APPLICATION OF THE NEW ZEALAND DOUGLAS-FIR SILVICULTURAL GROWTH MODEL (DF NAT) TO DATA FROM THE PACIFIC NORTHWEST

Leith Knowles and Lars W Hansen

Report no 41 September 2004

DOUGLAS-FIR COOPERATIVE

NEW ZEALAND DOUGLAS-FIR RESEARCH COOPERATIVE

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ABSTRACT

The New Zealand Douglas-fir stand level growth model DF NAT was applied to data from 303 sample plots located in 27 silvicultural trials run by the Stand management Cooperative, University of Washington, Seattle. A specific height/age curve was derived from the Pacific Northwest (PNW) data together with actual thinning coefficients, and these were inserted into the model. The PNW stands had a similar mean site index to those from NZ (31.5 m vs 32.5 m MTH @ 40 years) but the range was much less. The data showed quite clearly that site index declined with reduced stocking - an effect previously observed in the PNW, but not very evident in NZ. With a maximum age of 24 years, the stands were still too young to fully test the NZ mortality function, but within the stocking/age range available, the function appeared to work reasonably well, with a tendency of slightly under-predicting mortality. Small differences between observed and predicted crown lengths are probably due to differences in the definitions used for field measurement.

Large differences were found in estimated *Site Basal Area Potential*[1] (SBAP) between the PNW and NZ, with the former having a mean value of 1.17 and NZ having a mean value of 1.75. These translated into very large differences (around 50%) in yield for the same silviculture and history, as represented by *500 Index*[2]. Despite these large differences, the SBAP estimated by the NZ model for each PNW installation was relatively stable with respect to stocking, and stand age. Some over-estimation of basal area increment occurred in stands younger than 8-10 years, particularly in association with severe pruning, however, the NZ growth model performed well overall for a range of stockings and pruning regimes.

KEY WORDS
Pseudotsuga menziesii, growth, sample plots, site index, site basal area potential, New Zealand, Pacific Northwest.

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[1] *Site Basal Area Potential* is a site-specific basal area growth index, and is comparable to the annual average basal area increment over one rotation for a fully stocked stand. A detailed account is presented later in the paper.
[2] *500 Index* is the MAI of a stand of D-fir, when planted at around 1650 stems/ha, thinned to waste to a stocking of 500 stems/ha by 15m MTH, and grown to 40 years.

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INTRODUCTION

The New Zealand National Douglas-fir silvicultural growth model (DF NAT) is a system of equations that estimate the behaviour of key stand parameters for intensively managed Douglas-fir plantations throughout New Zealand. The model is based around two main sub-models, one for predicting height growth and the other for predicting basal area growth. The main purpose of the model is to utilise stand-level information, such as current condition and management regime, including pruning, to predict future growth from stand ages of around 5-10 years up to 80 years or more. The growth model links to log merchandising, sawn timber and financial programs within the software program STANDPAK (Whiteside and Sutton, 1983) to provide a complete stand-level modelling system. It is also available within version 2 of the Douglas-fir calculator that utilises the EXCEL® spreadsheet as a base (Halliday and Knowles 2003).

A summary of the functionality of the growth model suite is as follows [3]:

- Total stand crown length (CRL_0) is estimated from stand mean height (MH_0), mean height to crown base (CRH_0), and stocking (N_0). Both height to crown base and stocking can be split into pruned and unpruned elements, thus accounting for pruning treatments applied to various stand elements.
- If not measured, the stand mean height (MH_0) is estimated from mean top height (MTH_0)
- If not measured, the mean height to crown base (CRH_0) is estimated from mean top height (MTH_0) and stocking (N_0).
- The height growth model (height/age-curve) is a direct function of stand age and site index, with a small effect attributed to latitude. Site index (mean top height in metres at age 40 years, *SI40*) is an indicator of the potential for height growth on a particular site, forest, or region (depending on modelling resolution). Site index needs to be determined *a priori* from height/age data.
- Basal area (BA_1) at stand age T_1 is predicted from an earlier basal area value (BA_0) using total stand crown length (CRL_0), stand age, site basal area potential (SBAP) and a competition term consisting of basal area/ha relative to SBAP. The current parameterisation requires the model to work in time-steps of one month.
- SBAP is an index of a site's ability to support basal area growth. It is site, forest or region-specific (depending on modelling resolution) and needs to be determined *a priori* from growth data.
- For thinned stands, the thinning intensity must be expressed either as the number of trees removed, or by the amount of basal area removed. The thinning function then partitions either basal area removed to a number of trees, or a number of trees removed to a basal area. The parameter of the thinning function (termed the thinning coefficient) can be management-specific (e.g. 'thinning-from-below' as opposed to 'thinning-from-above'), and needs to be determined *a priori*. The default value for conventional thinning-from-below in New Zealand is 0.705.
- For unthinned stands the stocking (mortality) model predicts the stocking (N_1) as a function of an earlier stocking (N_0), quadratic mean diameter (D_0) and mean top height (MTH_0). The inherent logic of the density dependent mortality model is Reineke's –3/2-power rule (Reineke, 1933).

The model suite was originally developed and parameterised using growth information from some 550 permanent sample plots in the NZ Forest Research permanent sample plot system (Fight *et al.* 1995). Subsequently, the model has been refitted using data from some 1,300 sample plots.

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[3] $_0$=beginning of the increment step, $_1$ = end of the increment step.

The purpose of this study was to examine how the NZ National Douglas-fir growth model DF NAT behaved when exposed to independent growth data from 27 Douglas-fir silvicultural trials in the Pacific Northwest (PNW).

METHODS

Data

A selection of 303 plots from 27 silvicultural trial installations in the PNW was provided by the Stand Management Cooperative (SMC) and analysed. A summary of the trials and the plots available is given in Table 1.

No.	Name	State	Establ.	Age at 1st meas.	Age at final meas.	No Plots	Thinned	Fertilized	Pruned
353	Chandler pruning	OR	1995	19	23	3	0	0	2
501	Last Creek	OR	1993	19	25	11	11	0	9
703	Longbell Road	WA	1983	7	23	12	10	0	3
704	Ostrander Road	WA	1987	14	28	12	11	0	3
705	East Twin Creek	WA	1987	12	25	9	8	0	3
706	B & U Plantation	WA	1987	10	24	12	11	0	3
708	Copper Creek	WA	1988	8	20	12	11	0	3
711	Kitten Knob	WA	1988	7	21	10	9	0	3
713	Sauk Mountain	WA	1988	7	19	12	11	0	3
717	Grant Creek #1	OR	1989	6	18	10	9	0	3
718	Roaring River	OR	1989	8	20	12	11	0	3
722	Silver Creek	OR	1989	13	25	12	11	0	3
724	Vedder Mountain	BC	1989	7	19	10	9	0	3
725	Sandy Shore	WA	1990	10	22	12	11	0	3
726	Toledo	OR	1990	7	19	12	11	0	3
729	Gnat Creek	OR	1990	8	20	12	11	0	3
732	100-Lens East	BC	1990	12	24	12	9	0	3
735	Rayonier Sort Yard	WA	1991	10	20	10	9	0	3
736	Twin Peaks	WA	1992	9	19	16	15	4	5
737	Allegany	OR	1992	7	17	8	7	0	1
905	LaVerne Park	OR	1992	6	16	11	2	0	3
910	Kring Creek	WA	1992	6	16	13	4	0	3
915	Big Tree	OR	1992	4	14	11	2	0	3
916	Bobo's Bench	OR	1993	5	14	12	3	0	3
919	Brittain Creek #1	WA	1993	4	13	13	4	2	1
926	R.F. Sale	WA	-	8	12	12	3	0	3
932	Forks #3	WA	1992	3	13	12	5	0	3
Total						**303**	**218**	**6**	**84**

Table 1 - Summary of the 27 silvicultural trials

Application of DF NAT model

All analyses were performed using SAS® v8.2 (mainly PROC NLIN and PROC REG) and MatLab5®. All graphs were produced with MatLab5®.

