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Comparison of Radiata Pine Growth Models:
Stand Level Predictions from Mid-rotation Onwards

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EXECUTIVE SUMMARY

Three sets of empirical growth models have been developed at Scion for predicting the growth of radiata pine in New Zealand:

- Regional stand level models were developed using the “state-space” methodology of Garcia *et al*. in the 1980s.
- Regional individual tree – distance-independent growth models were developed using methodology of Shula *et al*. in the 1990s.
- The stand level 300 Index model was developed using methodology of Kimberley *et al*. in the 2000s.

The objective of this study was to compare the mid-rotation onward performance of these three groups of radiata pine growth models using a dataset that was totally independent from those used in model development. Of the three sets of growth models, the ITGM model is most restrictive in that it was designed to grow inventory data forward after silviculture had been completed, i.e., mid-rotation onward.

All simulations were carried out using the Forecaster Software. Graphical analyses indicate that the performance of the stand level regional models, ITGM regional models and 300 Index model for predicting mean top height, basal area per hectare and stems/ha is very similar for the Sands, Clays, Central North Island and Nelson growth modelling regions.

For all regions there are some simulations with large errors, and in these cases all three models tend to produce similar large errors.

In each region, the errors were also compared against three or four independent classification variables:

- Previous land use
- Number of height trees used to calculate site index
- Whether silviculture was known or unknown
- The genetic rating of the trees

An analysis using the SAS procedure (PROC MIXED) indicated that in some instances these classification variables had a significant impact on the predicted variables. However, no one model was obviously poorer than another.

In conclusion, all three types of model perform equally well from mid-rotation onward, and it is not possible to recommend one model over and above another.

It is recommended that the model used is chosen based on the data available, and type of analysis being carried out. For example:

- if one wishes to investigate the effects of alternative silviculture regimes, then the 300 index is the appropriate model,
- if one wishes to grow individual tree inventory data forward in time, then the ITGM is an appropriate model.

INTRODUCTION

Growth models are used to predict the development of stands and/or trees. There are three main uses for growth models:

- To examine the influence of alternative silvicultural treatments
- To schedule silvicultural operations
- To grow inventory data forward in time.

There are also many different modelling philosophies that can be used to develop such models, ranging in complexity from empirical growth models that are “best fits” to observed data through to process-based models that simulate the underlying physiology of tree growth. Models also vary in the amount of detail included on stand structure, ranging from stand-level models that do not consider individual trees, through to individual tree – distance-dependent models that consider the growth of individual trees in relation to the position of their neighbours.

Three sets of empirical growth models have been developed at Scion for predicting the growth of radiata pine in New Zealand:

- Regional stand levels model were developed using the “state-space” methodology of Garcia *et al*. in the 1980s [(1)].
- Regional individual tree – distance-independent growth (ITGM) models were developed using methodology of Shula *et al*. in the 1990s [(2)]. These models were designed to grow inventory data forward in time, starting from mid-rotation, after silviculture had been completed. An interesting feature of these models is that “tree age” is not used to estimate growth projections. This means that the methodology is suited to growing uneven-aged forests.
- The stand level 300 Index model was developed using methodology of Kimberley *et al*. [(3)] in the 2000s. Interesting features of this model are that it includes a productivity index for basal area as well as height, the growth equations were developed at a national level. Regional drift factors were included in later versions to account for differences between regions. This model is able to start at a younger age than the ITGM models, but requires knowledge of previous silviculture history.

The objective of this study was to compare the performance of these three sets of growth models in predicting stand level variables (mean top height, basal area per hectare and stems per hectare) using independent data (i.e. data that was not used in the development of the growth models). For this study the independent data came from Permanent Sample Plots (PSPs) that were previously owned by Carter Holt Harvey and are now managed by Hancocks. These PSPs came from four of the growth modelling regions: Sands, Clays, Central North Island, and Nelson.

In addition, we also investigated whether there were any other variables that might be influencing model performance. Four variables were considered:

- Previous land use
- Number of height trees available to calculate site index
- Whether the previous silviculture was known
- The genetic rating for trees planted.

The simulations were all carried out in the Forecaster Software developed by ATLAS. These simulations were carried out using a newly developed batch processing facility and a new upgrade to the 300 Index model (version 2.0 released October 2008).

METHODS

Growth Models Considered

The growth models that have been used for this project are:

- Regional stand level models developed using the methodology of Oscar Garcia: 'SANDS', 'CLAYSF', 'NM90' and 'PPM88' (see Appendices 1-4 for details).
- Regional Individual Tree – Distance Independent Growth Model 'ITGM' for the SANDS, CLAYS, Central North Island and Nelson Regions (see Appendix 5 for details).
- '300 Index' stand level model (see Appendix 6 for details).

Stand level pine growth models are available for other regions (see Appendix 7 for details), but have not been used in this particular exercise as no independent data were available.

Note: model details have been extracted from previous reports.

Data Selected for Model Comparisons

All the three sets of radiata pine growth models were developed using selected data from the PSPs stored in the PSP system. To provide a fair comparison of the three sets of models, it was decided to compare the performance of the models in projecting growth measurements forward in time for PSPs that were independent of those used in model development. These data were provided by Hancocks and came from four Growth Modelling Regions:

- Sands, Clays, Central North Island and Nelson

Of the three sets of growth models, the ITGM model is most restrictive in that it was designed to grow inventory data forward after silviculture had been completed. This put constraints on the plots selected for the simulations.

The constraints used in selecting the PSPs for this study were:

- The starting age for simulations was after all silviculture treatments had been completed and generally no younger than mid-rotation. The ranges for each region are shown in the results section.
- Plots that were not planted, but allowed to regenerate naturally were excluded.

Several issues arose from initial simulations and data needed checking before the final set of simulations shown in this report.

- Although the plot data were error-checked when added to the PSP system, silvicultural history, which is relevant for the correct use of the 300 Index Growth Model, had not been checked for errors and this caused problems.
- Issues included missing pruned sph even though a prune date was available, and missing MTH for some measurements.

Software Used: ATLAS Forecaster

Forecaster version 1.3.0.9 was used to import and simulate growth for PSP data with the different growth models. Some modifications had to be made to Forecaster to process the large numbers of plots and analyse them by using different growth models. A batch version of Forecaster (FCMD.exe) was written to import four different input files from the PSP system for each region. These files include a plot.csv file, a stemlist.cvs file and 2 historic silviculture files called thin history.csv and prune history.csv. This approach allowed fast data processing as well as minimising human error.

Approach

PSP data were imported at one age, and grown forward to a later age using the appropriate growth model. The predicted values for Stocking (SPH), Mean Top Height (MTH) and Basal Area (BA) of trees at a plot level were then compared with the actual measurements at that later age. The comparison was conducted between the 300 Index model, the appropriate regional ITGM and the regional stand level model for each of the four regions: Sands, Clays, Central North Island and Nelson.

Prediction periods ranged from less than one year to at least 50 years in the Central North Island. The range for each region is discussed in the results section.

The starting ages for the simulations varied from as young as nine years to ages close to harvest. The range for each region is discussed in the results section.

PSP data for the selected starting age was imported into Forecaster for simulating tree growth forward in time. Results from growth model simulations were then exported for each plot, stored in an EXCEL spreadsheet. The results were then summarised using the SAS statistical analysis package.

Design of Software Runs

A set of plots of each region was imported into Forecaster for simulating tree growth forward in time.

To simulate a dataset through Forecaster, several factors need to be specified prior to the start of a simulation. These factors are specified in three different entities, and include a 'Function set' (one per growth model), a 'Site' (one per plot) and a 'Crop' (one per simulation period per plot).

The following details must be specified per entity:

Function set
- Growth Model
- Height Age Table
- Monthly Adjustment Table
- DOS Function
- Sweep Model
- Forking Model
- Breakage Table
- Tree Taper Table
- Tree Volume Table
- Stiffness function
- Density function
- Height diameter relation type
- Branch Model
- Species set

Site

- GIS coordinates
- Altitude
- Site Index
- GF Rating

Crop

- Plant date
- Stocking
- Species
- Planted Stocking
- Current SPH
- Crop History if available
- Crop Information (stemlist or stand subset)

Function set settings identical for all growth models

- the generic sweep model,
- no forking,
- no breakage,
- stump height = 0.0m,
- tree volume and taper table 237,
- no density model,
- no branch model,
- x and y location from PSP,
- Altitude imported from PSP
- Site Index derived by Forecaster.

Seasonal adjustment to age

Because data from the PSP system were used, the Growth Adjustment Model 1 was applied. This table gives end-monthly adjustments to age which allow for seasonal growth. The table was derived in September 1978, and the end-monthly growth increments are:

	Height	Basal Area	Diameter
Jan	0.1	0.109	0.109
Feb	0.1	0.096	0.096
Mar	0.1	0.065	0.065
Apr	0.05	0.034	0.034
May	0	0.035	0.035
Jun	0	0.06	0.06
Jul	0.05	0.077	0.077
Aug	0.1	0.093	0.093
Sep	0.1	0.101	0.101
Oct	0.15	0.107	0.107
Nov	0.15	0.11	0.11
Dec	0.1	0.113	0.11

Function Set specifications that differed between the three growth model types

ITGM

The ITGM uses a default mortality adjustment of 0.0, as well as Nitrogen and Phosphorus scores. The Nitrogen and Phosphorus scores are only relevant to the Sands and Clays regions. The Sands region has a default score of two for Nitrogen and six for Phosphorus, whereas the Clays region only requires a Nitrogen score, which was set to two.

Each region in the ITGM growth model has its own regional code assigned, which had to be defined in the Forecaster's function set.

300 Index
The 300 Index growth model required Height/Age Table 112 and has regional drift factors that need to be adjusted for ex-forest sites and ex-farm sites.

The previous land use was extracted from the PSP system and classified into several groups (see results section). For PSPs where the previous land use was ex-farm, the ex-farm regional drift factor was used. The ex-forest regional drift factor was used for all other PSPs.

For ex-forest plots in the Clays region, the adjustment was -0.15 and for ex-farm sites the adjustment was -0.25.

For Nelson, ex-forest sites had a drift factor of 0.10, whereas ex-farm sites had a drift factor of 0.0.

For the Central North Island, the PSPs came from the Kinleith area, and very few PSPs could be classified as ex-farm. For this region it was assumed that all PSPs were ex-forest. The regional drift factor was +0.05. The factor for ex-farm sites was -0.05.

The Sands region, being the only region not differentiating between ex-farm and ex-forest sites, had all plots adjusted for -0.3.

‘State-Space’ models
All four regional models need the appropriate Height/ Age Table assigned to them, which is table 27 for the Sands model, table 34 for NM90 and PPM88 and table 32 for the Clays region. Furthermore the PPM88 model requires a Foliar P score, which was set to the default setting of 0.11% for this project.

Assumptions Made and Issues Encountered

It was assumed that silviculture has been recorded correctly for all CHH plots used in the project. Plots that contained a thinning after the simulation start age were excluded from the dataset because the ITGM model does not allow silviculture treatments to be simulated.

Not unexpectedly, plots with large reductions in stocking, probably due to mortality, were poorly predicted. Mortality is notoriously difficult to model, and models predict average trends. Such plots were left in the dataset, unless there was another reason for their exclusion.

Issues with incomplete or wrong pruning and thinning data were encountered. The data needed to be adjusted before being able to import and simulate it in Forecaster. Some plots were missing number of ‘sph pruned’, even though a pruning event and date had been recorded.

ATLAS put a rule in place that during import, empty cells for ‘sph pruned’ get replaced with 500sph if there are enough stems available. If not, Forecaster puts in the number of stems remaining after the closest thinning event if not otherwise specified. If the pruned height was missing, but a Mean Prune Height (MPH) was available, Forecaster derived the prune height by calculating it from MPH + 0.2m.

MTH in Forecaster is derived from the height trees recorded in the stemlist. In cases where less than two height trees were present, Forecaster does not import the plot and it was excluded from the project. If there were two height trees or more present in a plot the plot was used for simulation.

One could argue that two to ten height trees are insufficient to derive a reliable MTH, but looking at the ht-tree graphs that distinguish actual versus predicted parameters for plots with less than 10 height trees versus plots with 10 or more height trees, this did not seem to make any significant difference to model performance.

Validation Approach

The software program SAS was used to analyse all outcomes from Forecaster simulations.

To compare the three models in a region, a set of three graphs was produced for each predicted variable (mean top height, basal area and stems/ha).

The first graph in each pair shows the difference, actual – predicted, for each plot. Different colours and different sized points are used for the different models. Thus it is feasible to see larger data points hiding under smaller data points.

The second graph shows the mean and two times the standard deviation for the three models where simulations have been grouped into one year projection periods. This indicates the bias in the simulations.

The third graph shows the mean and two times the standard deviation for the absolute error for the three models where simulations have been grouped into one year projection periods. This indicates the accuracy of the models.

It is also important to identify whether there are any independent variables that may influence the model results. Any such variables that are shown to be important may be considered for inclusion in future model development if required.

For this study four variables were examined:

- Previous land use
- Number of height trees used to estimate site index
- Knowledge of silvicultural history
- Genetic rating for the planted trees

Different land use classes were used for the different regions and are discussed in the results section under each region.

The number of height trees was divided into two categories:

- Less than 10 height trees
- 10 or more height trees

Knowledge of silvicultural history was divided into two categories:

- Information on silvicultural history stored in PSP system
- No information on silvicultural history stored in PSP system.

The genetic rating was divided into three categories:

- Less than or equal to 7 (i.e. unimproved to climbing select seedlot)
- 14 (i.e. 1st generation of seed orchard improvement)
- greater than 14 (i.e. later generations of improvement)

There were multiple simulations for most plots due to different start age and different projection period. To account for the varying projection period, the residual (actual – predicted value) was divided by the length of the projection period, and then an "average" error was calculated for each plot.

The significance of the above four variables was tested using the "average" error in the SAS Proc Mixed procedure.

For the most significant predicted variable × model combinations, graphs showing the mean and two times the standard deviation for the classification variable were plotted, where simulations have been grouped into one-year projection periods

In this set of simulations, Forecaster was allowed to derive site index from the height measurements in the imported stem list. This approach was chosen as it was considered to be how the models would be used in practice. Earlier simulations (not reported here) used the site index estimated by the PSP system. This does have a small impact on the simulated results.

RESULTS

A detailed graphical analysis of the performance of the three types of growth models in the Sands, Clays, Central North Island and Nelson Regions is given in Appendix 8.

The performance of the models for growing PSP data for an increment period of a few months to several years was examined by comparing the difference between actual and predicted mean top height, basal area per hectare and stems/ha at the end of the increment period.

All simulations were started after silviculture had been complete, and the starting age was generally no less than 13 years. There were over 2500 individual simulations in each growth modelling region, and over 25,000 in the Central North Island. There was a wide range scatter of results for all three model types. The table below provides a high level summary. On average the performance was similar for short increment periods, and the trend with increment period was similar for all three models. There were some minor differences between models, particularly with longer increment periods. Overall, no one modelling approach stood out as being better than any other.

<table>
<tr><th>Region</th><th>Sands</th><th>Clays</th><th>CNI</th><th>Nelson</th></tr>
<tr><td>Growth models</td><td>SANDS, ITGM and 300 Index</td><td>CLAYSF, ITGM and 300 Index</td><td>PPM88, ITGM and 300 Index</td><td>NM90, ITGM and 300 Index</td></tr>
<tr><td># of individual simulations compared</td><td>3639</td><td>2730</td><td>25916</td><td>3120</td></tr>
<tr><td>Starting age range (years)</td><td>13 to 36</td><td>14 to 24</td><td>9 to 45</td><td>9 to 29</td></tr>
<tr><td>Projection period range</td><td>Less than 1 year to 18 years</td><td>Less than 1 year to 16 years</td><td>Less than 1 year to 55 years</td><td>Less than 1 year to 16 years</td></tr>
<tr><td>Mean Top Height projection</td><td>• all models performed similarly
• MTH generally predicted to within 2m
• range in errors for any projection period tends to increase with increasing projection period</td><td>• all models perform similarly
• at the extremes ITGM and 300 Index models predict lower MTH, whereas Clays model predicts higher MTH</td><td>• all models performed similarly
• MTH generally predicted to within 5m
• mean error very similar for projection periods of up to 10 years
• for projection periods 10 to 40 years: mean error is smaller for 300 index model
• For projection period > 40 years: smaller mean error using PPM88 & ITGM</td><td>• all models performed similarly
• range in errors for any projection period tends to be similar</td></tr>
<tr><td>Basal Area projection</td><td>• 300 index tends to predict less basal area than observed
• Sands and ITGM tend to predict more basal area than observed
• BA/ha generally predicted to within 10m^2/ha</td><td>• ITGM tends to predict less BA than observed, whereas 300 Index model tends to predict more</td><td>• In general all models performed similarly
• BA/ha generally predicted to within 20 m^2/ha
• Sometimes 300 index predicts less BA than observed and PPM88 and ITGM predict more</td><td>• In general all models performed similarly</td></tr>
<tr><td>Stocking</td><td>• similar results produced by all models
• difference between actual and predicted SPH generally less than 100
• standard deviation similar for all models, but generally slightly larger for Sands model</td><td>• mean absolute residual is similar for all models for projection periods < 9 years
• For longer projection periods, mean absolute residual tends to be larger for ITGM model</td><td>• All models over-predict sph, with most estimates being within 100sph</td><td>• errors are similar for all three models
• ITGM model tends to show slightly more positive residuals
• For short projection periods, the mean error is similar for all three models but increases with increasing projection period</td></tr>
</table>

Differences between actual and predicted values were also examined against four independent classification variables:

- Previous land use
- Number of height trees used to calculate site index
- Whether silviculture was known or unknown
- The genetic rating of the trees

In some instances there were significant differences in the performance against some of these classification variables, but again there was a lot of scatter, and no clear trends emerged between the three modelling approaches.

