard deviation. Hence the decreased R^2=0.46 for comparison between ages 70-200. We should remember that the model during evaluation run grows an average stand and therefore it can not pass near all the field data points. Moreover, to calculate the field data trend I used points of mature sites only. This is due to inability of age estimation for old-growth sites. Nonetheless, the model does reach the old-growth confidence interval for most of the attributes. The fact that the model does reach the interval increases its accuracy, but it is impossible to calculate how much will R^2 increase due to that fact. As a conclusion, for my opinion, the visual passage of the model line is a better indicator of model accuracy than the accuracy indices for current project.

Most of the attributes, except medium trees volume and small trees stems/ha, reached old-growth threshold within 95% confidence interval. That allows to use the final condition of the model as an old-growth condition in a simulation of different silviculture systems that are applied on old-growth forest. Those simulations are discussed in the next chapter. However, we do not need to limit ourselves to explore logging only in old-growth. As the model shows proper stand dynamics graphs in every point of time, we are able to use the model state in any time point to simulate the impact of the logging operations on forest with any age.

Model runs show the importance of wind caused mortality in the stand. Hence, stand level tree mortality measured for a short period can not be sufficient to simulate coastal sites for prolonged years. Unfortunately, most of the published material about wind mortality is concentrated on landscape level or on short term outcomes after logging operations. Further research is needed to describe low level wind disturbances on stand level for prolonged periods. That kind of information will greatly enhance the ability to simulate the dynamics of forested stands. Nonetheless, the assumption about periodic wind disturbance looks logical and the model produces CWD graph that follows the amplitude of the field data and shows good accuracy. The sensitivity of the model to change in period length shows that the period of windthrow should be between 30 to 50 years.

From the shape of CWD graph we can draw important conclusion that in real stand the amount of dead logs biomass fluctuates around the increasing trend. The fluctuation amplitude is on average 50[Mg/ha], but can obviously be higher. This is important for future chronosequence studies. In chronosequence field data noise can be reduced by choosing forest sites with similar classification. However, the amount of dead logs measured on the sites will be also very sensitive to the disturbance history of the site.

Graph-3.8 shows the comparison of the field data and model run for big snags (DBH>50cm) The model runs lower than the field averages for snags. The curve of the model output does pass within the lower section of the error bars, except for the old-growth stage. The model also fails to show the increasing trend of having more snags in old-growth stage comparing to the mature stage.

One explanation for the above problems can be the choice of the cutoff for the field snags heights. FORECAST shows the change in snag biomass due to decay process. However, it does not represent the change in snag height. The field data can have more or less snags per hectare due to a different cutoff in snag height. We measured snags as low as 1.3m. The problem with comparison to the model is to know which cutoff of snag heights to chose. As I noted in previous chapter half of the snags that were measured in the field had heights lower than 5 meters. The comparison shows the importance of measuring snag volume in the field to calculate snag biomass. This is a bit difficult, because the top diameter of the snag should be measured for this purpose. Special equipment is needed to perform such operation. Another option will be to estimate the volume by measuring the change of snag diameter in its lower part and extrapolating for the diameter at snag highest point. Nonetheless, the field data lacks those measurements and that may be the reason for the inefficiency of model and field data comparison.

!!!insert SD DBH discussion !!!

Sensitivity analysis supports the decisions for initial conditions and disturbance events. The number of cohorts in the model can not decrease, because otherwise it will not represent proper stand dynamics. There is no logic to complicate the model and to increase the number of cohorts, because the last cohorts will be suppressed. The number of seedling at the start of the simulation influence the output as theoretically would be expected from the stand. On the other hand, slight changes in times between successive cohorts did not change much. This is probably due to the fact that the first cohort is much more influential for the output than the others. Hence, even if the later cohorts appear in slightly different time, their lesser of greater suppression does not significantly influence the output.

Percentage of trees killed by disturbance was an initial guess that was calibrated by the output response. Since the model is pretty sensitive to change in this number, it supports the chosen percentage. The same is true for the number of trees killed by each disturbance event.

Limitation of the comparison between the field data and the model

The limitations of the comparison between the model output and the field data can be separated to limitation of the field data, limitation of model input and limitation of the modeling process.

The input in current project consists from the variables regarding initial conditions that were derived from the comparison of the model output to field data. Additional input are the assumptions regarding initial conditions and disturbance regime. The assumptions, although proved to be logical by sensitivity analysis, can still be not entirely true. Unfortunately, it is difficult to support them by other arguments, just because there was no scientific research done in those areas. As for the field data, it has significant variance as can be seen from the graphs. The variance is not only between the sites with similar ages, but also between each two plots on the same site. The variance between two plots is represented by the error bars and as can be seen on the graphs, some errors are substantially big.

Not only that the field data has errors, but it also has to be transformed for calculation of tree volume and CWD biomass. Those transformations obviously add additional errors. We can see it directly by comparison of graphs 2.10 and 2.11. CWD volume was calculated first and then transformed to biomass. We can see that graph 2.10 shows higher errors than graph 2.11.

In addition, the data for snags is questionable, because the plots for them appear to be too small, as discussed in previous chapter. Consequently, I could not perform additional sensitivity analysis to decide what would be the proper rate for killing trees for snags. As mentioned, this number depends on the percentage of trees that are killed by uprooting.

As the input and the field data have their own limitations, we can not put the entire fault for deviation from the field data on the model.

Additional problems in input consider the decay rates of snags and logs. Unfortunately, decay rate is a difficult parameter to estimate, because proper experiments for long periods of several decades are needed. However, those long term experiments are difficult to establish and usually done during only short periods. To complicate the situation further, only small amount of experiments deal with Tsuga heterophylla (Western Hemlock). That problem of decay rates affects directly the simulation of CWD decay in the model with consequences of possibly higher or lower accumulation of dead woody debris due to that fact.

The shrub percentage cover was not simulated properly by the model. The first reason to that problem is the transformation from foliage biomass represented in the model to percentage cover that was measured in the field. As noted in previous chapter the percentage cover and biomass may not be in good correlation for Vaccinium genus that is simulated in the model. Some may think that the problem in shrub simulation is due to FORECAST representation of forest canopy by evenly dispersed layer. That can be a problem when canopy gaps appear and allow some parts of the ground to receive more light. However, the miscalculation in shrub cover starts from the point of year 90 and on. During this time only minor amount of canopy gaps appear in real forest and hence there should be additional reason for miscalculation. Further model analysis should concentrate on this problem.

Conclusions

Based on the evaluation results the model can be used to simulate condition of forest in different ages. This is true for all the attributes that were

There are two goals for current master project:

1. To estimate the impact of logging on old-growth attributes of the forest.
2. To estimate the time of recovery of those attributes as well as their dynamics.

Model evaluation suggests that the model can show the dynamics of the recovery for most of the forest attributes discussed in chapter 2. Hence, the timing of the recovery can also be calculated by using the old-growth thresholds that were defined in previous chapter. The immediate impact can be estimated by the percentage value of the attribute relative to its old-growth average. The impact however is not limited to immediate outcome. During the recovery of each attribute, we are able to see in any point of time how far by value the attributes is from its old-growth average.

It is rare to see in scientific literature quantified discussion regarding the dynamics of the forest when it is in old-growth state. Some articles show how from field data we can acquire thresholds for some old-growth indicators. The indicators include big living and dead trees. However, to model the dynamics of old-growth forest it is also important to know what happens with smaller trees. Although the field data for trees with DBH<12.5cm was problematic in our project, FORECAST is able to give insights about the dynamics of medium sized trees with DBH>12.5cm.