Translating mean height to mean top height

The model utilises mean top height (MTH) as one of the main drivers. To avoid confusion over the definition of mean top height, an existing NZ model that translates mean top height to mean height was inverted and applied to the PNW data to get an estimate of mean top height from stand mean height. The observed and estimated mean top heights were subsequently compared to validate this approach.

Height/age-curves

The mean top height was modelled as a function of age using the recently developed NZ-wide height/age curve (van der Colff and Knowles, 2004). However, a reasonably poor (and biased) fit gave rise to the need for refitting the height/age model using the PNW data. The height/age curves were plotted along with the observations.

Site index
Through the iterative height/age-curve fitting process the site index (mean top height in metres at age 40 years) was estimated for each installation (and plot). The overall Site Index for all installations was calculated as the installation level mean, weighted by the number of plots per installation. The installation-level site indices were analysed visually by plotting the cumulative distribution, and by comparison to a similar cumulative distribution for NZ. Linear regressions of plot-level site index against stocking were fitted for each installation, and plotted. Finally, the mean top heights at different times, as predicted from stand age and installation-level site indices, were plotted against the observed heights.

Size-density relationships
The mortality/stocking model for unthinned stands was examined by predicting the stocking (based on quadratic mean diameter, mean top height and initial stocking) from one measurement to the next. The errors of the model predictions were calculated as the observed values minus the predicted values. As measurement intervals varied between 2 and 12 years, the difference between the observed and predicted stocking was divided by the measurement interval, thus giving annual average error. The annual average error was expressed as percentage of the observed initial stocking and these values were plotted.

Because it initially seemed that the stocking model under-predicted the mortality, the function was re-parameterised. However, when re-parameterised, the model no longer adhered to the inherent logic of the –3/2 power-rule, and was therefore discarded. The original NZ parameterisation was therefore used subsequently.

Crown length / height to crown base
The height to crown base model was examined by predicting height to crown base from mean top height and stocking for all unpruned stands. Subtracting height to crown base from mean height gave crown length, which was applied in the growth model. The predicted crown length was compared visually to the observed crown length by calculating the difference, and expressing it relative to the observed value.

The crown lengths estimated from mean height and height to crown base were quite different from the observed crown lengths. Furthermore, this seemed to bias the basal area model. In order to counter this problem, a new step-wise linear crown length function was parameterised instead, based on earlier work on *Pinus radiata* by Turner (1998). This re-parameterised model also fitted the NZ data well.

Thinning coefficient
Because the thinning ratio (the ratio between basal area removed and number of trees removed) is management specific, the thinning function was re-parameterised for the PNW data, and compared to values from NZ. The re-parameterisation did not influence the overall analyses of the growth model (basal area and height), as the true basal area and stocking after thinning was applied in those analyses. The bias of the growth models with thinning, when the post-thin stand parameters were not assessed, was thus not addressed.

Basal area
SBAP (site basal area potential, which is a site-specific basal area growth index, that is comparable to the annual average basal area increment over one rotation for a fully stocked stand) was estimated for each growth period and plot such that the predicted basal area at the end of the period equalled the observed. The plot SBAP was estimated as the average SBAP over all growth periods, weighted by the length of each period. The average installation SBAP was

estimated as the arithmetic mean of the plot means within each installation. Plot-level SBAP was regressed linearly against stocking for each installation and the results plotted. The average and the standard deviation of installation-level SBAP was analysed graphically. The overall SBAP for the PNW was calculated as the mean for each installation, weighted by the number of plots.

Based on the installation-level SBAP, the basal area growth was predicted for each plot from the first observation to the last. Height to crown base was modelled, except when stands were pruned, in which case the true height to crown base was used. As mentioned earlier, to avoid any 'contamination' from the thinning prediction function, the true plot-level values for basal area and stocking after thinning were applied. In other words, the accumulated error for thinned stands was 'reset' once they were thinned. Once the basal area was estimated, the prediction was plotted against the observed basal area, stand age, stand crown length, and relative density (Curtis, 1982). The procedure was repeated for groups of plots, e.g. thinned versus unthinned, pruned versus unpruned. Finally, the absolute basal area prediction error was plotted for each group, i.e. observed minus predicted basal area.

500 Index

Detailed analysis of output from multiple runs of DF NAT covering the NZ site productivity surface has shown that if SBAP and SI are multiplied together in the following format, the *500 Index* can be obtained.

$$500\ \text{Index} = 0.107 * SI^{1.33} * SBAP^{0.96}$$

This index is directly related ($r^2 = 0.9996$) to the MAI of a stand of D-fir, when planted at around 1650 stems/ha, thinned to waste to a stocking of 500 stems/ha at 15m MTH, and grown to 40 years. Because the NZ height/age curve has a latitude term, the average latitude of 42^0S for NZ Douglas-fir plantations was used.

The 500 Index can therefore be used to directly compare sites of different productivity potentials (as represented by SI and SBAP) in terms of yield. *500 Index* was calculated for each installation, and by weighting the index for each installation by the number of plots, for the PNW as represented by all installations.

RESULTS/DISCUSSION

A linear regression of the mean top height given in the PNW data and the estimated mean height (using the NZ mean height to mean top height model, inverted) showed an adjusted R-squared of 0.9998. Hence, the conversion from mean top height to mean height appears robust.

From Figure 3 it is evident that the existing NZ height/age-curve (Figure 1) does not seem to fit the PNW data well, whereas the refitted function (Figure 1) does. (Figure 2 and Figure 4). However, the refitted height/age-curve shows a logical break, in that the height model may be too flat for older ages and also not be a good fit for low site-index sites. (Figure 1). These effects are most probably attributable to the relatively narrow range of age classes represented in the PNW data. The refitted model should be used with caution outside the range of the data. Despite these limitations, in general the fitted height/age model performs well, with the exception of installation 501, which has the lowest site index. Based on visual interpretation of Figure 2 and 4, it was determined that the refitted height/age model should be used in the following analyses.