CONCLUSION

This study examined the performance of three groups of radiata pine growth models using a data set totally independent of the model development.

The graphs (Appendix 8) indicate that the performance of the stand level regional model, ITGM regional model and 300 Index model for predicting Mean Top Height, Basal Area per hectare and stems/ha is very similar for the Sands, Clays, Central North Island and Nelson regions.

For all regions there are some simulations with large errors, and in these cases all three models tend to produce similar large errors.

In each region, the errors were also compared against three or four independent classification variables:

- Previous land use
- Number of height trees used to calculate site index
- Whether silviculture was known or unknown
- The genetic rating of the trees

An analysis using the SAS procedure (PROC MIXED) indicated that in some instances these classification variables had a significant impact on the predicted variables. Selected graphs show the impact of these differences.

Given the above results it is not possible to recommend one model over and above another in terms of its performance. This result is not surprising since all three models have been derived using to a large extent the same PSP data.

It is recommended that the model used is chosen based on the data available, and type of analysis being carried out. For example:

- if one wishes to investigate the effects of alternative silviculture regimes, then the 300 Index is the appropriate model,
- if one wishes to grow individual tree inventory data forward in time, then the ITGM is an appropriate model.

ACKNOWLEDGEMENTS

Andrew and Joel Gordon for help with Forecaster.

REFERENCES

There are no references for the main report; nonetheless, the appendices cite relevant references.

APPENDICES

Appendix 1 - SANDS Stand-Level Growth Model

Database

This model uses the state-space methodology of Garcia (1988), and was developed using data from a total of 513 plots located in all the sand dune forests in Auckland and Wellington conservancies.

Aupouri	80
Mangawhai	8
Woodhill	166
Waiuku	131
Santoft	75
Tangimoana	11
Waitarere	42

Ranges for the major variables for the main model:

Variables	**Minimum**	**Maximum**
Age (yrs)	3.8	46.1
Site index (m)	12.8	35.6
Basal area (m^2/ha)	0.8	70.7
Stocking	99	2536
Mean top height	3.1	42.3

Ranges for the data used in the functions:

Thinning function variables	**Minimum**	**Maximum**
Age	5	41
Stocking before thin	220	2339
BA before	2.18	61.94
Stocking after	148	1664
BA after	1.52	49.63
Stocking removed	6	2092
BA removed	0.08	45.92
Volume function variables	**Minimum**	**Maximum**
Basal area	0.83	70.71
Height	3.1	42.3
Stocking	99	2787
TSV	2	886.2

Scope
The model's primary area of use is in forests mentioned above, and is intended for yield prediction.

Accuracy
All the validation is done on a plot basis, therefore I cannot comment on stand accuracy.

Validation
Two forms of validation have been done (Dunningham, 1985) to try to disprove the model:

(1) The model is checked to see if it behaves illogically. This is done by plotting residuals of the major variables against others to check for bias etc., and by plotting graphs of intermediate variables.
(2) The models' predictive capability is validated by comparing the actual plot projections against the model projections for each plot or for a subset of plots.

Caveats

(1) Unthinned stands cannot be simulated over a long period of time with any confidence.
(2) Basal areas predicted above 70 m^2/ha should be treated with caution as it is not known what happens to growth at this level. [This is enforced in the model by constraining the basal area to be not greater than about 75 m^2/ha.]
(3) Very low sites are not predicted well (i.e., the model is not designed for protection stands). [A low site index is defined as around 12-15 m. The resources forester actually using the model would define it more specifically according to his situation.]
(4) The model should be started from a known starting point rather than using the early function. [This is due to the large range of average diameters at low height limiting the formulation of an accurate function.]

Input data

(1) The model can only be run knowing the site index and initial stocking – starting from age zero.
(2) The model can also be started knowing any two of site index, height and age – the third to be calculated. Then the stocking and basal area are also required.
(3) To thin, the requirements are the residual stocking.

Sensitivity

No sensitivity analysis has been done.

Pruning

The model does not distinguish between pruned and unpruned trees in the data.

Reference

Dunningham, A. 1985: Growth model for sand dune radiata pine stands. NZ Forest Research Institute, Project Record No. 715.

Garcia, O. 1988: Experience with and advanced growth modelling methodology. Forest growth modelling and prediction U.S.D.A. Forest Service, General Technical Report NC-120. Pp 668-675.

Appendix 2 - CLAYSF (CLAYSFERT) Stand-Level Model

This model is for forests on clay soils in the former Auckland conservancy. It was developed in 1987 (Shula, 1987b), and is the recommended replacement for CLAYS (Shula, 1987a).

Database

The data for model development came from four former Auckland Conservancy forests. Contributions of measurements by forest for the various 'fertiliser effect' analyses are given below.

Forest	Number of measurements		
	Lambda vs foliar 'P'	Rise in foliar 'P'	Decay in foliar 'P'
Whangapoua	179	16	197
Glenbervie	30	7	55
Maramarua	32	6	47
Riverhead	0	5	84
Total	241	34	383

A descriptive breakdown of the foliar 'P' data in the lambda vs. foliar 'P' analysis by forest and fertiliser treatment is given below.

Forest	Fertiliser treatment	Foliar 'P' (%)			
		Min	Mean	Max	n
Whangapoua	Control (C)	.062	.090	.127	41
	Fertilised (F)	.076	.129	.199	138
Glenbervie	C	.101	.117	.127	6
	F	.101	.149	.263	24
Maramarua	C	.084	.092	.100	5
	F	.067	.149	.251	27

The method to model 'fertiliser effects' involves: (1) retaining all the critical growth relationships and ancillary functions in the CLAYS model (Shula 1987a), and (2) unaltered use of the basic form of the CLAYS model equations to predict top height, basal area and stocking.

The 'fertiliser effects' are produced by three distinct relationships, i.e.

(1) 'time-scale multipliers' (lambda values L, for BA, HT, SPH, site occupancy), or the time required to achieve growth are predicted as a function of foliar 'P'

$$L = [a * (\frac{P - .06}{P - .06 + b})] * c$$

(2) change in foliar 'P' (rise) as a result of fertilisation is predicted as a function of fertiliser rate (F, kg/ha superphosphate),

$$R = EXP\ (a) * F^b$$

(3) foliar 'P' following a change in foliar 'P' (decay) as a result of natural decline in fertility is predicted as a function of time and initial 'P' (P_o).

$$P = EXP\ (-a)^T * (P_o - .06) + .06$$

The derivation of the 'fertiliser effects' relationships is based on data from an FRI fertiliser trial, AK 286, which has plots located in the above forests. This trial covers a range of super-phosphate fertiliser application frequencies and rates (including unfertilised controls). Frequency ranges from

1 to 4, while rates include 625, 1250, and 2500 kg/ha. Plots have been thinned one to two times between the ages of 6 and13 years.

Scope

The model is applicable to forests occurring on 'classic' clay soils in the former Auckland Conservancy locale. Predictions of growth and yield are possible for a full range of phosphorus fertility levels (dependent on foliar 'P' %).

Accuracy

Residual statistics for consecutive measurements in the lambda vs foliar 'P' analysis (n = 241; mean time-lapse = 1.7 years) are given below.

Variables	Mean Error	Standard Deviation
Basal area (m^2/ha)	– 0.2865	1.3219
Stocking (stems/ha)	– 0.4700	11.1424
Top Height (m)	0.1328	0.8734
Mean DBH (cm)	– 0.1044	0.5525
Average spacing (m)	0.0018	0.0553
BA x HT (m^3/ha)	– 2.3468	43.3489

Validation

CLAYSFERT performance has been evaluated with respect to:

(a) the effect of input variables on the prediction of basal area and top height (with a selected 'standard' regime), and

(b) the accuracy of stand parameter predictions given plot history as input.

i. Effect of input variables (with 'standardised' regime)

Site Index:

A change in site index from 27 metres to 29 and 31 metres results in a percentage change in BA and HT at stand age 25 of +9 to +18 and +5 to +11, respectively.

Initial foliar 'P':

A change in initial foliar 'P' from 0.07% to 0.11% and 0.15% results in a percentage change in BA and HT at stand age 25 of +120 to +150 and +48 to +58, respectively.

Fertiliser application rate:

The table below presents predicted BA and HT for an unfertilised stand (age 25) at low, medium and high initial foliar 'P' levels; and the percentage change in these predictions at varying rates of fertiliser application (relative to no fertiliser application).

Foliar 'P' %	Basal area for fertiliser rates				Top height for fertiliser rates			
	0	625	1250	2500	0	625	1250	2500
.07	20.0	+111	+133	+151	21.2	+45	+52	+58
.11	44.0	+ 12	+ 16	+ 20	31.4	+ 6	+ 8	+10
.15	49.0	+ 5	+ 7	+ 9	33.5	+ 2	+ 3	+ 4

ii. Accuracy of stand parameter predictions (with plot history)

Twenty-three (23) plots were selected to simulate plot histories, and for the final stand parameters, calculate the ratio of predicted to actual. A total of six fertiliser treatments were simulated (including controls). Thinning was regulated by inputting residual stocking and basal area to circumvent errors in using the 'thinning function'.

The table below presents a comparison of accuracy of prediction for both CLAYSFERT and CLAYS with respect to the ratio of predicted to actual. Time-lapse in the prediction of HT and foliar 'P' ranges from 11 to 19 years; BA and SPH, 6 to 16 years.

Stand parameter	**Model**	**Mean Ratio**	
Unfertilised		**Fertilised**	
		(n = 8)	**(n = 15)**
Stocking	CLAYSFERT (CF)	.993	.998
	CLAYS (C)	.962	.994
Top Height	CF	1.001	.975
	C	1.109	.987
Basal area	CF	.928	.919
	C	1.124	.939
Volume	CF	.917	.906
	C	1.177	.934
Foliar 'P'	CF	.871	.923
	C	NA	NA

Caveats

(a) Site index must be input (or be determined from height and age) as top height at age 20 years for an adequately fertilised stand (foliar 'P' of at least 0.11%).

(b) CLAYSFERT can be run assuming the use of phosphorus fertilisers other than 'super' (e.g. triple super or PARR), however growth response to fertilisation in the model is based on a fertiliser trial using 'super-phosphate'.

(c) The model's 'early growth' function is used only when initial foliar 'P' is greater than or equal to 0.125%; otherwise, the user must also specify initial age and top height. The function enables a user to start a simulation at age zero by extrapolating to an initial BA corresponding to a top height of five metres.

(d) The model has been conditioned to approach a lower limit for foliar 'P' of 0.06%. At this limit, predicted growth is zero.

Input data

Initial input data includes:

(a) foliar 'P' (%),
(b) site index (equivalent fertilised),
(c) top height and/or age,
(d) stocking,
(e) basal area, and
(f) whether or not the stand has been thinned within four years.

Additional input data, either initially or during simulation involves management prescriptions, namely:

(a) thinning to a residual stocking, basal area, or both; and
(b) fertilisation with kg/ha, or nominating a 'new' foliar 'P'.

Note that allowance for use of phosphorus fertilisers other than 'super' is made by asking the user to alter the application rate in proportion to the % P of the chosen fertiliser to super-phosphate, e.g., 625 kg/ha 'super' (9% P) equates to 331 kg/ha of PARR (17% P).

References

Shula, R.G. 1987a: Auckland Clays radiata pine growth and yield model development history and performance. Stand Growth Modelling Cooperative Report No. 2. NZ Forest Research Institute, Project Record No. 1384.

Shula, R.G. 1987b: Auckland Clays growth model with phosphorous fertiliser effects. Stand Growth Modelling Cooperative Report No. 6. NZ Forest Research Institute, project Record No. 1688.

Appendix 3 - PPM88 Stand-Level Model

This model was developed in 1988 for Kaingaroa and Tarawera forests.

Database
The database for model development consisted of radiata pine PSP data from Kaingaroa and Tarawera forests. All plots were from stands planted after 1955. The data from the Interim Pumice Plateau model (KGM3) were used, after eliminating measurements with any windthrow, post-thinning mortality, or without thinning/pruning history information. For the basal area growth and mortality relationships, 2050 measurement pairs from the original 2295 were used. In addition, data from 43 unthinned initial measurements were included to extend the model down to top height 1.4 m. The height growth, thinned basal area and volume equations from KGM3 are used without change. The data base is described by Dunningham and Lawrence (1987).

The initial stocking and thinning/pruning history information was obtained from the PSP plot history sheets. These data are very unreliable, but this is not expected to have a marked effect on the predictions.

Scope
The model describes radiata pine growth in Kaingaroa and Tarawera, and hopefully in other areas of the Central North Island Pumice Plateau, over a wide range of ages and treatments. It tries to predict growth losses from low site occupancy following heavy thinning and/or pruning. In KGM3 these losses are averaged-out and confounded over all the treatments represented in the data base.

This model is a recommended replacement for KGM3 for general use. In some special applications it might be more convenient to use KGM3 because it is simpler and does not require information about initial stocking or thinning and pruning history.

Accuracy
Overall residual statistics are similar to those for KGM3 (see below). These residuals (measured minus predicted) are for predictions at consecutive measurements on the new data set described above. The average time interval is 1.24 years. A large part of the variation is due to plot measurement and sampling error.

Variables	**Mean**		**Std. dev.**	
	PPM88	**KGM3**	**PPM88**	**KGM3**
Basal area (m^2/ha)	-0.001	0.068	1.020	0.999
Stocking (stems/ha)	-4.3	-2.9	38.2	37.9
Top height (m)	0.019		0.537	

The residuals for both models are fairly similar. However, an examination of residuals for stands that are not fully closed, either because of recent thinning and/or pruning or because of young age and/or wide initial spacing, indicates some differences.

The models use different approaches to predict the initial growth when starting simulations from age zero. KGM3 estimates the basal area at top height 4 m as a function of the stocking, and uses this as a starting point. PPM88 starts with a basal area of zero at top height 1.4 m. PPM88 over-estimates the basal areas at very young ages. The estimates appear somewhat better than those from KGM3 later on. Large variations in initial growth can be expected, depending on establishment techniques, weed competition, etc. Actual measurements (above top height 8 m) should be used as starting points for prediction, whenever possible.

The few older unthinned plots, largely from Tarawera forest, tend to have lower basal areas than those predicted by both models, especially at the higher stockings. It is difficult to know how representative these plots are, but it must be concluded that predictions are unreliable for old unthinned stands, at least for those above 2000 sph.

Validation

Analysis of residuals, part of it discussed above, and some comparisons against individual plots and experiments have been done. Because of the relatively small differences between the two models, much of the validation done on KGM3 is applicable (See Dunningham and Lawrence, 1987; Hayward *et al.* 1987).

Caveats

The model is unreliable for unthinned plots above 20 m top height. Basal area is likely to be overestimated at top heights below 8 m.

The green crown levels shown are a very rough estimate. They are used only at the time of pruning to estimate the amount of foliage removed.

Occasionally the model may show the stocking increasing by a few stems per hectare. Usually this happens at the start from age zero, or beyond the range of the data. The discrepancy represents a fraction of 1%, and should be ignored.

All values are on a net stocked area basis, and exclude windthrow or other damage.

Input data

In addition to the state variables basal area, stocking, and top height (Garcia, 1988), the model uses a fourth state variable called "relative closure", or closure for short. Roughly, this can be thought of as the amount of foliage relative to that of a fully closed stand (although it might represent also soil utilisation by the roots, etc.). The relative closure starts at a small value proportional to the stocking at the time of planting, and increases asymptotically to a final value of one. Thinning decreases closure in proportion to the fraction of basal area removed. Pruning decreases closure according to a non-linear function of the fraction of canopy depth removed. For a given basal area, stocking, and height growth is non-linearly related to closure in such a way that small reductions in closure at values close to one have a negligible effect, the effect increasing as the stand becomes more open. This models the lack of full site occupancy following heavy thinning and/or pruning (and before crown closure in young stands); nearly full use of the site potential is maintained with moderate treatments.

Simulations could, therefore, be started at any age, knowing the current basal area, stocking, top height, and relative closure. Since it may be difficult to know the closure, the computer program is set up so that it starts from age zero (or rather top height 1.4 m), and the closure is derived from the planting stocking and thinning/pruning history. The state variables, including closure, can be altered at any age by the user, so that this does not limit flexibility. Note that for nearly-closed stands the exact value of the relative closure is not critical.

Thinnings may be specified by the residual stocking, residual basal area, or both. Pruning is specified by the pruned height or, more accurately, by the new green crown level.

A green crown level, the maximum of that at the last pruning and one derived from an estimate of potential crown depth, is carried forward by the program. This is used to compute the reduction in closure in case of pruning. Note that the program cannot know how to update correctly the crown level when "growing" backwards in time, so that in this instance the user must change it manually (the value is irrelevant if there is no pruning). Some accuracy may be lost when going backwards from old ages.

Mortality occurring within 4 years after thinning was excluded from the data. This mortality appears to be associated with thinning or pruning, and is small and extremely variable. It was estimated as an average of 0.77 stems per hectare, and applied by the program at the time of thinning.

Pruning
Pruning effects on growth are modelled as described above. Specifying pruning by green crown level or pruning height assumes that all trees are pruned to the same height. Some variation can be accommodated by averaging, keeping in mind that the driving factor is the amount of foliage.

Functions
Growth described by differential equations as in KGM3 (Dunningham and Lawrence, 1987; Garcia, 1988). Growth is modified by reduction factors that are functions of relative closure. The theory of these is described by Garcia (1989). The height growth, thinned basal area, and volume equations from KGM3 are used without change.

References

Dunningham, A.G. and Lawrence, M.E. 1987. An "interim" stand growth model for radiata pine grown on the Central North Island Pumice Plateau. Stand Growth Modelling Cooperative Report No. 3 (FRI Project Record 1497).

Garcia, O. 1988. Experience with an advanced growth modelling methodology. Forest Growth Modelling and Prediction. USDA Forest Service, General Technical Report NC-120. 1988.

Garcia, O. 1988. Growth Modelling - A review. *New Zealand Forestry 33* (3), 14-17.

Garcia, O. 1989. Growth Modelling - New developments. JAFS/FRI Meeting, Rot, Oct. 1988.

Hayward, W. Jenkin, I. and New, D. 1987. Evaluation of the performance of growth models for Kaingaroa. Stand Growth Modelling Cooperative Report No. 7.

Appendix 4 - NM90 Stand-Level Model

Data

All the data are taken from the Ministry of Forestry's permanent sample plot system. This data set includes measurements from forests owned by NZ Timberlands Ltd and Baigent Forest Industries Ltd in the Nelson/Marlborough region.

1655 measurement pairs from 410 plots are used in the development of this model. Table 1 describes the range of data used in the model.

Table 1. Range of Data

Variables	Minimum	Mean	Maximum
Age (years)	3.0	27.4	46.7
Site Index (metres)	18.7	28.5	35.7
Basal area (m^2/ha)	0.3	24.3	86.8
Stocking (stems/ha)	110	597	4075
Top Height (m)	2.0	38.2	49.0

Scope

The model may be used to derive yield tables and predict the effects of different management regimes on stands in the Nelson/Marlborough region. All ages, as defined by the database, and thinning treatments are covered by the model.

Validation and accuracy

As illustrated in the full report describing this model (Law, 1990), there has been extensive plotting and analysis of residuals. A tendency to over-predict at high basal areas (>50m^2/ha) has now been rectified (Lawrence, 1990) and the program altered accordingly. The new residual mean squares (RMS) are shown in Table 2.

Table 2. Residual Mean Squares

Variables	RMS
Basal area (m^2/ha)	1.61
Stocking (stems/ha)	14.30
Top height (m)	0.65
Basal area * height (m^3/ha)	44.72
Mean DBH (cm)	0.163
Average spacing (m)	0.024

Input data

Input data required includes at least two of the following: age, top height or site index. The user is also prompted for initial stocking and basal area, one of which must be known. If the effects of thinning are to be modelled then stocking before and after thinning must be known as well as the age or height when thinned.

Pruning

The model does not distinguish between pruned and unpruned trees in the data set.

Methodology

The methodology used is the same as that in the Golden Downs Model (Garcia, 1984)

References

Garcia, O., 1984: New class of growth models for even-aged stands - *Pinus radiata* in Golden Downs forest. New Zealand Journal of Forestry 24(1): 108-124.

Law, K.R.N, 1990: A growth model for radiata pine grown in the Nelson/Marlborough region. Stand Growth Modelling Cooperative Report No. 18

Lawrence, M.E., 1990: Investigations into the possible causes of bias in the Nelson growth model. Stand Growth Modelling Cooperative Report No 19.

Appendix 5 - Individual-tree (ITGM) models

ITGM

Since the early 1990s, the Stand Growth Modelling Cooperative has been instrumental in pioneering the development of tree-level growth models. The Individual-Tree Growth Model (ITGM) is a fully-functional, prototype individual-tree growth model for radiata pine.

Stand Growth Modelling Cooperative Reports Nos. 34, 47, 54, 58, 59, 60, 77 and 79 document the development of the individual-tree growth model for *Pinus radiata* in New Zealand from 1994 to 2000.

Database

A total of 291 plots were extracted from the PSP system from seven different growth modelling regions to form a general dataset. Plots were selected with the following criteria:

- first measurement between 15 to 25 years
- 15 or more trees per plot
- or more consecutive measurements per plot
- 'normal' levels of mortality
- thinning operations completed prior to age15.

Of the 291 plots, 41 were in the SANDS growth modelling region; 37 in CLAYS; 15 in CANTY; 63 in NELSON; 67 in CNI; 33 in SOUTH and 35 in HBAY. A subset of some 5000 observations was randomly selected to extract approximately 750 from each region.

Scope

ITGM implements in combination, tree-level growth (height and diameter) and survival equations to project stand- and tree-level growth and yield. ITGM prediction equations require data specific to each of seven growth modelling regions, and operate on an annual cycle to grow trees from plantation age 15 to rotation age.

Validation and accuracy

Validation, as an integrated system of equations, using a fully-functional growth simulator was carried out in 2000 (SGMC Report No. 79). During validation, the previously documented modelling approach used to predict static tree height resulted in severely biased prediction of tree height increment.

Therefore a major revision to tree height-growth prediction was undertaken and implemented in ITGM. Diameter and height growth equations for the West Coast Region were also fitted (previously not included – 168 plots from West Coast PSPs were used) and tested. The validation supported the use of the Nelson equations for the West Coast region rather than developing a specific regional equation.

The ordering of regions by descending magnitude of the coefficient for the regional dummy variable provides a ranking of largest to smallest regional ht_i base-increment.

	Dummy coeff.	**correspondent $\underline{ht}_i$ increment (m)**
CNI	-0.98	0.38
HBAY	-1.07	0.34
NELSON	-1.12	0.33
SOUTH	-1.15	0.32
CLAYS	-1.2	0.30
CANTY	-1.30	0.27
SANDS	-1.46	0.23

In practice, these regional ht_i base-increments are then adjusted up or down by the other explanatory variables in the equation (i.e., diameter, height, height potential index, relative tree-size) with coefficients common to all regions.

Overall, validation statistics reveal that, on average, 5- and 10-year tree- and stand-level diameter and height prediction error is generally $\leq$ 3% (usually over-predicted), while absolute prediction error is generally $\leq$ 7%. Accompanying predicted tree-diameter distributions generally appear reasonable, and skewed and multi-modal diameter distributions (i.e. not "normal") are accommodated well.

These results of this validation (SGMC Report No. 79) indicate that ITGM, as an iterative prediction system for mid-rotation onward tree and stand growth and survival, operates within acceptable error limits without any obvious anomalies or mechanistic mathematical flaws.

A further study was carried out in 2007 (SGMC Report No. 143) and the following conclusions were drawn:

- ITGM performs reasonably well when the increment period is short
- ITGM performs better if the starting age is several years after the thinning
- ITGM performs reasonably with starting ages below 15 years provided that the starting age is several years after thinning
- It is considered that uneven thinning may cause problems if ITGM is started immediately after thinning

Input data required

Stand Information:

- Initial stand age
- Stocking
- Basal area
- Mean top height
- Mean DBH

Site data

Region	Select the growth modelling region from this list.
Age	Enter the stand age in years
Altitude	Enter the stand altitude in metres above sea level.
Rainfall	Average rainfall is required by month
Nitrogen score	These scores are defined by Hunter *et al.* in the Atlas of Radiata Pine Nutrition. The scores are 1 - deficient, 2 - marginal (high probability of deficiency), 3 - marginal (medium probability of deficiency), 4 - marginal (low probability of deficiency), 5 – satisfactory (high probability of deficiency), 6 – satisfactory (medium probability of deficiency), 7 – satisfactory (low probability of deficiency).
Phosphorus score	Definitions as for Nitrogen
Mortality Adjustment	Can be set to any value between zero (no mortality) and 200%. Full mortality predicted by the model is obtained at 100%.

Individual Tree Data is imported as a tree list from MARVL V2 or PSP data files, and includes a tree ID, DBH, total height and stems/ha.

Functions

The following variables (or transformations, thereof) were useful across most of the seven regions:

- HPIT, height potential index
- SDI, stand density index
- RD, relative density
- Bal_ratio, ratio of basal area in trees larger than the subject tree to subject tree DBH
- chg_pdbh, potential site productivity as a function of DBH and projection period.

These variables represent new approaches to index New Zealand radiata pine relative stand density and/or productivity potential. Another new and beneficial approach to growth prediction was to use a 'pre-'estimate of growth itself (i.e., chg_pdbh, HPIT) in a growth equation. This approach incorporates a predicted pattern of dominant-tree diameter growth to aid in the diameter growth prediction of any subject tree.

Another feature of this model is that age is not used in the equations predicting growth. This is therefore a useful approach for modelling mixed-aged stands.

References

Stand Growth Modelling Co-op reports (SGMC)

No. 34 – Gordon, A. D., Lawrence, M. E., 1994: Projecting inventory data: predicting individual tree diameter growth.

No. 47 - Gordon, A. D., 1996: Projecting inventory data: Predicting individual tree height growth.

No. 54 – Lundgren, C., Gordon, A. D., 1997: Modelling individual tree survival of radiata pine in NZ: Progress to July 1996.

No. 58 – Shula, R. G., 1997: Projecting inventory data: Revised individual-tree diameter growth equations.

No. 59 - Shula, R. G., 1997: Projecting inventory data: Revised individual-tree static height equation.

No. 60 - Shula, B., 1997: Modelling individual-tree probability of survival of unthinned radiata pine.

No. 77 – Gordon, A. D., Shula, R. G., 1999: A guide to using the individual-tree growth model.

No. 79 – Shula, R. G., Gordon, A. D., 2000: Validation of the individual-tree growth model (ITGM)

No. 143 - Grace, J. C., Blomquist, L., 2007: Performance of post-silvicultural individual-tree Growth Model (ITGM).

Other

Hunter, I. R., Rodgers, B. E., Dunningham, A., Prince, J. M., Thorn, A. J., An Atlas of Radiata Pine nutrition in New Zealand. FRI Bulletin No. 165.

Appendix 6 - 300-Index Growth Model

The 300 Index was initially developed as an index for comparing site productivity using extensive growth and field trial data available in NZ. The 300 Index is a volume productivity index, and is defined as the mean annual volume increment, at an age of 30 years, assuming a final stocking of 300 stems/ha, timely pruning to 6 m and thinning to final crop stocking at completion of pruning. The 300 Index Growth Model predicts basal area and height growth and stocking of radiata pine stands in New Zealand. It is calibrated to individual sites using the 300 Index and the Site Index.

Database

Initial Dataset

A total of 775 growth and stocking-trial plots were used to develop the model. Site Index ranged from 12 to 40 m and averaged 28 m. An important component was data from 20 final-crop stocking trials established throughout New Zealand in the 1970s and 1980s with final stockings of 50, 100, 200, 400 and 600 stems/ha, and with SI ranging from 16 m to nearly 40 m. An additional 353 growth plots were also used. Further field trials were used specifically to establish thinning and pruning effects. To ensure that the model performed best for commonly used regimes, the maximum final crop stocking was restricted to 800 stems per ha. Only 11% of the plots had measurements older than 30 years and only 3% older than 35 years, and the model can therefore be expected to perform well only within these stocking and age limits.

Validation dataset

Extensive validation of the model has been performed using 5,089 plots selected from stands from throughout New Zealand established after 1959 with final stockings less than 3000 stems/ha, and plot measurements of greater than age 6 years. A further 602 plots in stands established prior to 1960 were used to test the model against historic data. Plots were classified according to previous vegetation cover into ex-pasture ‘Farm’ sites, traditional ‘Forest’ sites, and coastal ‘Sand’ sites.

Scope

The 300 Index Model is intended for use in any site in New Zealand. The growth model is calibrated for any given site using the two site productivity indices SI (mean top height at age 20 years) and 300 Index. It predicts yield from planting and has been found to perform well up to and beyond age 50 years for a wide range of site types.

The 300 Index Model is a silvicultural model which is sensitive to different levels of stocking, and to thinning and pruning operations. The method of modelling both thinning and pruning is based on a time-shift approach. For example, the growth effects of pruning are modelled using the 'effective' age. This is calculated from the 'actual' age by a pruning age-shift term which is a function of pruned height, crown length and stocking.

To estimate the 300-index from a stand measurement, an iterative procedure is used, which finds the 300-index that achieves the measured BA (or DBH or Volume) at the given age for the specified stocking and pruning history.

The original 300 Index model is a stand-level model which produces a yield table (Age, Stocking, MTH, BA, and Stem Volume). However, an individual-tree version of the model which predicts height, diameter and survival probability of a list of individual trees is currently under development.

Validation and accuracy

a. Testing the 300 Index Growth Model on three contrasting site types: Dry East Coast, Fertile ex-farmland, and Coastal sand-dunes

An approach that tested for drift in the index over time was used. A stable index indicates that the model is performing well while a positive drift is evidence of model under-prediction and a negative drift indicates over-prediction.

For most sites, the 300 Index appears to be relatively stable over a wide range of age classes and stockings. Within a forest, average drift in 300 Index estimation will normally lie within a range of ±1%/yr, even when stands as young as five years are used for calibration. Some outliers with drift up to 2% will occasionally appear for no apparent reason.

Sites which are the exception to this general rule are as follows:

- Sand-dune sites north of Auckland. Calibration of 300 Index using young stands (5-10 years) will tend to over-predict the index by a significant amount. The over-prediction averages 65% for stands aged 5-10 years, and 28% for stands age 10-15 years.
- Low-rainfall sites at Taradale (Hawkes Bay), Marlborough (South Bank) and Eyrewell (Canterbury). The index will be over-predicted by about 39% in stands aged 5-10 years, and by about 23% in stands aged 10-15 years.
- Ex-farm sites in Otago/Southland. Indices estimated from young stands may tend to be under-predicted.

b. Validate the 300 Index Growth Model for a wide variety of sites and regimes from throughout New Zealand.

The stability of the 300 Index Growth Model was tested against more than 5,000 sample plots located throughout the country.

For most sites and regimes, the model performs well up to age 30 years and at final crop stockings below 800 stems/ha. However, it under-predicts yield above age 30 years and over-predicts at stockings above 800 stems/ha. The effects of pruning and thinning are accurately modelled. A slight tendency to over-predict yield on low-productivity sites was detected. There was also a slight tendency to under-predict yield on traditional Forest sites but to be unbiased on Farm sites.

There was some regional variation in the performance of the model. It over-predicts yield on Coastal Sand sites, and also has a slight tendency to over-predict in Northland, Auckland, the South Island West Coast and Canterbury. It under-predicts yield in Otago and Southland and also in Gisborne and Wellington (based on limited data). There is also a slight tendency to under-predict yield in Bay of Plenty, Nelson and Marlborough.

On the basis of these validation studies, corrections to account for the regional and age-related biases were developed, and these are implemented in the current version of the model.

Input data

The 300 Index Model is calibrated for any site using two measures of site productivity, Site Index, a measure of height growth productivity, and the 300 Index, a measure of volume productivity. Both Indices can be supplied directly by a user based on knowledge of expected productivity for a particular site. Alternatively, the indices can be estimated from a growth measurement (age, stocking, basal area and mean top height) from an existing stand. The model assumes that Site Index and 300 Index do not vary over time and do not change with stocking.

In addition to site productivity indices and/or a stand measurement, the user must input the stand silvicultural history. This consists of the initial stocking, the age and stocking following each thinning, and the age, prune height and stocking of each pruning lift. The latest version of the model currently under development has the capability to fill in missing silvicultural history when this unavailable. It will therefore be possible to run this new version of the model using a stand measurement as the only input.

References relating to model development

Hansen, L., Knowles, R.L., and Kimberley, M. 2004: Functionality contained in the NZ Farm Forestry Radiata pine Calculator. FFPM Cooperative Report No. 91.

Kimberley, M., West, G., Dean, M. and Knowles, L. 2005: The 300 Index- a volume productivity index for radiata pine. NZ J. For. Sci. August 2005.

Kimberley, M., Knowles, L., and Dean, M. 2005: Validation of the 300 Index growth model for radiata pine on three contrasting sites. FFPM Cooperative Report No. 92.

Kimberley, M. and Dean, M. 2006: Validation of the 300 Index growth model. FFPM Cooperative Report No. 98.

Kimberley, M. 2006: Extension of the 300 Index growth model for non-performing site types – Stage 1. FFPM Cooperative Report No. 99.

Kimberley, M. 2007: Extension of the 300 Index growth model for non-performing site types – Stage 2. FFPM Cooperative Report No. 107.

Appendix 7 - Other Stand-Level Models

The following stand level models for other regions were not investigated in this study, but are summarised here, so that a summary of the most recent regional stand level growth models is provided in one document:

- NAPIRAD (Hawkes Bay forests)
- CANTY (Canterbury forests)
- SGM3 (Southland forests)

NAPIRAD

Database
The data were drawn from forests immediately in the Hawkes Bay region as opposed to adhering rigidly to Conservancy boundaries. The contributions of each of the six forests to the database were Wharerata – 24 plots, Patunamu – 16 plots, Mohaka – 31 plots, Esk – 78 plots, Kaweka – 11 plots and Gwavas – 47 plots.

The data originated from FRI experiments, Conservancy experiments and growth and yield plots. It was extracted from the PSP system in early 1982.