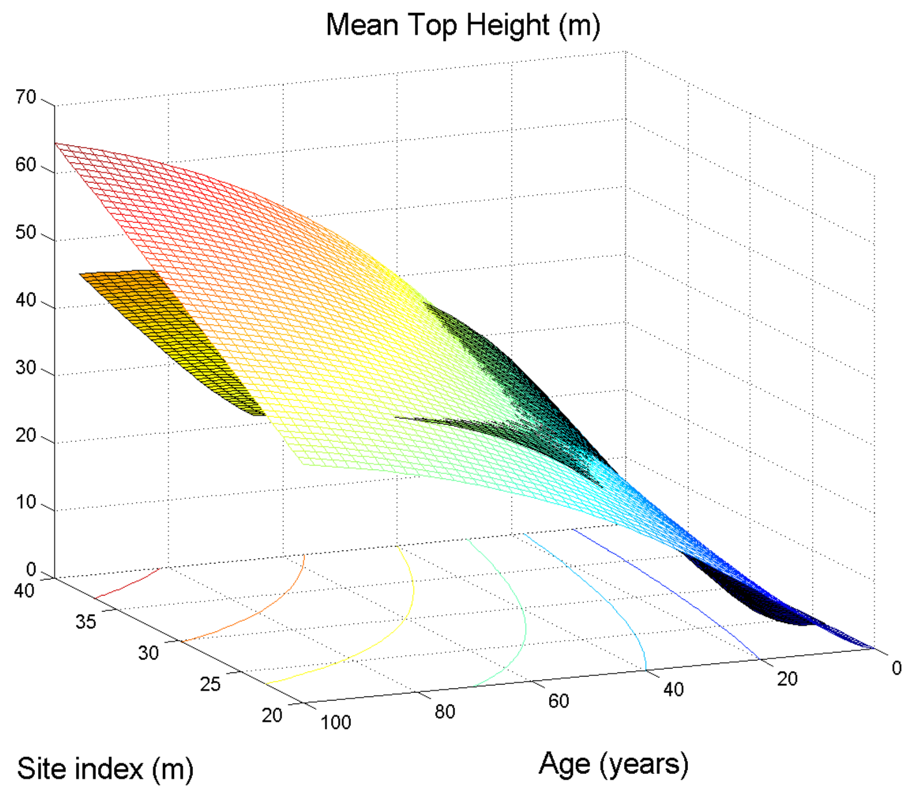

Figure 1 - Height/Age-curves for NZ and PNW. The fully coloured surface is the refitted height/age-curve for the PNW data. The contour lines in the age/site-index plane also represent the NZ model.

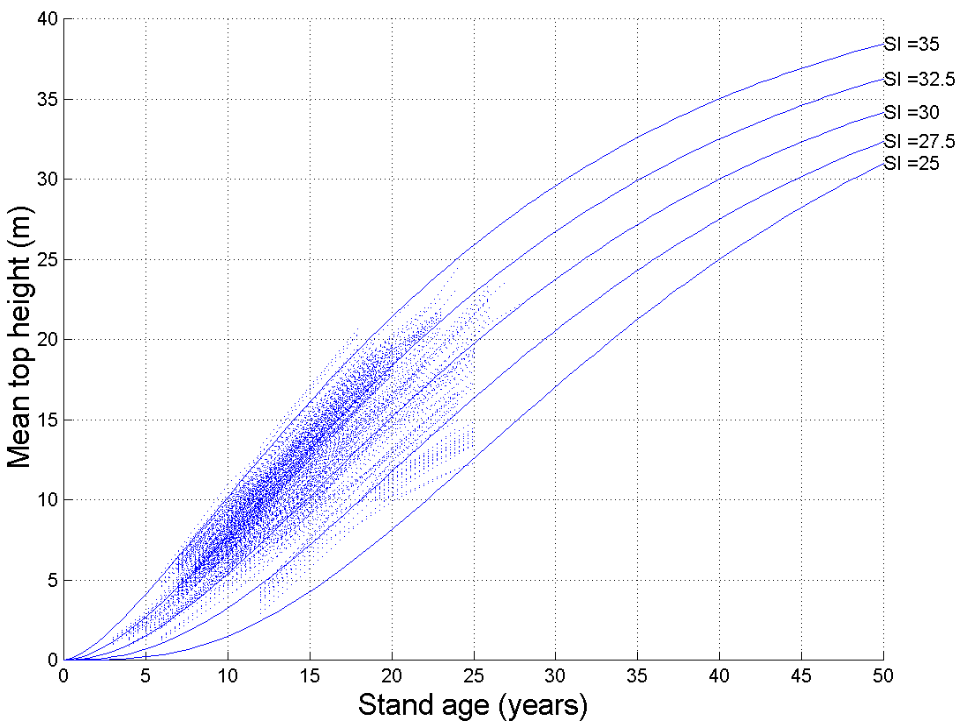

Figure 2 - Fitted height/age curves and observations of height and age (SI40) for the PNW data. Dotted lines represent individual plots

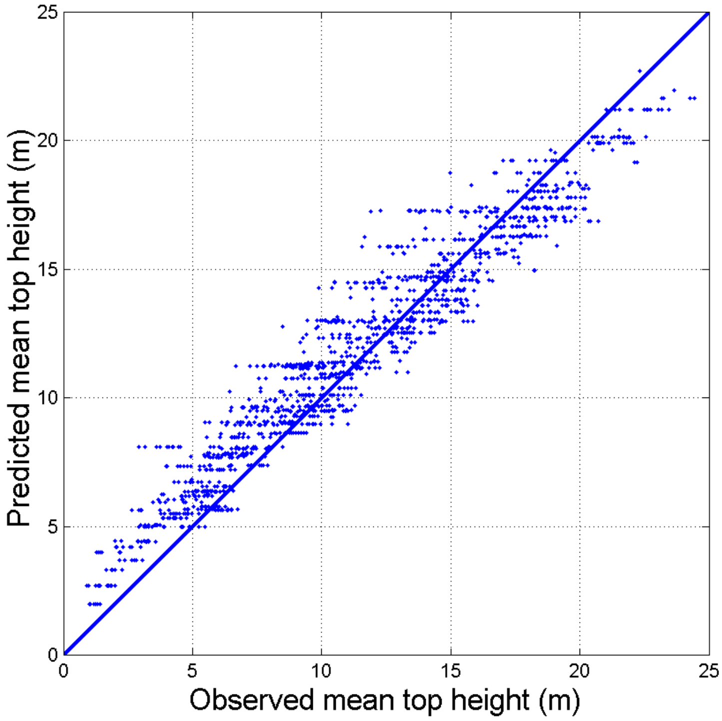

Figure 3 – Predicted mean top height using the NZ height/age curve against the PNW 'observed' values

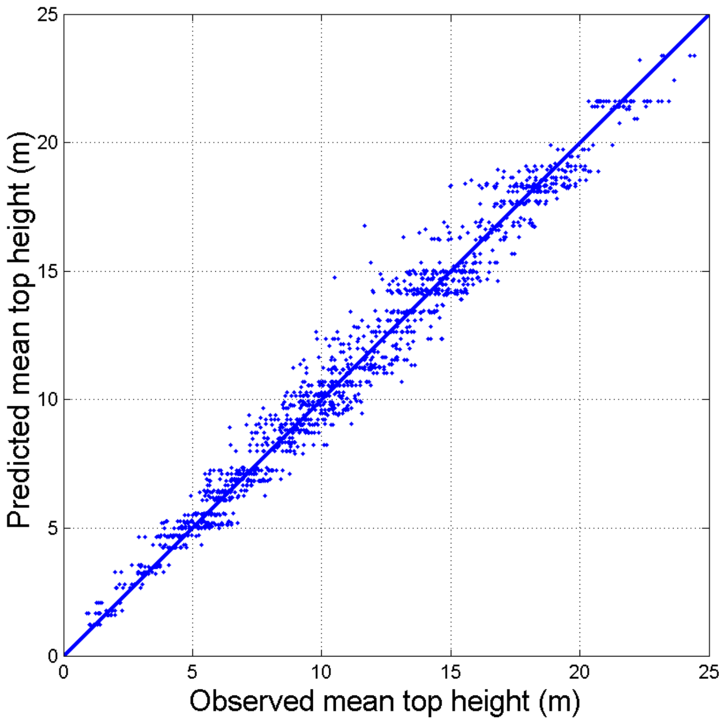

Figure 4 - Predicted mean top height (based on installation-level site indices) using the re-fitted height/age curve against the PNW 'observed' values

From Figure 5 it is evident that the distribution of the site indices predicted from the refitted height/age-curve for PNW is similar to the distribution of site indices for NZ. The mean for PNW is slightly lower, and the distribution narrower. One obvious reason for this is that the PNW data represents silvicultural trials, rather than a combination of trials and the nation-wide resource, as is the case for the NZ data.