Variables	Minimum	Maximum
Age (years)	4.1	29.2
Site index (m)	20.6	38.5
Basal area (m^2/ha)	0.6	90.3
Stocking (sph)	99	2772
Mean top height (m)	3.6	47.0

Total number of plots = 207
Total number of increment periods = 634

Notes: (i) Pruning is confounded with heavy early thinning.
(ii) There are very few unthinned plots.
(iii) There is only a limited amount of data from the poorer sites, i.e., Kaweka.

Scope
The model was designed to be used primarily by Wellington Conservancy. It was developed as part of a series of regional growth models and accorded a high priority because of a tight wood supply situation and the lack of a suitable existing model for the region.

Accuracy
The validation is carried out in a similar manner to the model's development – on a plot-by-plot basis.

Validation
Initial validation consisted of looking at the residuals for each of the major variables, basal area, stocking, top height and volume. This was followed by plotting predictions using the initial measurements as starting points and comparing them with the actual database for each of the major variables. Finally, plot by plot comparisons of actual versus predicted were carried out on a variety of plots chosen to represent different silvicultural treatments.

Subsequent to this, the model was handed over to Wellington Conservancy staff and the Resource Inventory Group (as future users of the model) on a trial basis for them to conduct their own validation, 'test to destruction', confidence building exercises. The results of these tests and comparisons with other growth models are available in a series of reports from the Resource Inventory Group. (RIG File 9/0/1)

Caveats

Users should be wary of using the model to predict the growth of unthinned stands. There is a distinct lack of data from plots with high stockings, and the model will predict little mortality (c.f. Kaingaroa growth model) for unthinned stands. It must be said, however, that in spite of a very close look at the limited data and stands available in this area, there is no evidence to suggest that the predictions are in fact incorrect.

Input data

Input data are basal area, stocking and top height, as available from standard inventory procedures and the Stand Record System. For thinnings, stocking before and after thinning is required, and knowledge of basal area would improve accuracy. In general, the model is stable, i.e., errors in input data would cause errors of the same order of magnitude in the projections.

Pruning

No data on pruning was available, so that any pruning effects are confounded with thinning. The fact that no "shock effects" immediately after thinning were found suggests, however, that past pruning practices did not significantly affect growth. Heavier pruning could cause the model to over-predict.

Functions

The functions are differential equations for basal area growth, mortality and height growth.

Reference:

Garcia, O P 1988: Experience with and advanced growth modelling methodology. Forest growth modelling and prediction U.S.D.A. Forest Service, General Technical Report NC-120. Pp 668-675.

CANTY

Data

The data originated from FRI experiments, Timberlands experiments, and Timberlands and Selwyn Plantation Board growth and yield plots. An additional source of data was from sectional measurements. Table 1 provides a breakdown of plots and measurements by location, and Table 2 describes the range of data used in the model.

Table 1: Summary by location

Forest	No. of plots	No. of measurements
Eyrewell	51	213
Balmoral	37	147
Burnham	12	45
Bottle Lake	3	33
Ashley	41	147
Hanmer	7	17
Omihi	17	50
Waimate	6	16
Geraldine	16	50
Sectional measurements	11	49

Table 2: Range of data

Variables Mean	Minimum	Maximum
Age (years)	4.0	35.0
Site Index (m)	15.4	31.3
Basal area (m^2/ha)	0.6	73.1
Stocking (stems/ha)	124	5377
Top height (m)	2.8	38.1

Scope
The model may be used to derive yield tables and reliably predict the effects of different management options on stands grown on the Canterbury foothills or plains.

Accuracy
Overall residual statistics of major variables, from consecutive measurements, are in Table 3.

Table 3: Measurement pair residuals (mean time interval 2.2 years)

Variables	Mean	RMS*
Basal area (m^2/ha)	0.0131	2.09
Stocking (stems/ha)	1.25	33.8
Top Height (m)	0.0745	0.687
Mean DBH (cm)	–0.0305	0.725
Average spacing (m)	–0.000977	0.0512
Basal area * height (m^3/ha)	5.66	62.8

* Residual Mean Square

Validation
Extensive plotting and analysis of residuals, see Lawrence (1988).

Methodology
The methodology and model formulation is almost identical to that used in the "interim" Kaingaroa growth model.

Reference
Lawrence, M.E. 1988: A growth model for radiata pine grown in Canterbury. Stand Growth Modelling Cooperative Report No. 8. Forest Research Institute, Project Record No. 1862.

SGM3
SGM3 is a new Southland Growth Model that provides a better predictor of height, particularly at ages less than 15 years. The new height model has been incorporated into SGM2 resulting in the construction of SGM3.

Database
The majority of the data was drawn from the PSP system. Sectional measurements also provided data at the younger age range. The plots are located in 13 different forests throughout the Southland region.

The height model shows the following range:

Variables	Minimum	Mean	Maximum
Age (yr)	1.0	16.1	57.3
Site index (m)	15.4	24.5	32.8
Top Height (m)	0.1	18.2	56.6

Total no. of plots: 258
Total no. of measurements: 1199

Scope
The model is designed to predict growth in the radiata pine forests of the Southland region. All ages, as defined by the database, and thinning treatments are covered by the model.

Validation and accuracy
Validation of SGM3 (Law, 1988) was carried out in a similar manner as that for SGM2 (Milne *et al.* 1987). The model is found to have a high degree of accuracy over the validation set.

Overall residual statistics for measurements are:

Variables	Mean	RMS*
Basal area (m^2/ha)	0.151	2.11
Stocking (stems/ha)	7.20	47.9
Top height (m)	-0.1219	0.946
Mean DBH (cm)	-0.0378	0.484
Average spacing (m)	-0.00315	0.063
Basal area* height (m^3/ha)	-7.51	95.3

* Residual mean square.

Input data required
This varies from a minimum of site index, stocking at age 0 and the silvicultural regime specified by ages and residual stocking of thinning, through to age, top height, basal area, number of stems, site index, age of last thin, stocking before and after last thinning.

Pruning
The model does not distinguish between pruned and unpruned trees in the data. Any pruning effects are confounded with thinning.

Functions
The definitions of the functions used in the development of the models are described by Garcia (1988).

References
Law, K.R.N. 1988: SGM3: A revised version of the Southland growth model. Stand Growth Modelling Cooperative Report No. 9. (Forest Research Institute, Project Record No. 1941)
Milne, P.G. et al. 1987: Growth models for radiata pine: a validation for Otago Southland forests, 1987.
Garcia, O. 1984: New class of growth models for even-aged stands - *Pinus radiata* in Golden Downs forest. New Zealand Journal of Forestry 24(1): 108-124.

Appendix 8 - Results

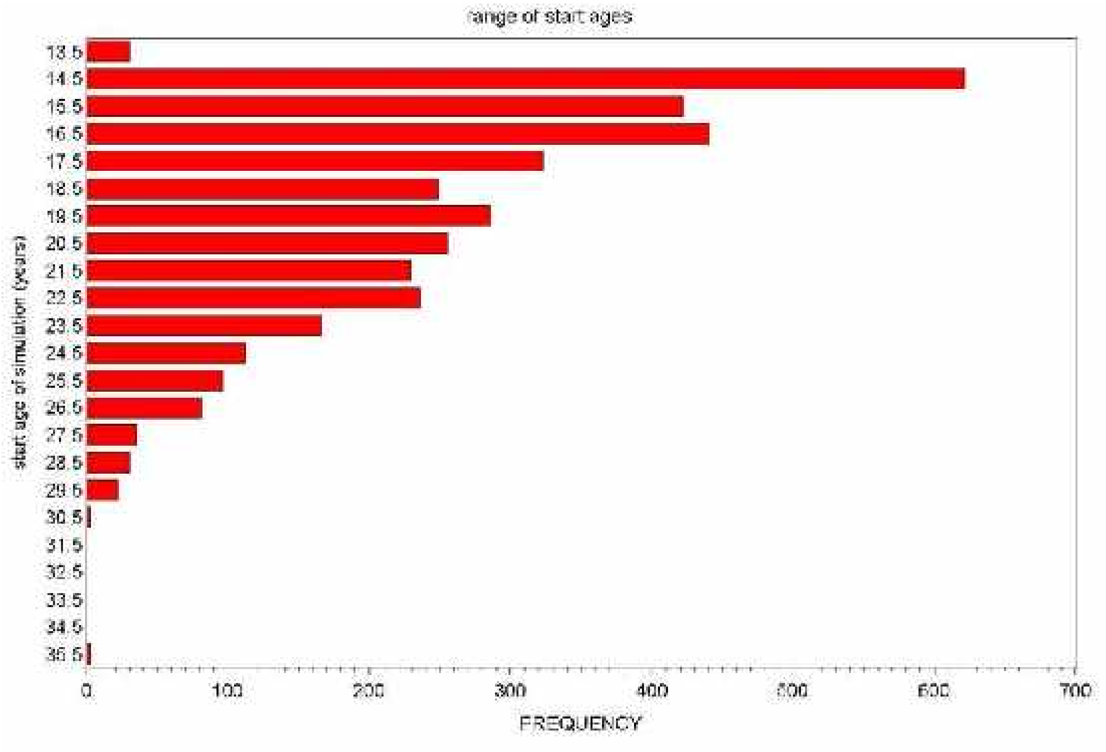
Note:
The following colour scheme is used on the graphs comparing the three models:

- Regional stand level models: Black
- Regional ITGM models: Red
- 300 Index model: Blue-green

Performance of models in the SANDS Growth Modelling Region

There were 3639 individual simulations where the performance of the three growth models: SANDS, ITGM and 300 Index models could be compared at a stand level.

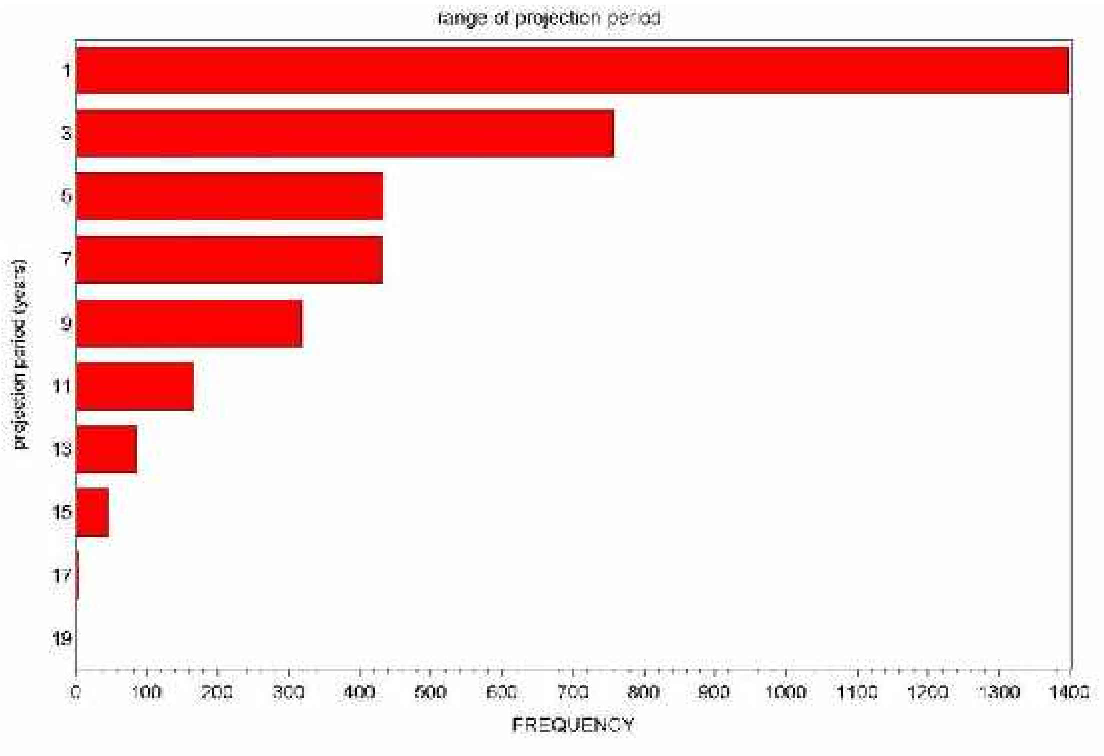
The ITGM models were designed to grow data forward from mid-rotation, and consequently the starting age of the simulations was no younger than 13 years. A few simulations started towards the end of the rotation (Figure 1).



Note: values on the vertical axis are the mid-point value for each bar.

Figure 1. Bar chart showing the starting age of simulations in years.

The projection period varied from a few months to nearly 20 years, with shorter projection periods being more frequent (Figure 2).



Note: values on the vertical axis are the mid-point value for each bar.

Figure 2. Bar chart showing the distribution of projection period in years.

For each simulation the difference (actual – predicted) was calculated for three variables: mean top height (MTH), basal area per ha, and stems per hectare.

The performance of the three models in predicting the above three variables was examined visually by plotting the differences against projection period.

Figure 3 shows the errors in predicting MTH using the three models. The following points may be noted:

- The performance of all three models is similar.
- While MTH is generally predicted to within 2 m, all three models produce large errors in some instances.
- The range in errors for any projection period tends to increase with increasing projection period.

Figure 4 shows the errors in predicting MTH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean error and the trend are similar for all three models.
- Twice the standard deviation is similar for all three models, but generally slightly wider for ITGM.

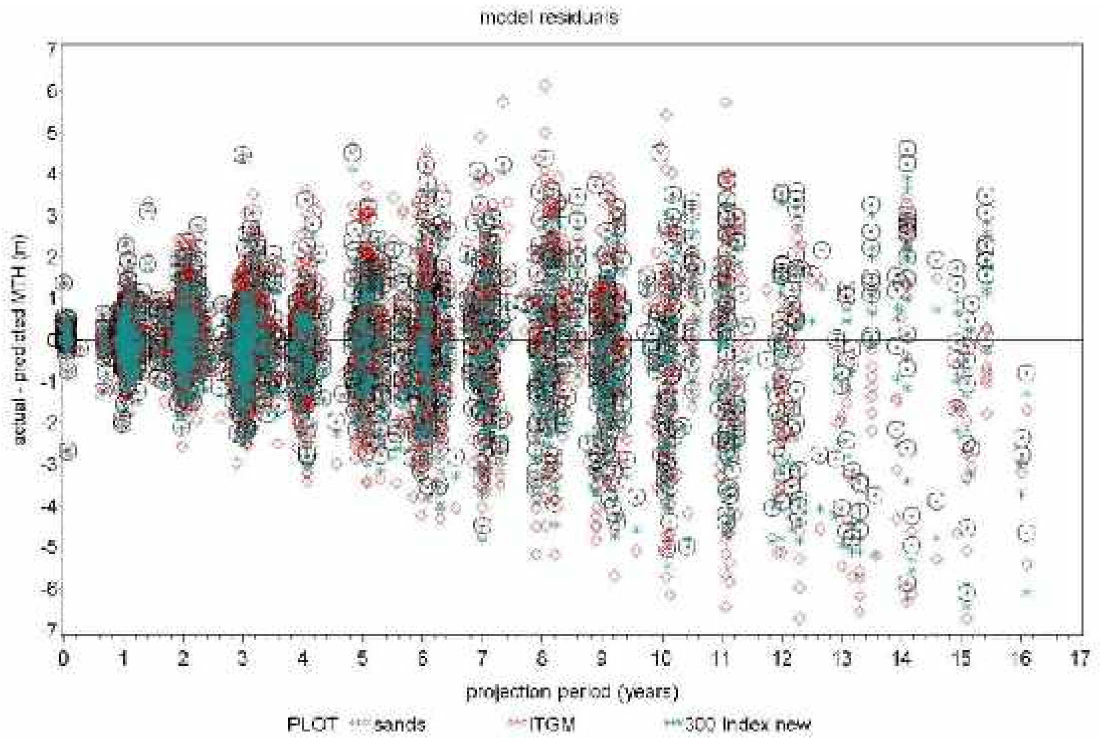


Figure 3. Graph showing actual – predicted mean top height from the Sands, ITGM and 300 Index growth models.