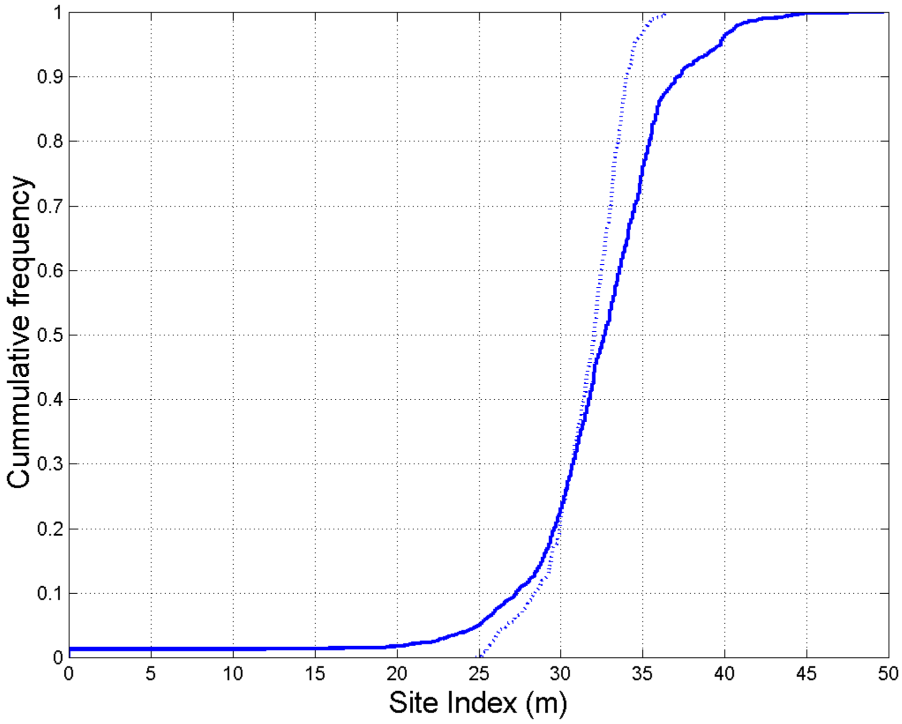

Figure 5 - Cumulative distribution of site index for NZ (bold) and PNW (dotted) sample plots.

The linear regressions of plot-level site index against plot-level stocking for each installation (Figure 6) appear to indicate that there is a slight density effect in that higher stocked stands of the same installation generally have higher site indices. Similar results have been reported in the literature (Scott *et al*. 1998, Flewelling *et. al.* 2001).

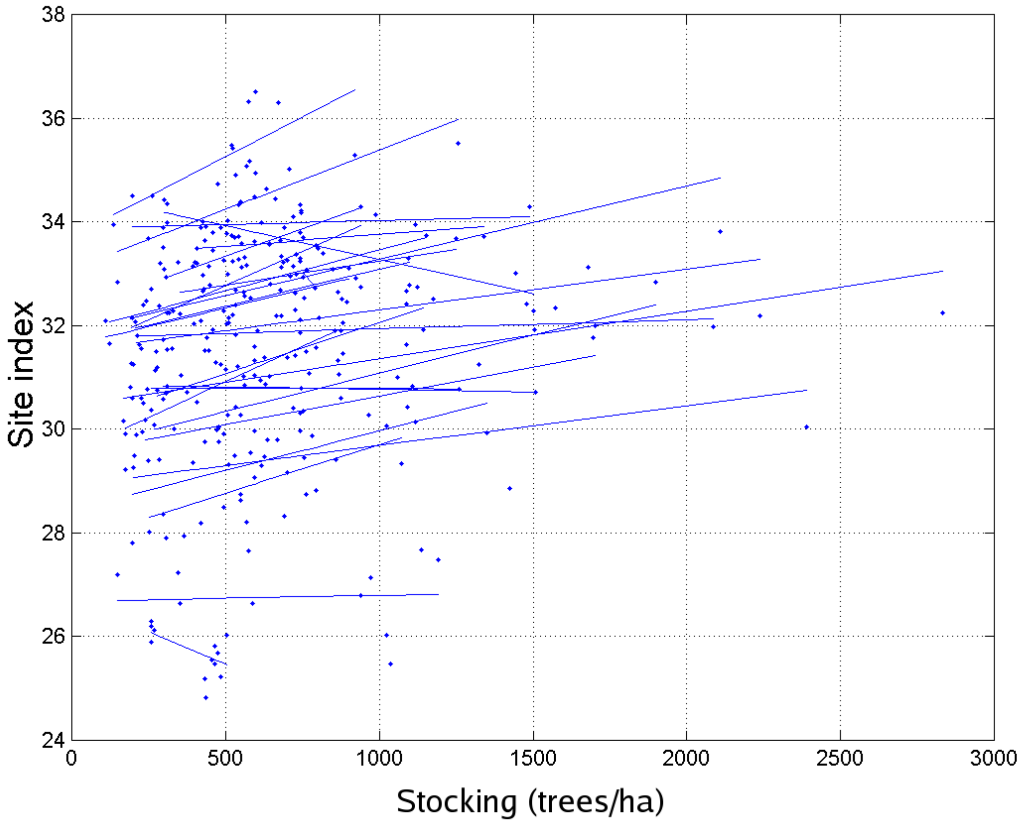

Figure 6 - Linear regressions and observations of site index against stocking for the PNW data. Each line represents an installation. Dots represent plots.

From Fig 7 it is evident that the observed stocking generally is less than the predicted. In other words, the NZ density dependent model tends to over-predict the stocking (under-predicts mortality). This is to be expected, as there are suites of damaging root-rot fungi naturally not present in the NZ ecosystem that increase mortality in the PNW. Despite the over-prediction, the model works reasonably well, with annual prediction errors in the order of 0-2% of initial stocking. A few observations show extreme errors of 4-7%, a closer look at these (not presented) show that the observed values are subject to abrupt changes or remain constant over a period of time – indicating that the measurement/estimation procedure is not capturing the real (observed) stocking correctly. Refitting the existing model to the PNW data did remove the bias, but not the errors, and the inner logic (Reineke's –3/2 power-rule) of the model broke down with the re-fitting. The original NZ mortality model was therefore used in all other analyses, and predicted values are shown in comparison to the actual PNW data in Figure 8.

Analysis of the thinning coefficient, i.e. the ratio between the basal before and after thinning relative to the stocking before and after thinning, showed that the thinning coefficient was 0.792 for the PNW data. The mean value for 1st thinning was 0.767, while 2nd thinning on average showed a ratio of 0.818. These values compare to an average of 0.705 for NZ, and 0.662 for Great Britain. The average thinning ratios in the data from the PNW were significantly higher than for NZ and Great Britain. In other words, larger-diameter trees relative to the stand-mean-diameter were thinned in the PNW stands than is the case in NZ, where thinning is more focused on smaller-diameter suppressed trees. This may be an artefact of the data, and should not necessarily be extrapolated to cover the current management regimes in the PNW. The thinning ratio is user defined in the NZ model, so these differences need not affect the general growth predictions of the model.

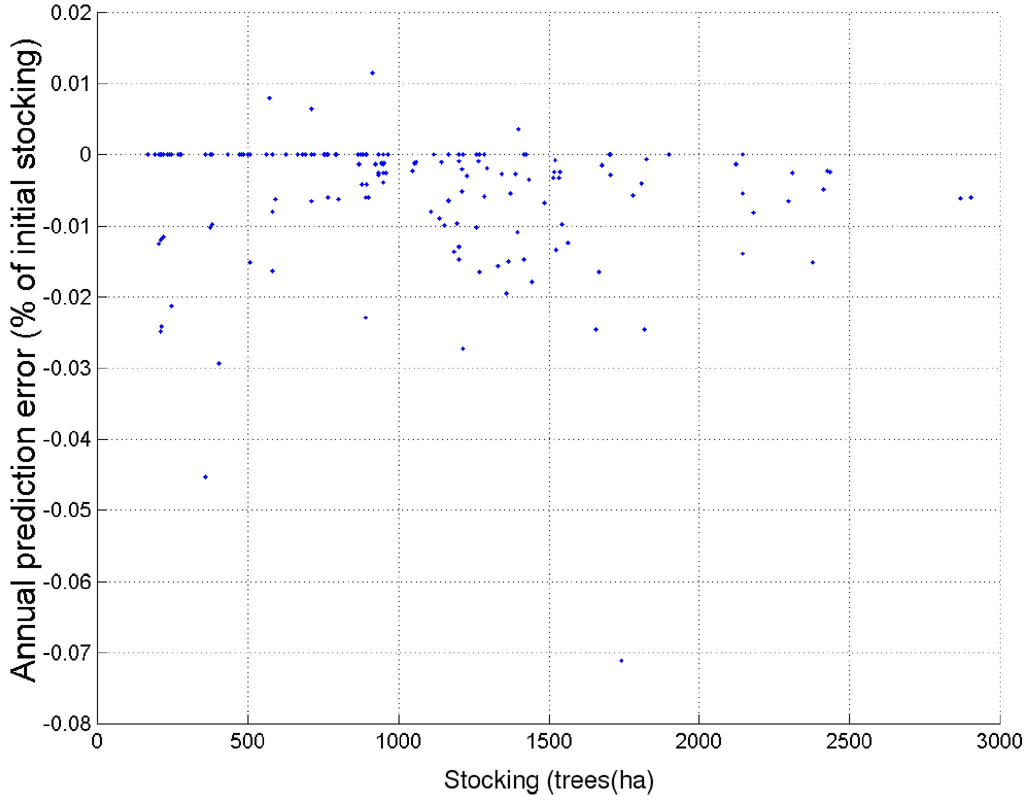

Figure 7 - Annual stocking prediction error (observed minus predicted as percentage of initial observed stocking) for the PNW data using the NZ mortality function.

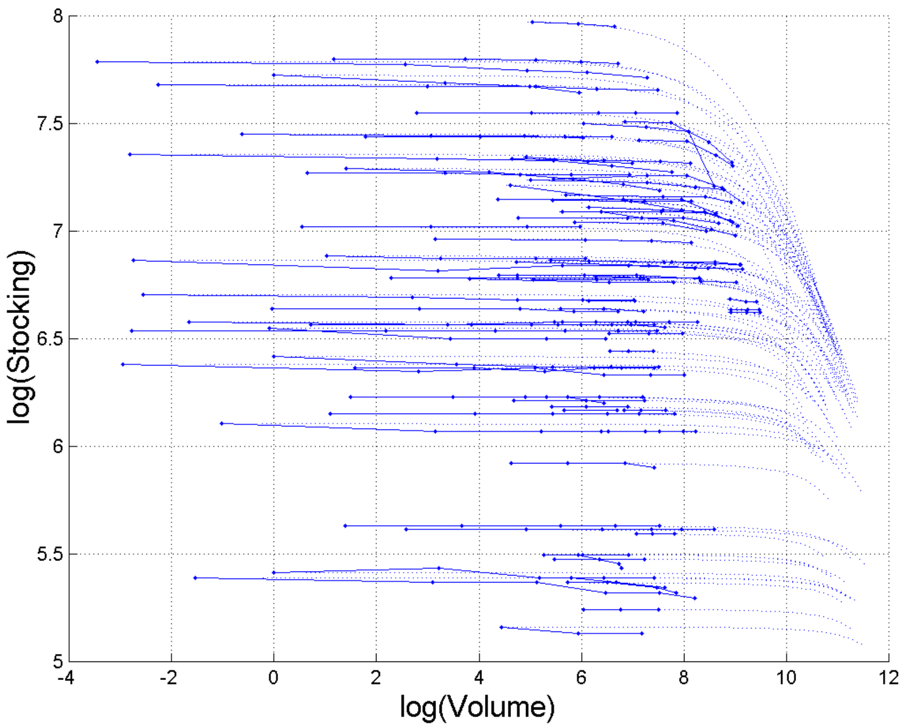

Figure 8 - Observed (bold) and predicted (dotted) stocking, for the PNW data using the NZ mortality function.

The analysis of the crown length model (Figure 9) shows the following trends. First, for crown lengths less than 6 m, the observed crown length is consistently less than the predicted. This indicates a consistent bias, which is explained by different definitions of crown length in the PNW and NZ. In NZ, height to crown base is defined as the average of the height above ground to the lowest live branch, and the height to the lowest whorl where the majority of branches are live (Ellis and Hayes, 1997). In the PNW, height to crown base is the height above ground to the whorl where three quadrants out of four contain live branches (Anon, 2002). For crown lengths between 6 m and 10 m in length, the model predictions seem unbiased. For crown lengths longer than 10 m, when height to crown base is increasing, presumably due to crown recession, the observed values are generally larger than the predicted values, and the difference seems to be increasing (few observations in point plots can, however, be misleading). In conclusion, there seems to be scope for fitting an improved function to predict crown length for the PNW resource.