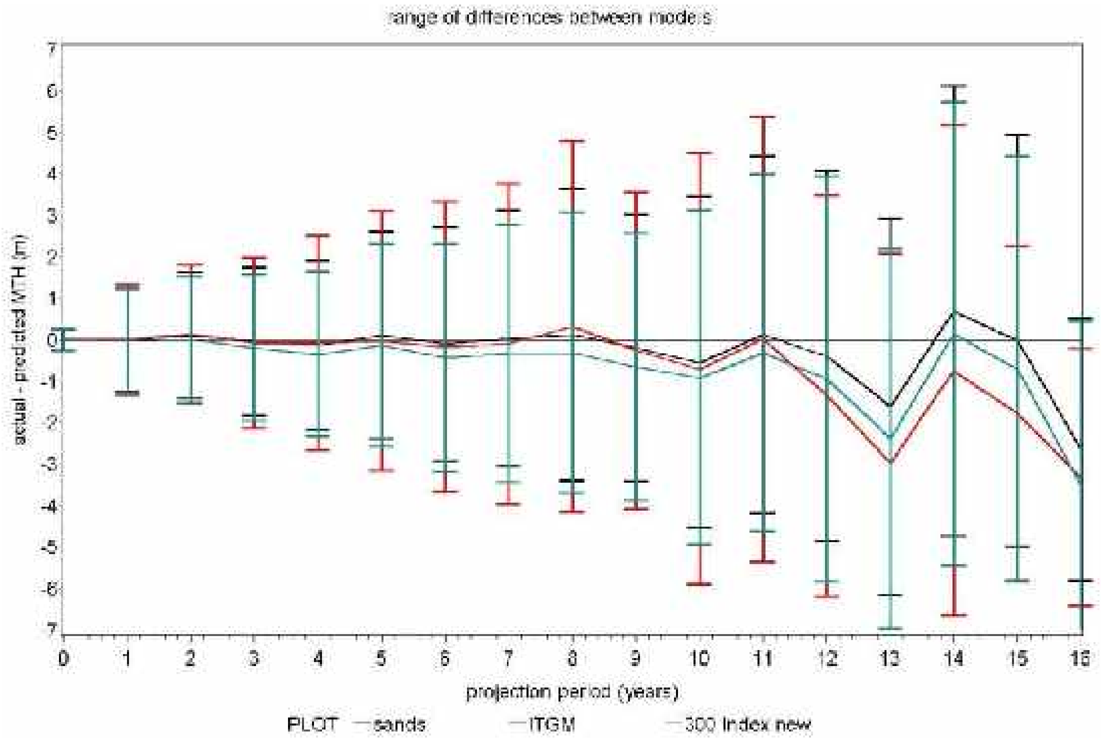


Figure 4. Graph showing mean and two standard deviations for actual – predicted mean top height where projection period has been rounded to the nearest integer.

Figure 5 shows the errors in predicting basal area per hectare (BA/ha) using the three models. The following points may be noted:

- The 300 index tends to predict less basal area than observed (actual – predicted basal area is positive).
- Sands and ITGM tend to predict more basal area than observed (actual – predicted basal area is negative).
- While BA/ha is generally predicted to within 10 m^2/ha, there are larger errors for all three models.

Figure 6 shows the errors in predicting BA/ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- It shows that the mean error tends to be positive for the 300 Index model, and similar but negative for the Sands and ITGM models.
- The standard deviation is similar for all three models and tends to increase with increasing projection period.

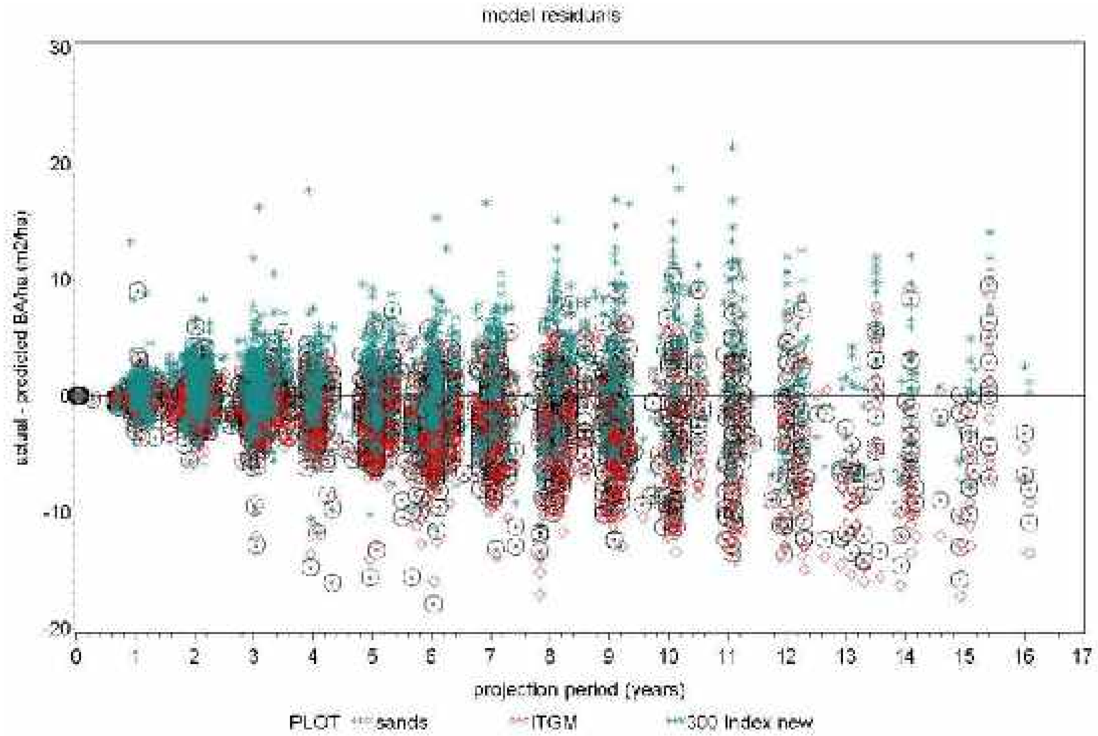


Figure 5. Graph showing actual – predicted basal area from the Sands, ITGM and 300 Index growth models.

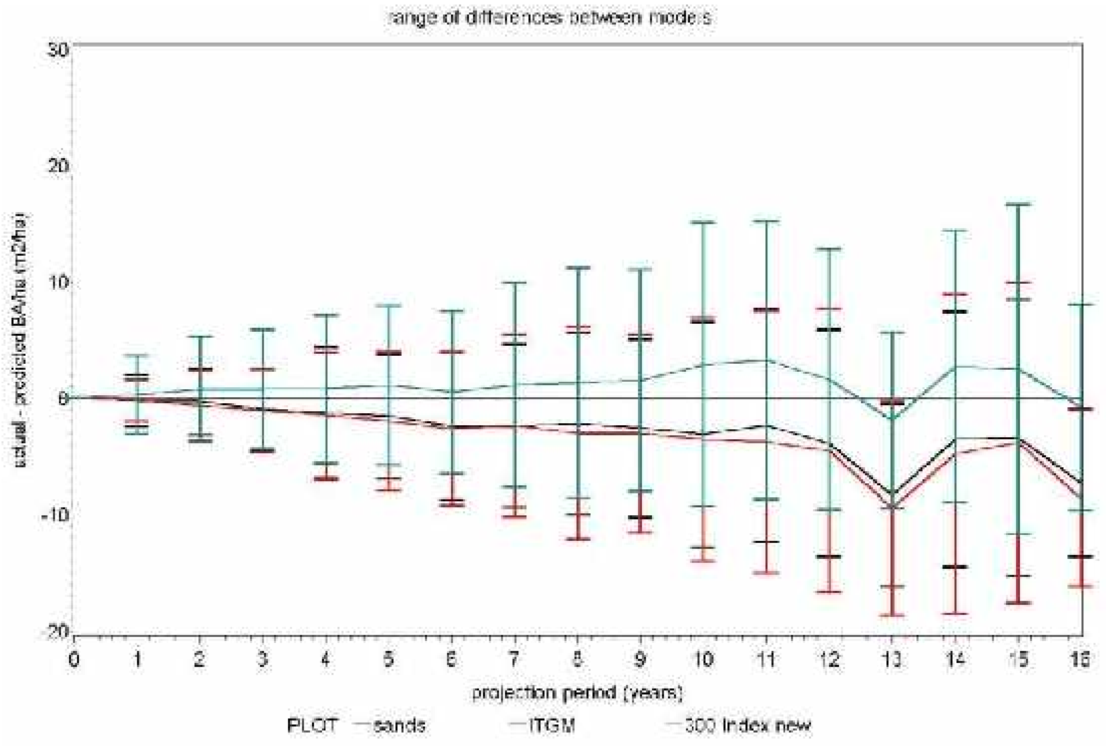


Figure 6. Graph showing mean and two standard deviations for actual – predicted basal area where projection period has been rounded to the nearest integer.

Figure 7 shows the errors in predicting stems per hectare (SPH) using the three models. The following points may be noted:

- All three models produce similar results.
- The difference between actual and predicted SPH is generally less than 100, but there are some large errors using all three models.

Figure 8 shows the errors in predicting SPH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean is similar and close to zero for all three models.
- The standard deviation is similar for all three models, but is generally slightly larger for the Sands model.
- The standard deviation does not tend to increase with increasing projection period.

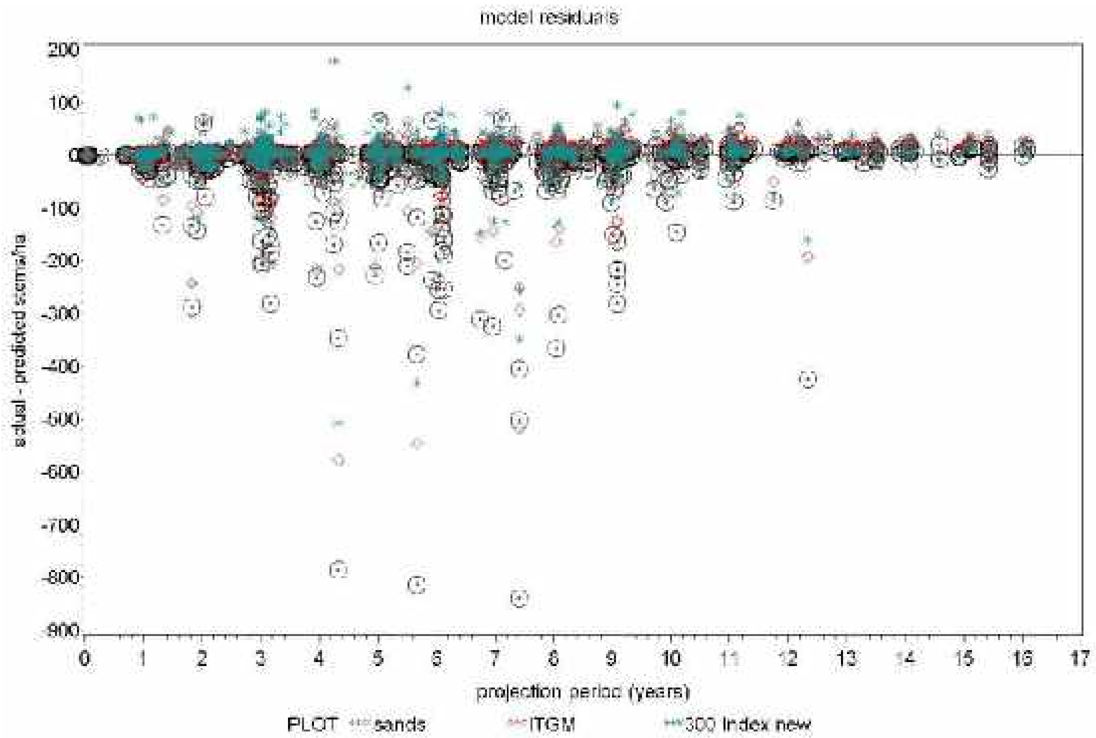


Figure 7. Graph showing actual – predicted stems/ha (SPH) from the Sands, ITGM and 300 Index growth models.

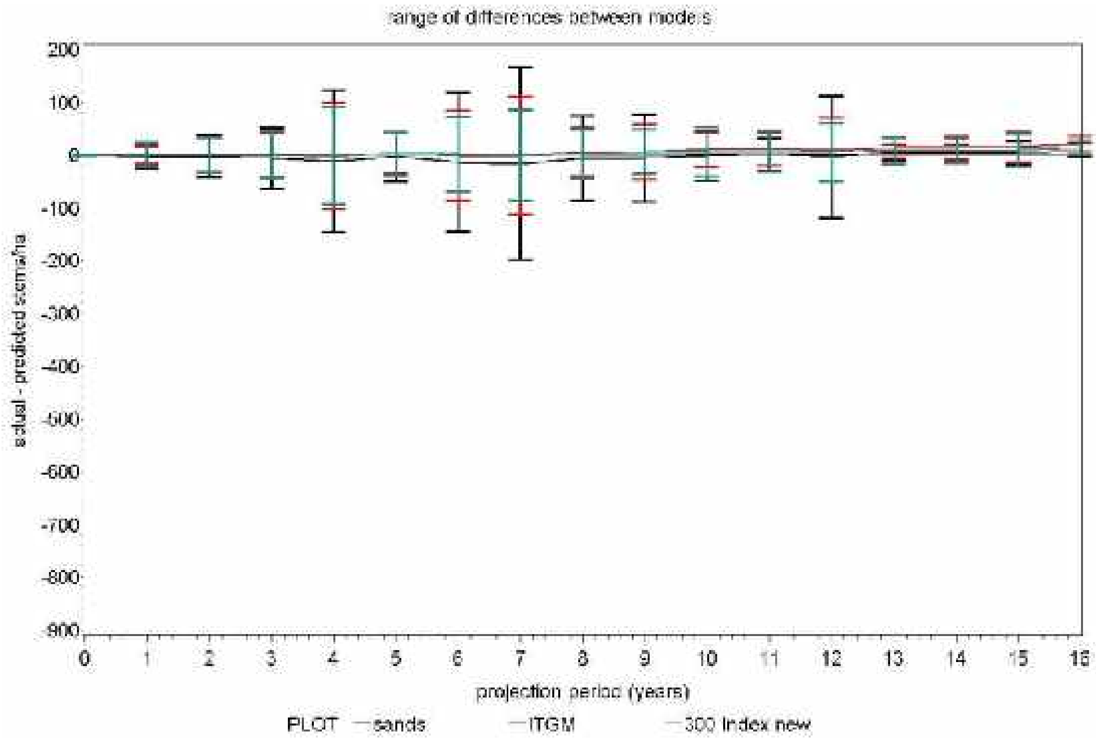


Figure 8. Graph showing mean and two standard deviations for actual – predicted stems/ha where projection period has been rounded to the nearest integer.

It is also important to identify whether there are any independent variables that may influence the model results. Any such variables that are shown to be important may be considered for inclusion in future model development if required.

For this study four variables were examined:

- Previous land use
- Number of height trees used to estimate site index
- Knowledge of silvicultural history
- Genetic rating for the planted trees

In the PSP system, many different descriptors have been used for previous land use. They have been summarised into five categories for this analysis (see below):

Previous land use for this analysis	Previous land use from PSP system
Plantation	Exotic plantation
Farmland	Farmland Pasture
Native vegetation	Indigenous grassland Native scrub Indigenous scrub
Open sand	Open sand SANDS
Unknown	Scrub Not recorded

The number of height trees was divided into two categories:

- Less than 10 height trees
- 10 or more height trees

Knowledge of silvicultural history was divided into two categories:

- Information on silvicultural history stored in PSP system
- No information on silvicultural history stored in PSP system.

The genetic (GF) rating was divided into three categories:

- Less than or equal to seven (i.e. unimproved to climbing select seedlot)
- 14 (i.e. 1st generation of seed orchard improvement)
- greater than 14 (i.e. later generations of improvement)

There were multiple simulations for most plots due to different start age and different projection period. To account for the varying projection period, the residual (actual – predicted value) was divided by the length of the projection period, and then an "average" error was calculated for each plot.

The significance of the above four classification variables was tested using the "average" error in the SAS Proc Mixed procedure. The tables below show the significance of these factors for the different models and the different predicted variables (basal area (BA), mean top height (MTH) and stocking (SPH)). The number reported is the probability of being greater than the calculated F value. Low probabilities indicate a significant effect.

Previous land use

	Sands	ITGM	300Index
BA	0.0207	0.5728	0.0001
MTH	0.0039	0.0005	0.0009
SPH	0.3539	0.4299	0.1624

Height trees

	Sands	ITGM	300Index
BA	0.8643	0.3090	0.6163
MTH	0.0033	0.0057	0.0045
SPH	0.7669	0.8186	0.8832

Silviculture

	Sands	ITGM	300Index
BA	< 0.0001	0.0128	0.0642
MTH	0.7413	0.5418	0.9465
SPH	0.0107	0.0786	0.5671

GF rating

	Sands	ITGM	300Index
BA	0.4340	0.2896	< 0.0001
MTH	0.3969	< 0.0001	0.8328
SPH	0.5413	0.8066	0.1965

Graphs were plotted to illustrate the more significant differences (highlighted in tables above). Each graph shows the mean value and two standard deviations when the projection period is rounded to the nearest integer.

For these graphs, it was decided to allow SAS to choose the scale automatically so that no data points are missed when using the same generic code for different regions.

Previous land use

Figure 9 shows variation in “actual – predicted basal area” for different land uses with the 300 index model. Points to note:

- The mean difference is similar for small projection periods.
- For longer projection periods, the mean predicted basal area is often positive, i.e. predicted basal area is less than observed.

Figure 10 shows the variation in “actual – predicted mean top height” for different land uses with the ITGM model. Points to note:

- There is an obvious trend in the mean difference when the previous land use is “Open Sand”, or “Plantation”.

Figure 11 shows the variation in “actual – predicted mean top height” for different land uses with the 300 Index model. Points to note:

- There is an obvious trend in the mean difference when the previous land use is “Open Sand”, or “Plantation”. The trend is similar to that predicted by the ITGM model (see Figure 10).