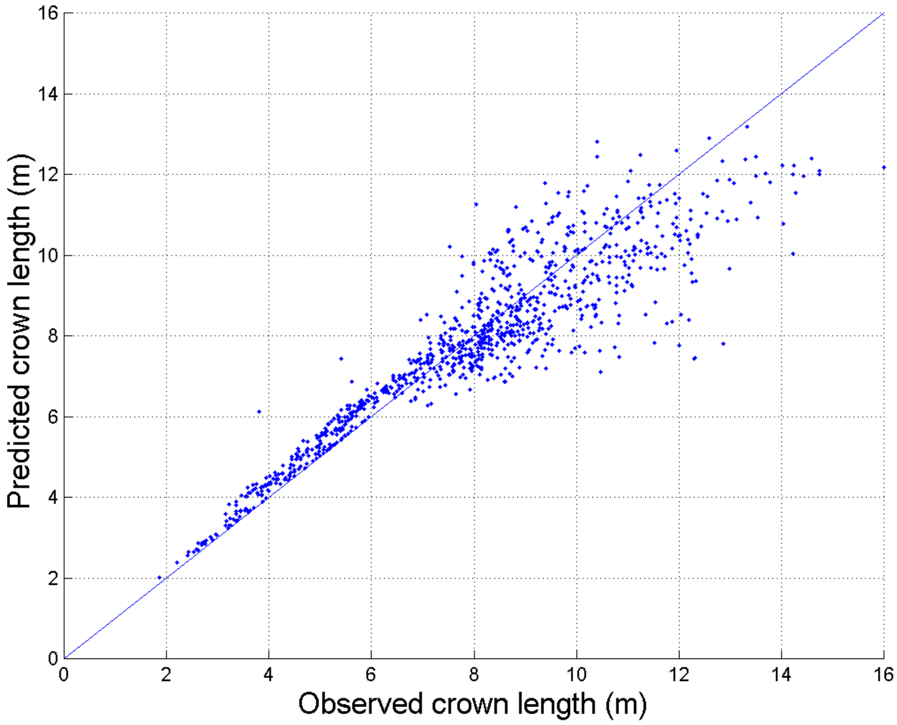

Figure 9 - Observed and predicted crown length for the PNW data using the NZ crown length function.

The cumulative distribution of SBAP (Figure 10) shows significantly higher SBAP for NZ compared to the PNW. When translated through into 500 Index (Table 2), these differences are highly significant. The average 500 Index for the PNW of 12.41 compares to 18.86 for New Zealand- indicating that NZ has an advantage in total standing volume (for the same rotation age and silvicultural history) of more than 50%. Thus, the most productive installation in the PNW (717) with a 500 Index of 17.39 can be expected to produce less yield for the same silviculture and history than the average site in New Zealand. The most productive sites in New Zealand have a 500 Index of around 25.

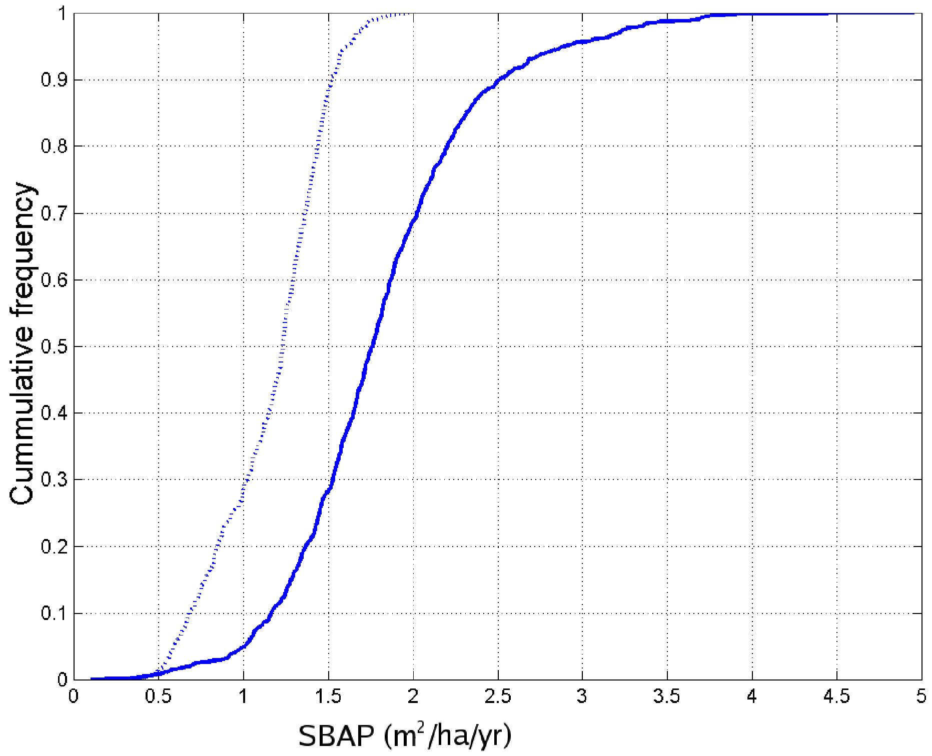

Figure 10 - Cumulative distribution of SBAP for NZ (bold) and PNW (dotted) sample plots

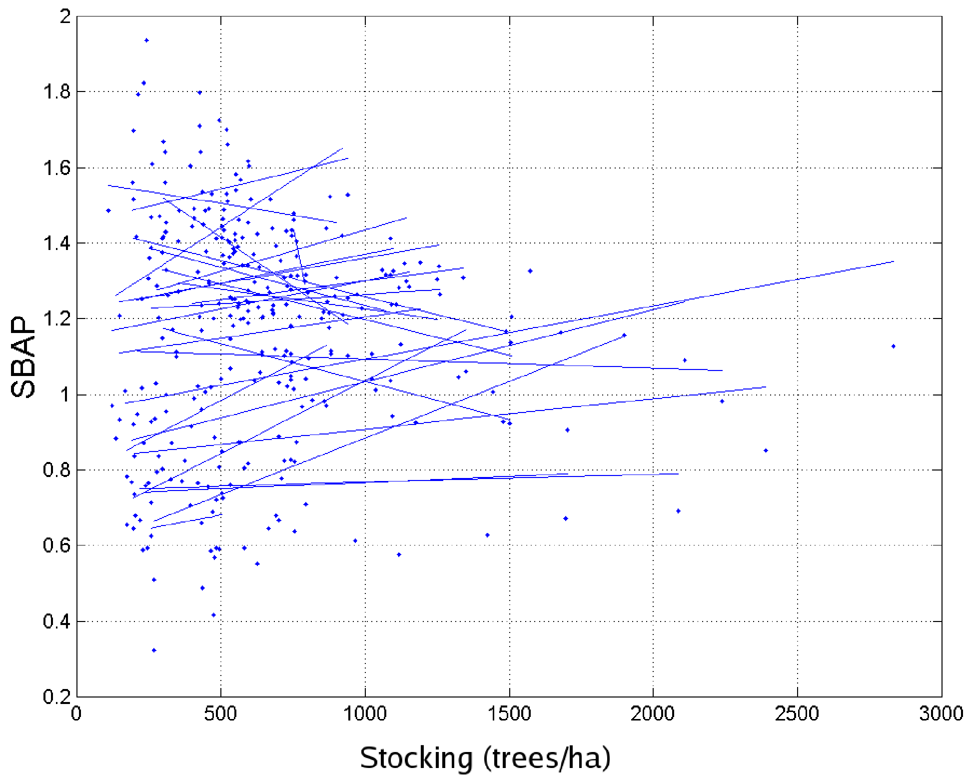

Figure 11 - Linear regressions and observations of SBAP against stocking for the PNW data. The lines represent installations and the dots represent individual plots.

Installation	Mean Site Index	SI sd	Mean SBAP	SBAP sd	500 Index	Min. age	Max. age	No of plots
353	32.91	0.18	1.38	0.08	15.27	19	23	3
501	25.74	0.45	0.67	0.21	5.50	19	25	11
703	32.97	0.56	1.27	0.14	14.13	7	23	12
704	30.8	0.55	1.28	0.13	13.00	14	28	12
705	29.39	0.91	0.91	0.2	8.81	12	25	9
706	33.97	0.44	1.35	0.12	15.59	10	24	12
708	32.61	0.99	1.52	0.26	16.55	8	20	12
711	34.29	0.82	1.3	0.17	15.23	7	21	10
713	33.63	1.21	1.1	0.21	12.64	7	19	12
717	35.2	0.99	1.44	0.28	17.39	6	18	10
718	32.73	0.74	1.25	0.18	13.78	8	20	12
722	28.84	0.62	1.33	0.16	12.36	13	25	12
724	33.63	0.42	1.29	0.19	14.73	7	19	10
725	31.22	0.83	1.35	0.21	13.94	10	22	12
726	32.26	0.86	1.52	0.33	16.31	7	19	12
729	33.4	0.65	1.4	0.18	15.79	8	20	12
732	26.76	0.82	1.19	0.24	10.06	12	24	12
735	30.79	0.5	1.26	0.24	12.80	10	20	10
736	32.37	0.66	1.29	0.21	14.00	9	19	16
737	31.08	0.94	1.02	0.21	10.58	7	17	8
905	30.9	1.56	0.86	0.36	8.92	6	16	11
910	29.54	0.96	0.9	0.21	8.77	6	16	13
915	32.1	1.28	1.1	0.24	11.88	4	14	11
916	30.34	0.94	0.76	0.18	7.73	5	14	12
919	31.9	0.59	0.77	0.18	8.37	4	13	13
926	31.35	0.89	1.09	0.26	11.41	8	12	12
932	32.92	1.09	0.99	0.23	11.10	3	13	12
Overall mean	**31.58**	**0.79**	**1.17**	**0.21**	**12.41**	**8.74**	**19.59**	**11.22**

Table 2 - Mean site index (MTH@ age 40 years), SBAP, and 500 Index for the PNW installations

From Table 2 it is evident that there is considerable variation in the estimated SBAP for the different installations. In addition, plot-level SBAP within some installations vary considerably (e.g. 905), while plot-level SBAP within other installations vary much less (e.g. 919), but overall the variation of SBAP within installations is acceptable, with the model seeming to work well. Over all 27 installations, there is only a weak correlation between SI40, and SBAP (r^2 0.28). Correlation at the plot level is also quite weak (r^2 0.26). These results are in line with similar findings in NZ and Great Britain. Installation 501 attracts comment in that it is an outlier in terms of overall low productivity.

Likewise, from Figure 11 it is evident that there seems to be no immediate trend in SBAP with stocking, which contrasts with results from a preliminary analysis of thinning experiments in NZ (Knowles and Hansen, 2004). This difference may be caused by the relatively short age span of the data available for the PNW. However, it can be concluded that based on the existing PNW data, which is quite comprehensive, the New Zealand growth model does not seem biased in basal area prediction relative to stocking. This is a reassuring discovery.

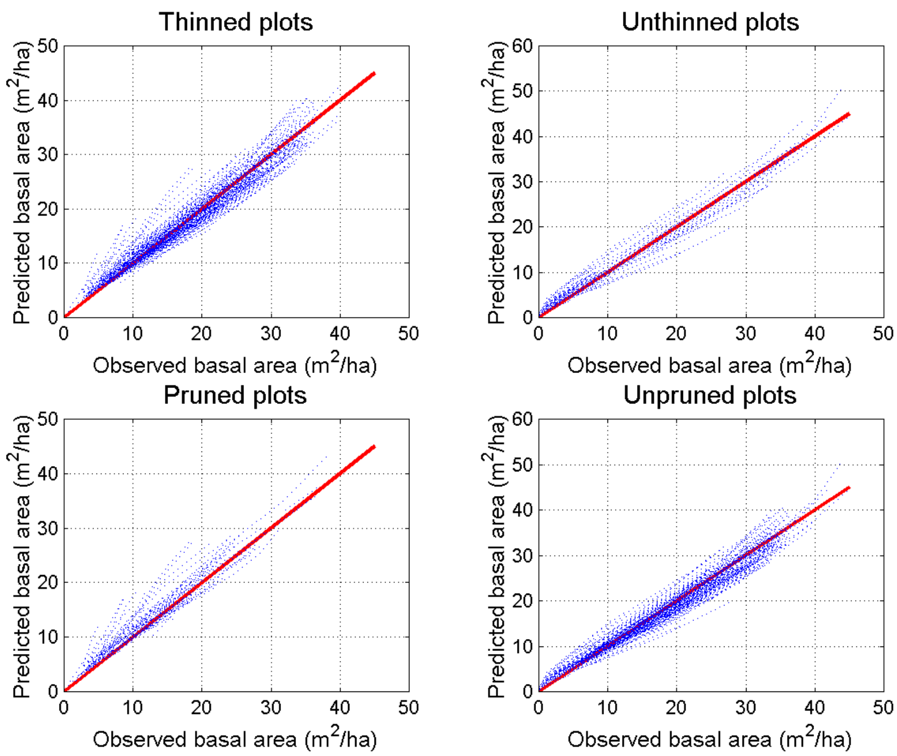

Figure 12 – Predicted basal area against observed basal area (m^2/ha), lines represent plots.

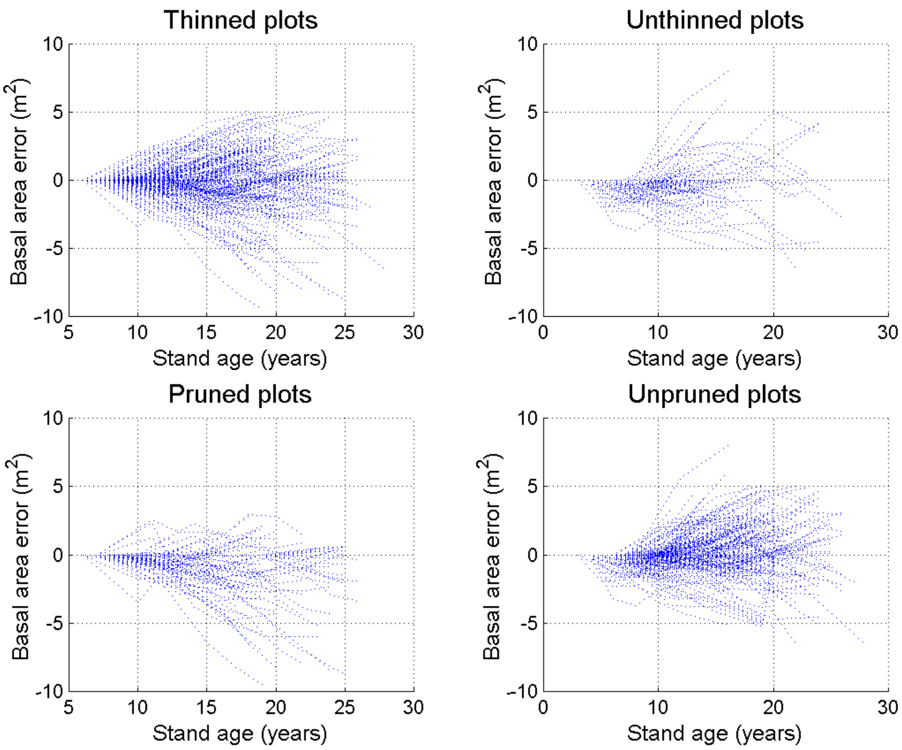

Figure 13 – Basal area absolute error (observed basal area minus predicted) against stand age, lines represent plots.