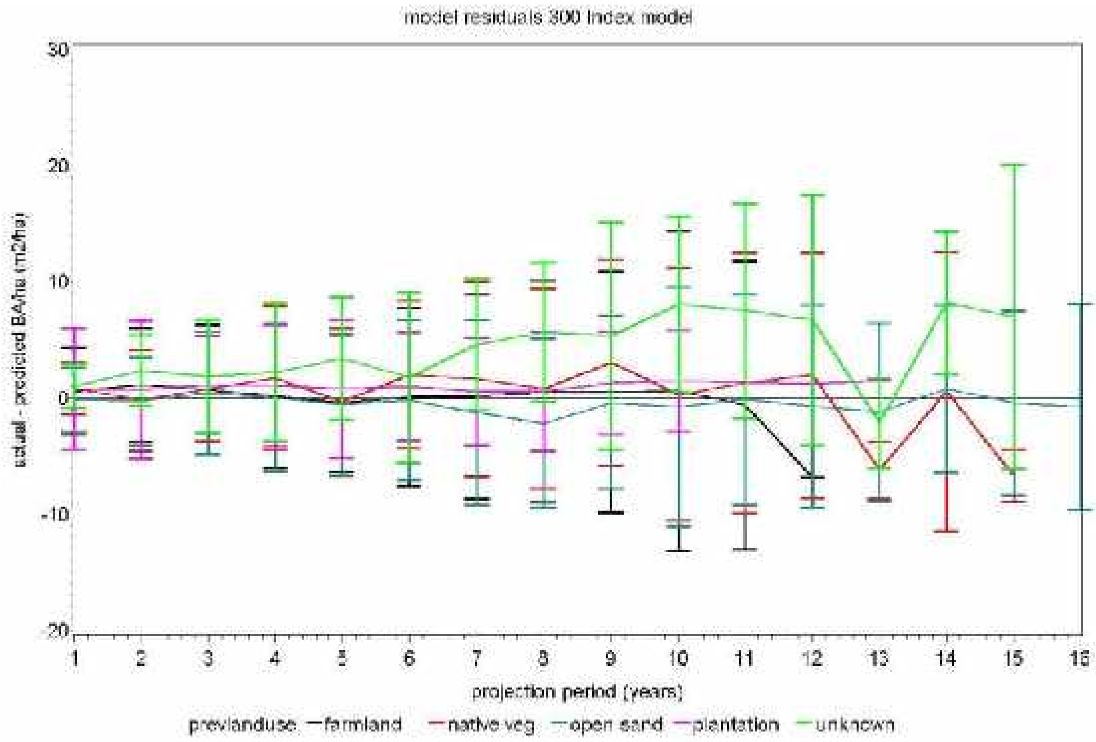


Figure 9. Graph showing mean and two standard deviations for actual – predicted basal area using the 300 Index model where projection period has been rounded to the nearest integer.

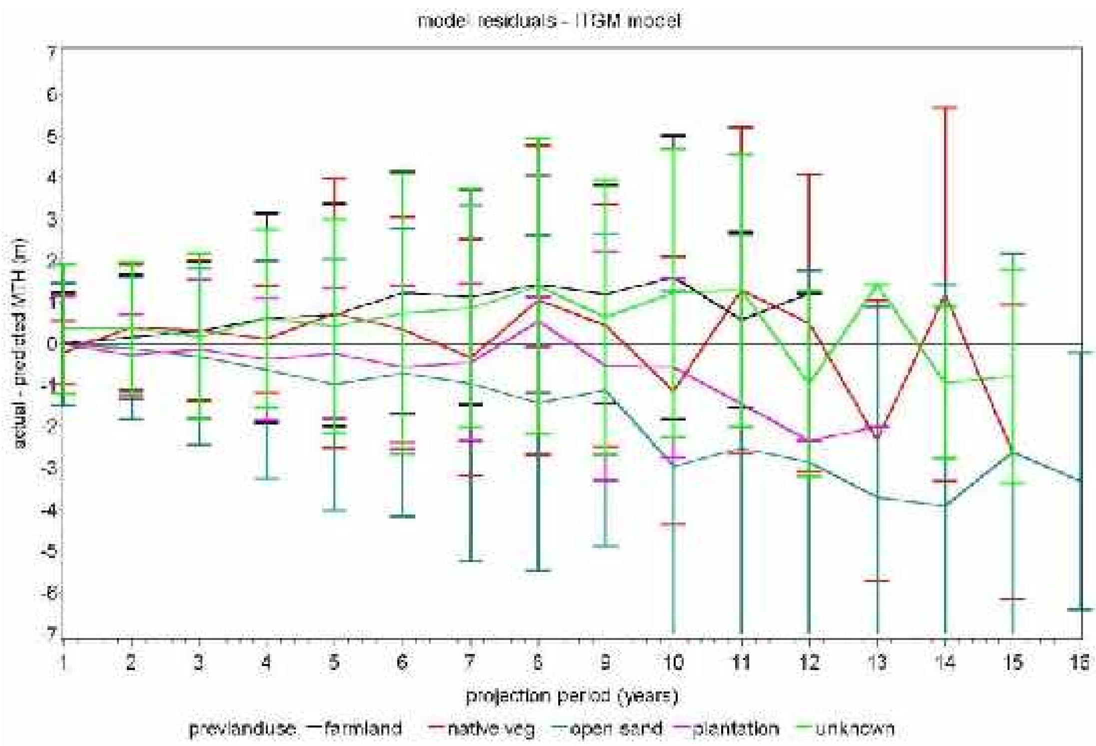


Figure 10. Graph showing mean and two standard deviations for actual – predicted mean top height using the ITGM model where projection period has been rounded to the nearest integer.

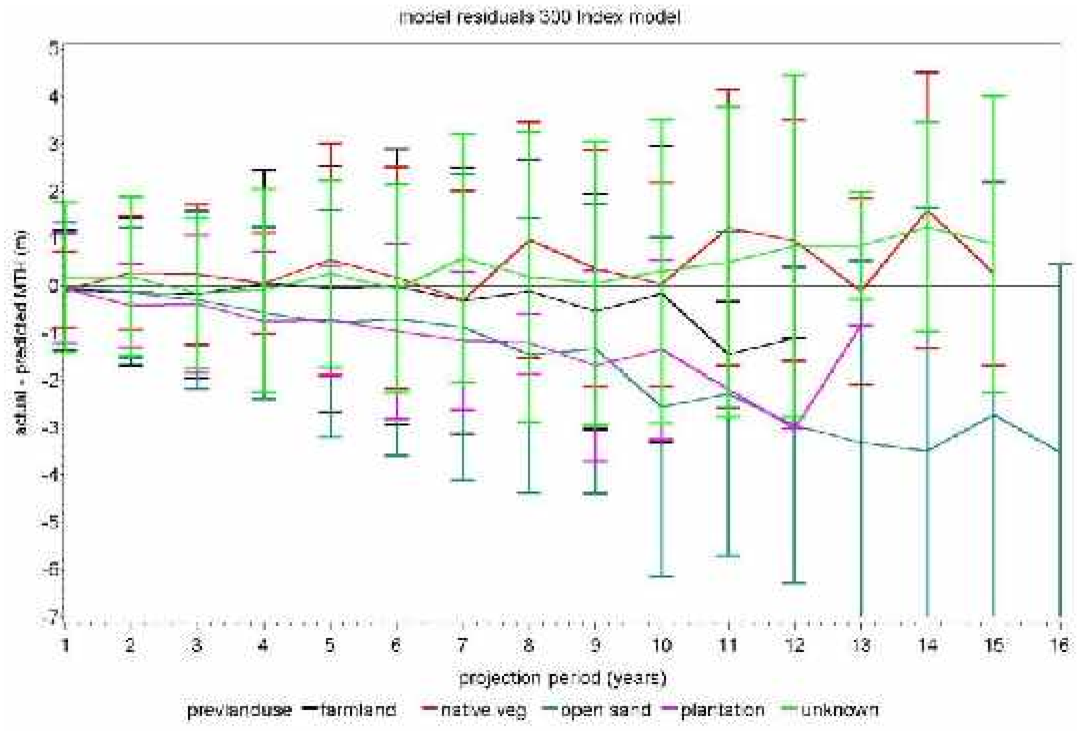


Figure 11. Graph showing mean and two standard deviations for actual – predicted mean top height using the 300 Index model where projection period has been rounded to the nearest integer.

Silviculture

Figure 12 shows variation in "actual – predicted basal area" for the two silviculture classes with the Sands model. Points to note:

- Both classes of silviculture show the same trend.
- Generally the model performance is slightly better when the silviculture is known.

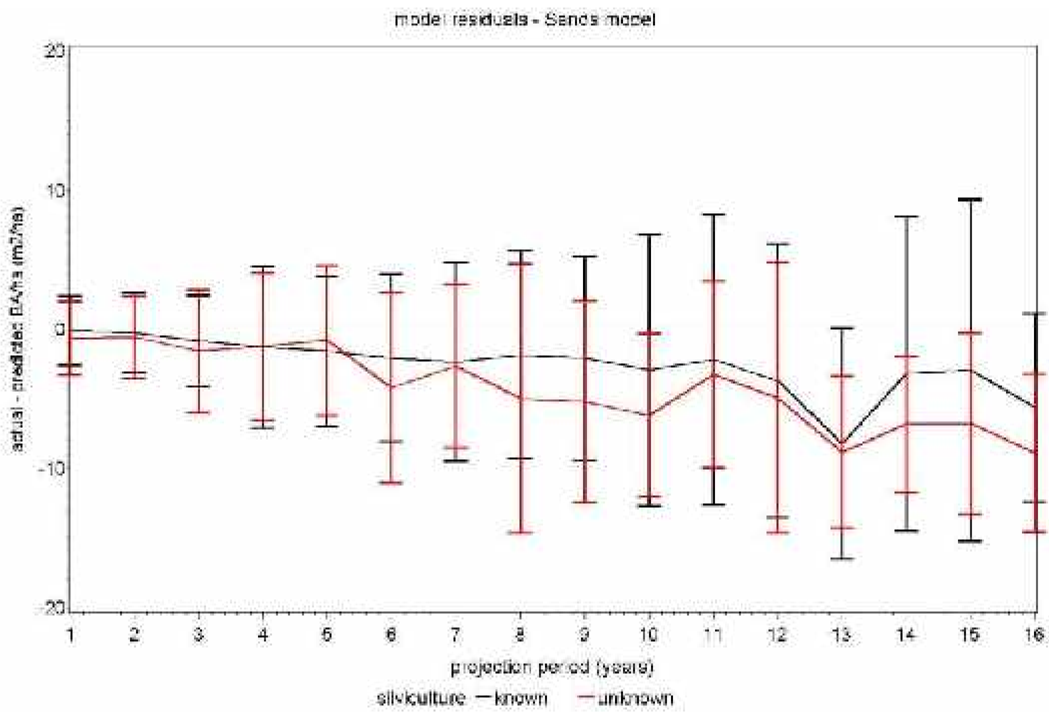


Figure 12. Graph showing mean and two standard deviations for actual – predicted basal area using the sands model where projection period has been rounded to the nearest integer.

GF rating

Figure 13 shows variation in “actual – predicted basal area” for different seedlots with the 300 Index model. Points to note:

- The mean difference is similar for small projection periods.
- “Actual – predicted basal area” becomes more positive with longer projection periods for the GF 14 seedlot.

Figure 14 shows the variation in “actual – predicted mean top height” for different seedlots with the ITGM model. Points to note:

- Actual – predicted mean top height tends to be positive for seedlots with a rating of GF14 or greater.
- Actual – predicted mean top height tends to be negative for seedlots with a GF rating of seven or less.

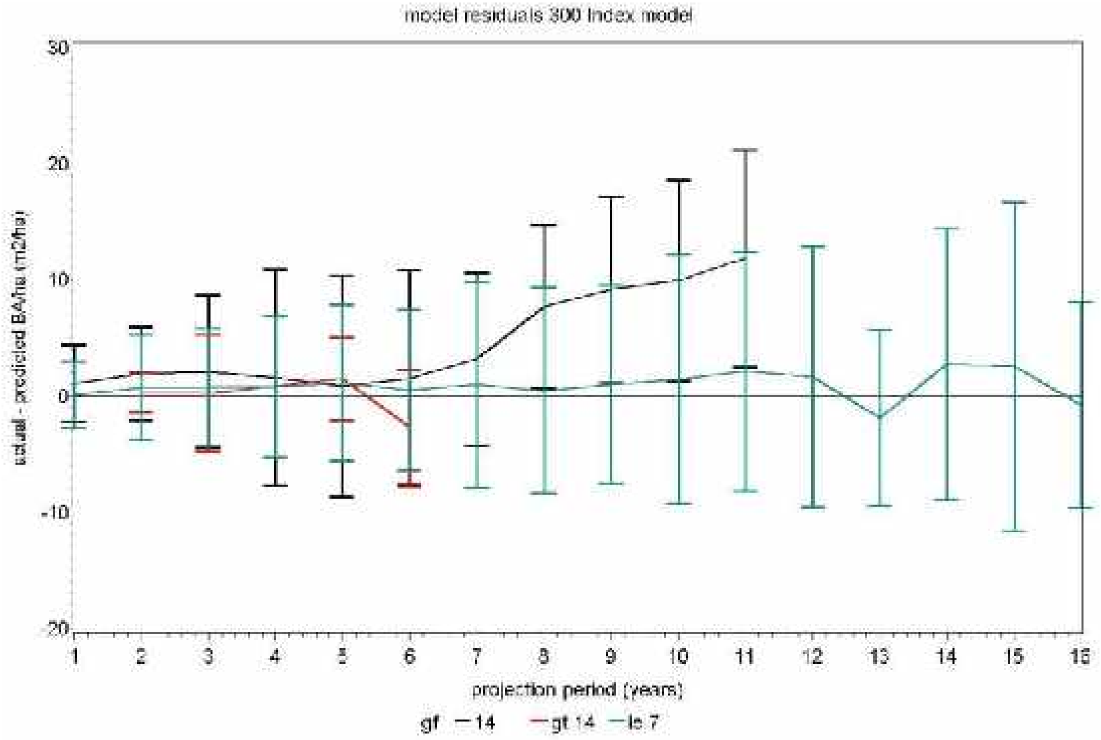


Figure 13. Graph showing mean and two standard deviations for actual – predicted basal area using the 300 Index model where projection period has been rounded to the nearest integer.

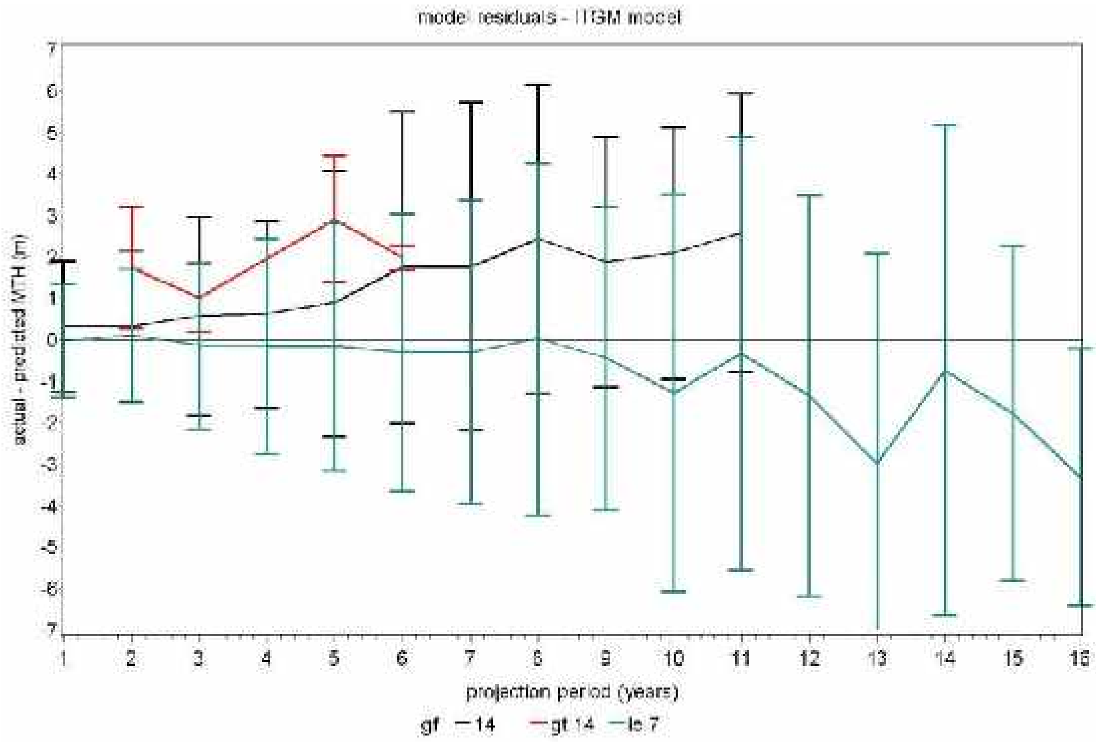


Figure 14. Graph showing mean and two standard deviations for actual – predicted mean top height using the ITGM model where projection period has been rounded to the nearest integer.

The above graphs show that there are differences in the model predictions with different classification variables. However it needs to be borne in mind that these differences are more when the projection period is longer and there are less data points.

Performance of models in Clays Growth Modelling Region

The ITGM models were designed to growth data forward from after mid-rotation. For the Clays region, the majority of the simulations started between ages 14 and 24 years (Figure 15).

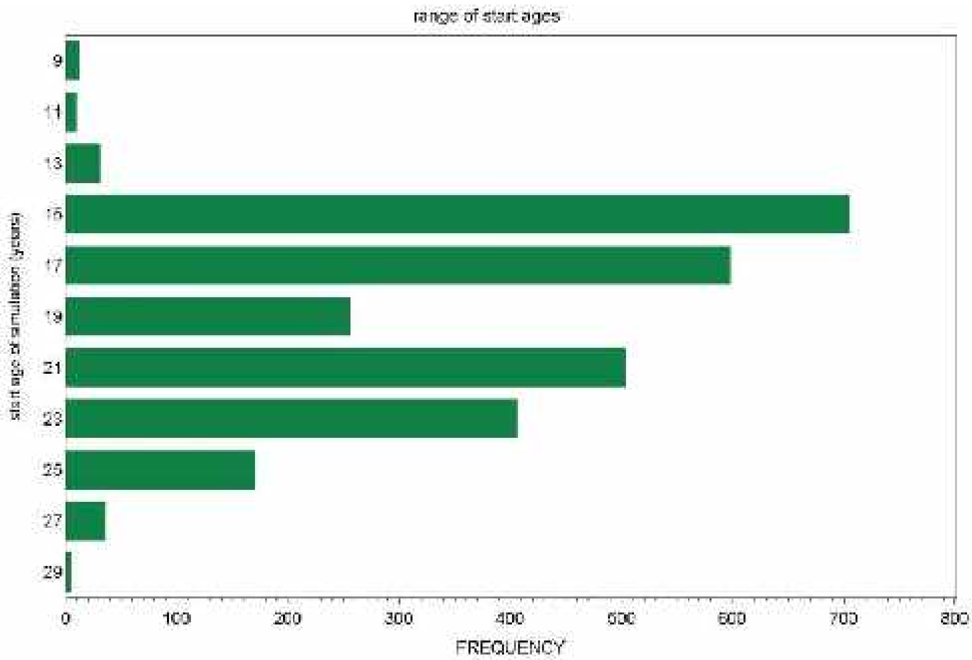


Figure 15. Bar chart showing the starting age of simulations in years.

The projection period varied from a few months to 16 years, with shorter projection periods being more frequent (Figure 16).

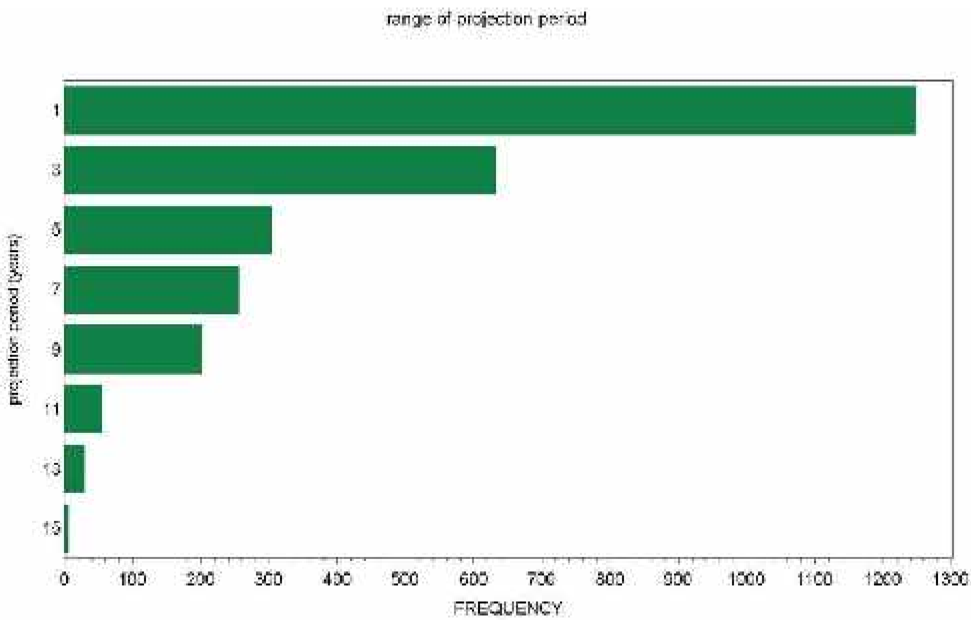


Figure 16. Bar chart showing the distribution of projection period in years.

Figure 17 shows the individual residuals in predicting MTH using the three models. The following points may be noted:

- All three models perform similarly as shown by the large blocks of colour. For longer projection periods, there are some positive residuals for the Clays model, and some negative residuals for the ITGM and 300 Index models.
- There is a slight trend for the range of residual values to increase with increasing projection period.

Figure 18 shows the errors in predicting MTH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean residual is positive for the Clays model, and increases with increasing projection period.
- The mean residual is similar and negative for both the ITGM and 300 Index model.
- The standard deviation increases with increasing projection period.

Figure 19 shows the mean and two standard deviations for the absolute error in MTH predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The absolute error is similar for all three models for projection periods of up to 10 years.
- There are small differences between the models with longer projection period, but the number of simulations is small.
- The standard deviation increases with increasing projection period.

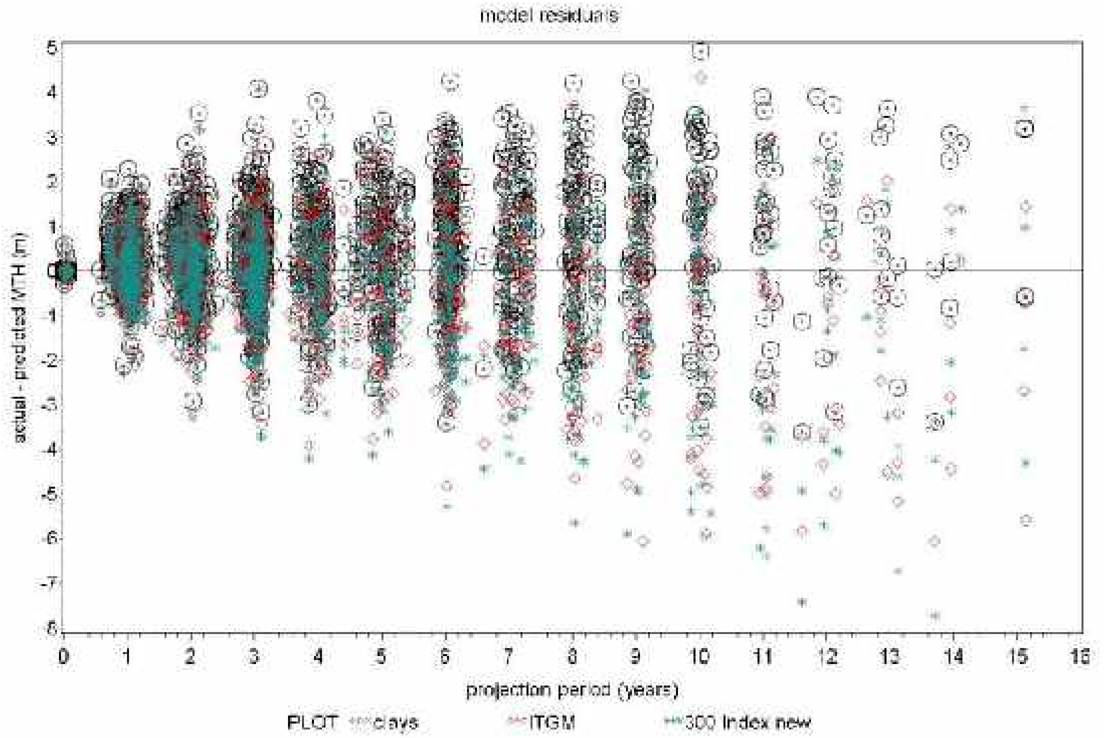


Figure 17. Graph showing actual – predicted mean top height from the Clays, ITGM and 300 Index growth models.

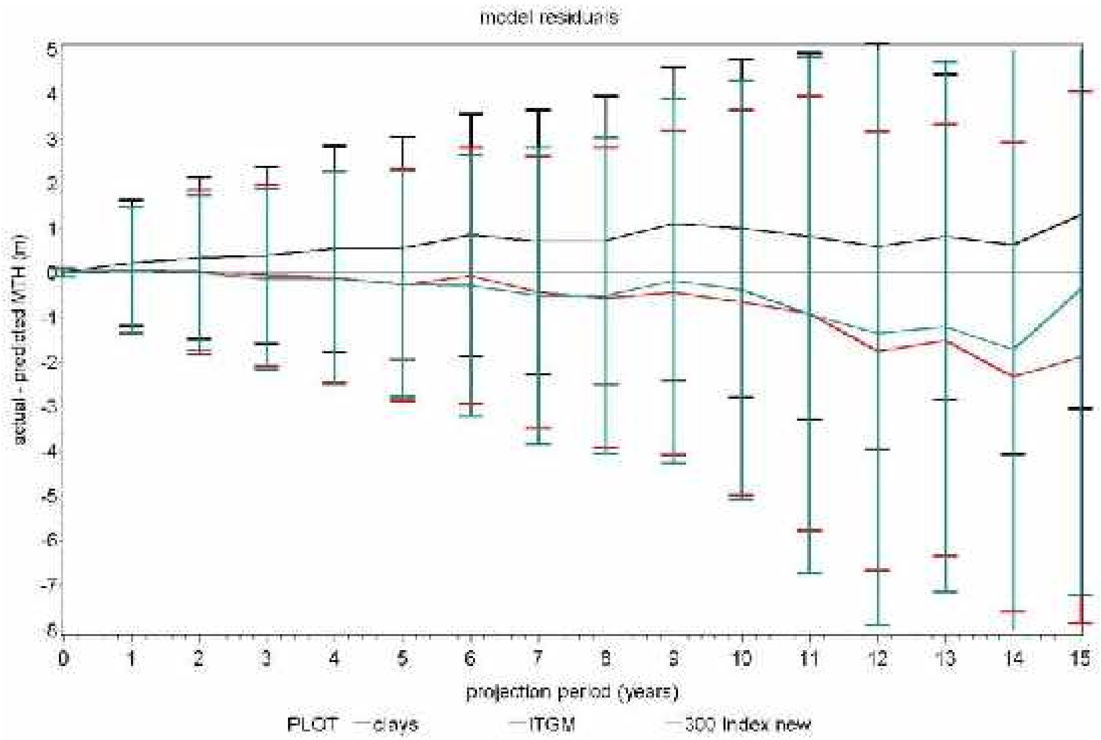


Figure 18. Graph showing mean and two standard deviations for actual – predicted mean top height where projection period has been rounded to the nearest integer.

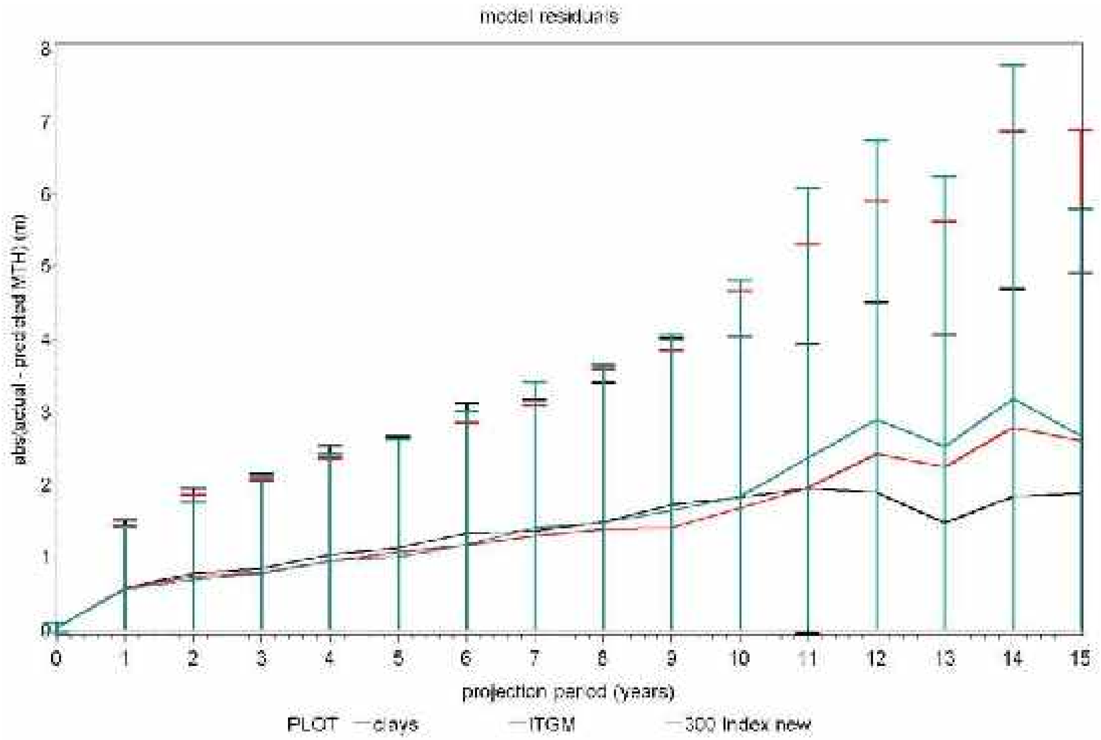


Figure 19. Graph showing mean and two standard deviations for the absolute value of actual – predicted mean top height where projection period has been rounded to the nearest integer.

Figure 20 shows the individual residuals in predicting basal area per hectare using the three models. The following points may be noted:

- There is a tendency for the residuals from the ITGM model to be negative.
- There is a tendency for the residuals from the 300 Index model to be positive.

- The range in residuals tends to increase with increasing projection period.

Figure 21 shows the errors in predicting basal area per ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean residual is similar and positive for both the Clays and 300 Index model.
- The mean residual is negative for the ITGM model.
- The size of the standard deviation is similar for all three models
- The standard deviation around the mean value increases with increasing projection period.

Figure 22 shows the mean and two standard deviations for the absolute error in stems per ha predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean absolute residual is similar for all three models for projection periods up to approximately nine years.
- For longer projection periods, the mean absolute residual tends to be larger for the ITGM model.

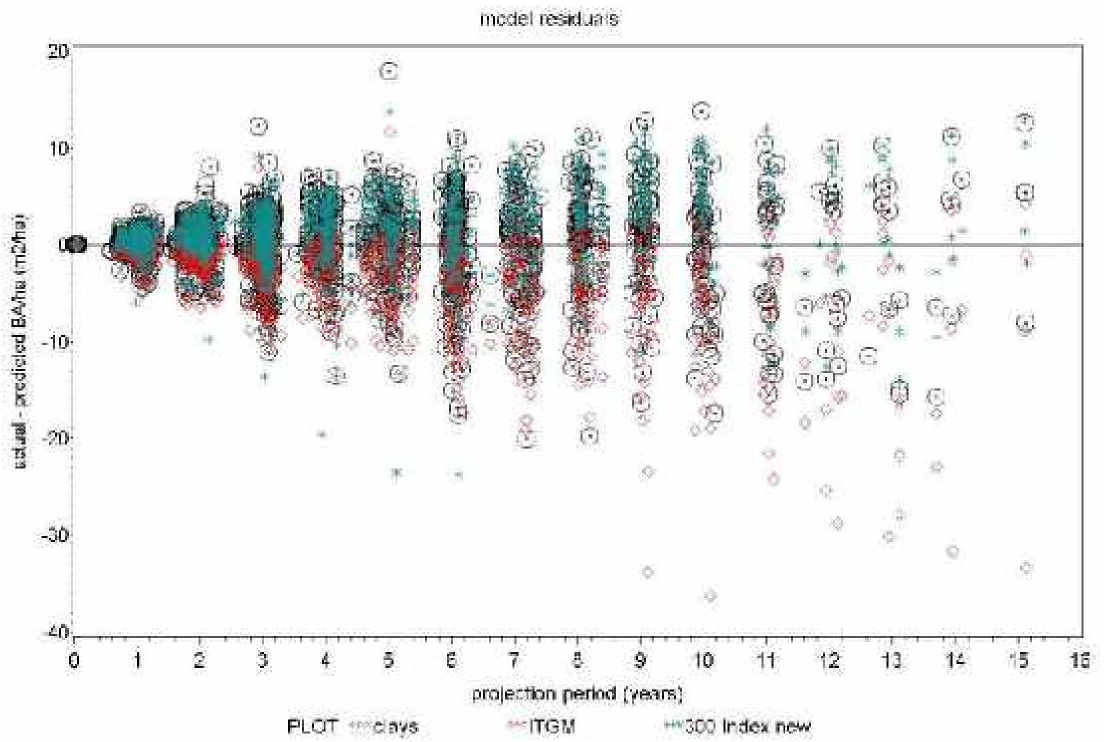


Figure 20. Graph showing actual – predicted basal area from the Clays, ITGM and 300 Index growth models.