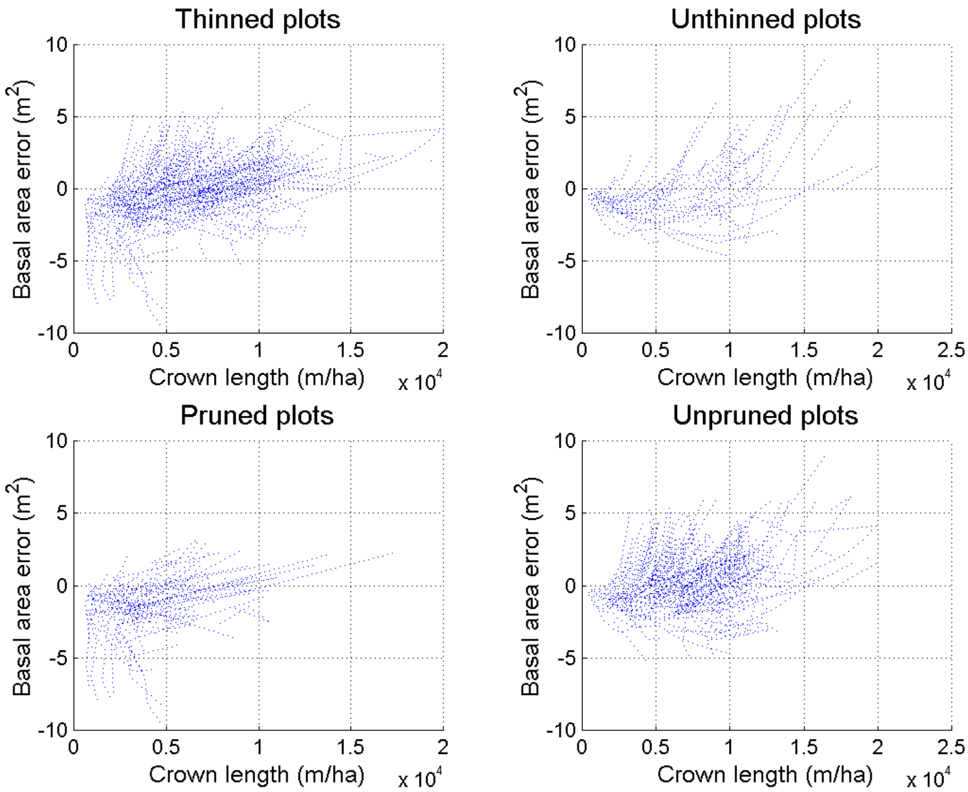

Figure 14 – Basal area absolute error (observed basal area minus predicted) against crown length per hectare. Lines represent plots.

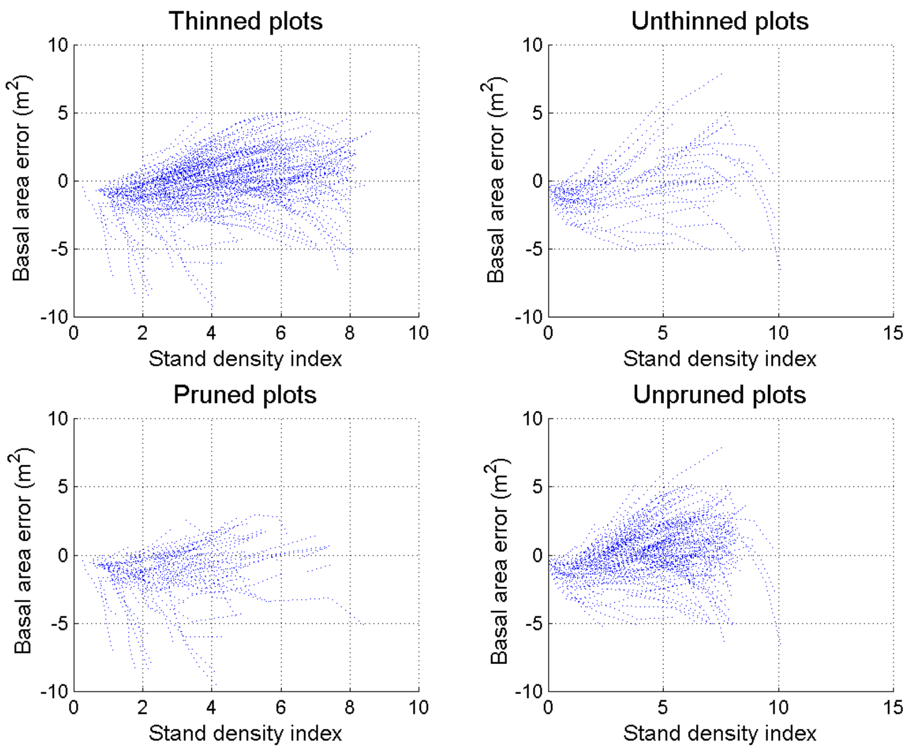

Figure 15 – Basal area absolute error (observed basal area minus predicted) against stand density index (Curtis 1982). Lines represent plots.

The plot of predicted basal area and observed basal area in Figure 12 and the corresponding residuals in Figures 13-15 reveal that overall the model seems to work well. There are some trends in the errors, namely that errors seem to increase for increasing crown length. In other words, the basal area is over-predicted for short crown lengths, and under-predicted for long crown lengths. Hence, the 'true' effect of the crown length may not be captured that well, as was also evident from the study of the crown length model component. Similarly, there is a consistent over-prediction of basal area in stands younger than 8-10 years (in particular for pruned stands). This is likely caused by the fact that stands this young were not well represented when the model was originally parameterised for NZ. However, despite these concerns, the error is in the order of only ±0-10% for the periods investigated (i.e. 2-14 years), thus from a management perspective the error is relatively minor.

Overall, the NZ National Douglas-fir growth model and its components seem robust and able to perform well, when applied to stands in the PNW. The basal area predictions are unbiased and rarely more than ±5 m^2/ha of the observed value, despite the great differences in treatment represented in the data, i.e. range of initial stocking, thinning and pruning. There was, however, a need to re-parameterise the thinning ratio and the height/age curves for the PNW. Similar refitting of the crown length model and the overall basal area prediction function for the PNW would seem justified if the model was to be used in the PNW, especially if data could be made available from more mature trials.

ACKNOWLEDGEMENTS

The authors are grateful to Dr Roger Fight, USDA, Portland, who facilitated the study, to staff of the Stand Management Cooperative, University of Washington, Seattle, for making the data available, and to Dr Jim Flewelling, Seattle, who transcribed and checked the data, and provided essential interpretation.

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