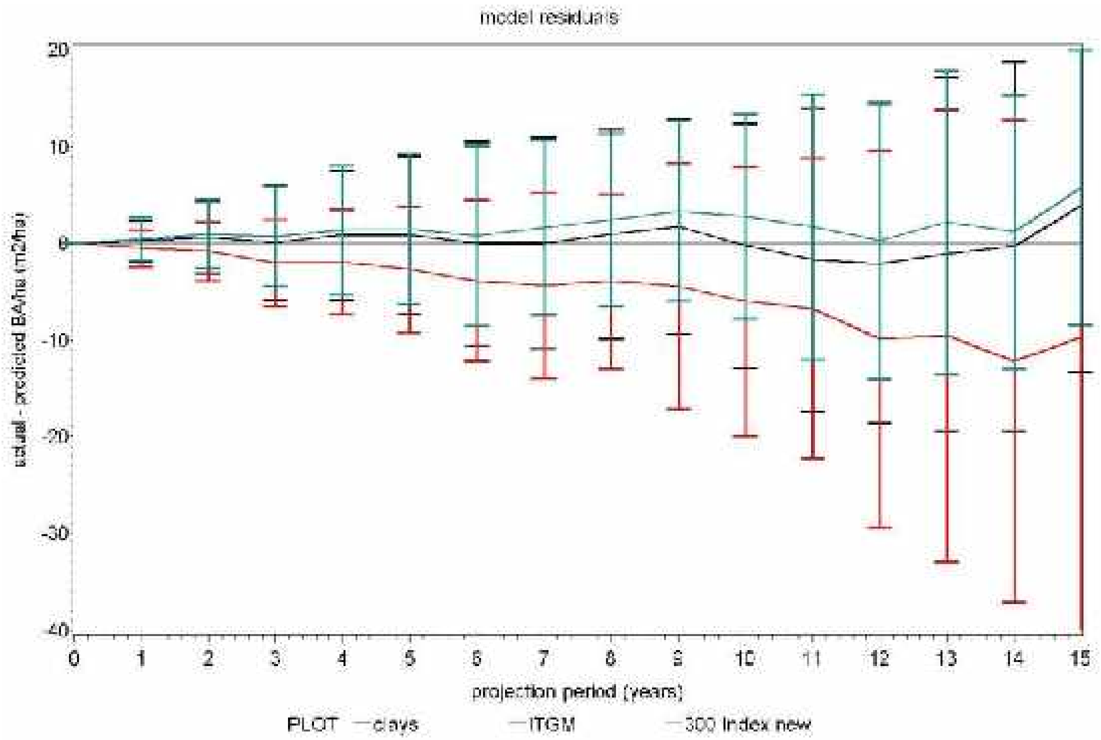


Figure 21. Graph showing mean and two standard deviations for actual – predicted basal area where projection period has been rounded to the nearest integer.

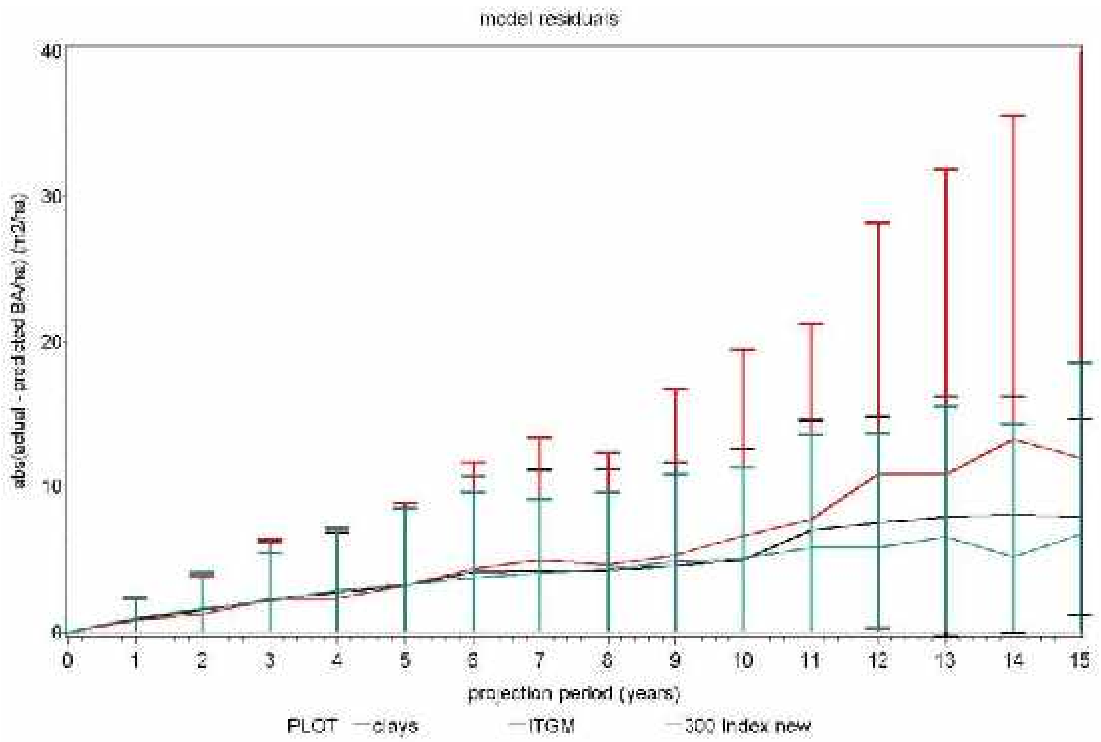


Figure 22. Graph showing mean and two standard deviations for the absolute value of actual – predicted basal area per ha where projection period has been rounded to the nearest integer.

Figure 23 shows the individual residuals in predicting stems per hectare using the three models. The following points may be noted:

- Apart from a few simulations, the three models perform similarly. This is indicated by the large blocks of colour where one can see black and red below the blue colour.

Figure 24 shows the errors in predicting stems per ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean error is similar for all three models.
- The standard deviation tends to increase with increasing projection period.
- The standard deviation tends to be larger for the Clays model. This is the result of the few large negative errors visible in Figure 23.

Figure 25 shows the mean and two standard deviations for the absolute error in stems per ha predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean absolute error is similar for all three models for any projection period.
- The standard deviation tends to be larger for the Clays model. This is the result of the few large negative errors visible in Figure 23.

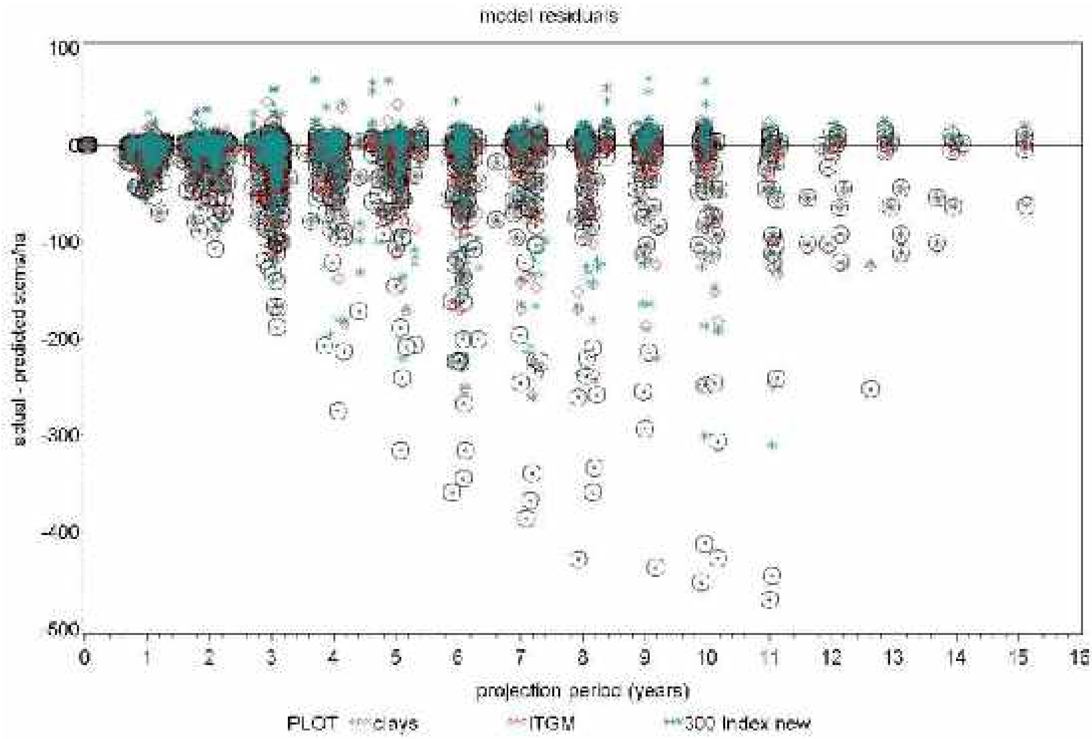


Figure 23. Graph showing actual – predicted stems/ha (SPH) from the Clays, ITGM and 300 Index growth models.

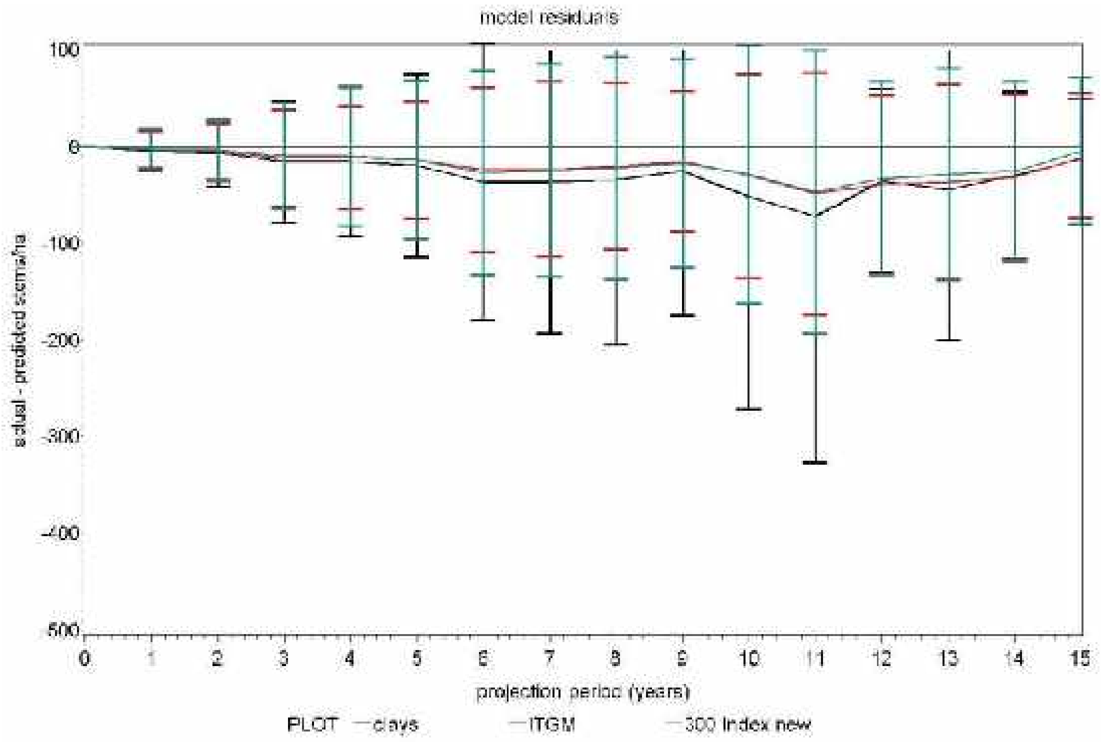


Figure 24. Graph showing mean and two standard deviations for actual – predicted stems/ha where projection period has been rounded to the nearest integer.

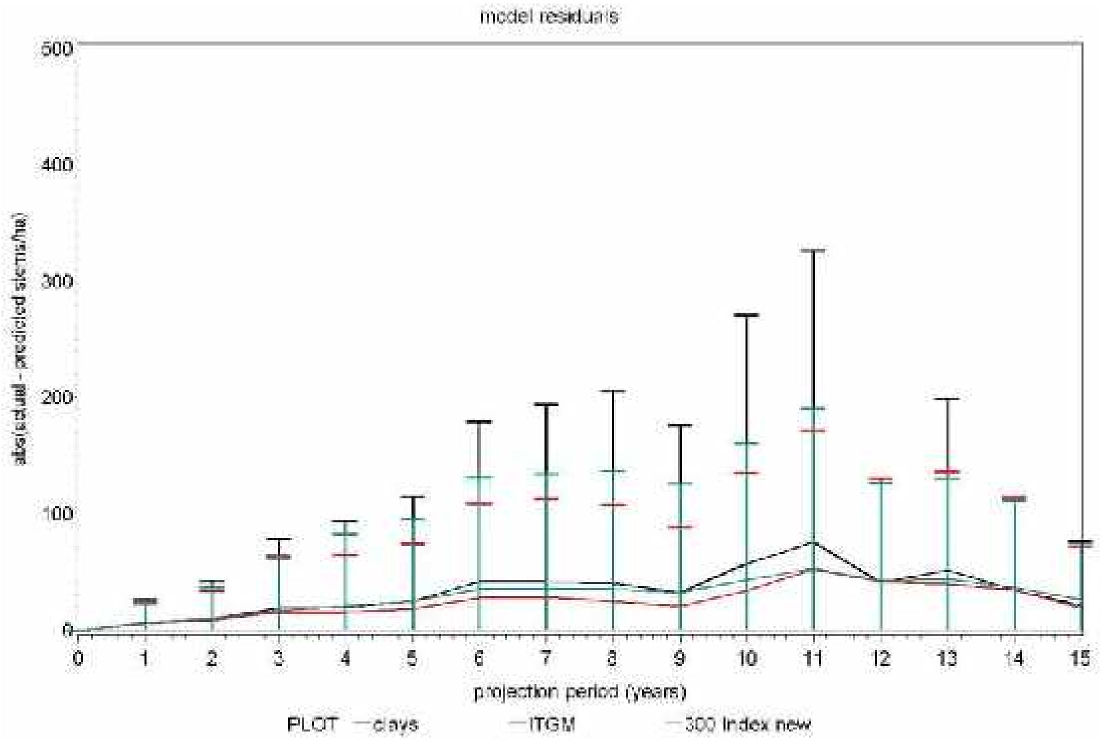


Figure 25. Graph showing mean and two standard deviations for the absolute value of actual – predicted stems per ha where projection period has been rounded to the nearest integer.

It is also important to identify whether there are any independent variables that may influence the model results. Any such variables that are shown to be important may be considered for inclusion in future model development if required.

For this study four variables were examined:

- Previous land use
- Number of height trees used to estimate site index
- Knowledge of silvicultural history
- Genetic rating for the planted trees

In the PSP system, many different descriptors have been used for previous land use. The table below shows how these have been summarised into four categories.

Previous land use for analysis	Previous land use from PSP system
Plantation	Forest (pine)
Farmland	Grass Grazed pasture Pasture Pasture & native fern Pasture & native grass Pasture & native scrub Pasture/scrub Unproductive pasture
Native vegetation	Grass wilding Totara Manuka Manuka scrub Manuka scrub/gorse Manuka/bracken Native scrub Native hardwoods Native bush Native grass Native grass & fern Scrub-Ti tree Native Regen
Unknown	Scrub Not recorded

The number of height trees was divided into two categories:

- Less than 10 height trees
- 10 or more height trees

Knowledge of silvicultural history was divided into two categories:

- Information on silvicultural history stored in PSP system
- No information on silvicultural history stored in PSP system

The genetic (GF) rating was divided into three categories:

- Less than or equal to 7 (i.e. unimproved to climbing select seedlot)
- 14 (i.e. 1st generation of seed orchard improvement)
- greater than 14 (i.e. later generations of improvement)

There were multiple simulations for most plots due to different start age and different projection period. To account for the varying projection period, the residual (actual – predicted value) was divided by the length of the projection period, then an “average” error was calculated for each plot, and then an “average” error was calculated for each plot.

The significance of the above four variables was tested using the “average” error in the SAS Proc Mixed procedure. The tables below show the significance of these factors for the different models and the different predicted variables (basal area (BA), mean top height (MTH) and stocking (SPH)). The number reported is the probability of being greater than the calculated F value. Low probabilities indicate a significant effect.

Previous land use

	CLAYSF	ITGM	300Index
BA	< 0.0001	< 0.0001	0.0040
MTH	0.1769	0.0081	< 0.0001
SPH	0.0150	< 0.0002	0.0021

Height trees

	CLAYSF	ITGM	300Index
BA	0.1438	0.2573	0.0307
MTH	0.0639	0.0072	0.3164
SPH	0.7801	0.2879	0.2555

Silviculture

	CLAYSF	ITGM	300Index
BA	< 0.0001	0.1898	0.8005
MTH	0.2043	0.0028	0.5021
SPH	< 0.0001	< 0.0001	< 0.0032

GF rating

	CLAYSF	ITGM	300Index
BA	0.0053	0.0003	0.0320
MTH	< 0.0001	< 0.0001	0.0300
SPH	0.0042	0.0073	0.0094

Graphs were plotted to illustrate the more significant differences (highlighted in tables above). Each graph shows the mean value and two standard deviations when the projection period is rounded to the nearest integer.

Previous land use

Previous land use generally influences the average error for a plot.
Four model – dependent variable combinations are shown to illustrate the influence of land use.

Figure 26 shows the mean and two standard deviations for actual – predicted basal area using the Clays model. The following points may be noted:

- There were very few simulations where the previous land use was “plantation”. (Simulations with a projection period of 3 years are visible.)
- The mean residual is negative for plots where the previous land use was farmland, i.e. the model tends to predict more basal area than observed.
- The mean residual is positive but closer to zero where the previous land use was either “native vegetation” or “unknown”.

Figure 27 shows the mean and two standard deviations for actual – predicted basal area using the ITGM model. The following points may be noted:

- The difference between this figure and Figure 26 is the growth model used.
- These results for the 300 Index model are very similar to those for the ITGM model.
- Of particular note is the fact that the mean error is negative for plots where the previous land use was “farmland”.

Figure 28 shows the mean and two standard deviations for actual – predicted mean top height using the 300 Index model. The following points may be noted:

- The mean error is negative when the previous land use is farmland.

Figure 29 shows the mean and two standard deviations for actual – predicted stems per hectare using the ITGM model. The following points may be noted:

- The mean error is negative when the previous land use is farmland.

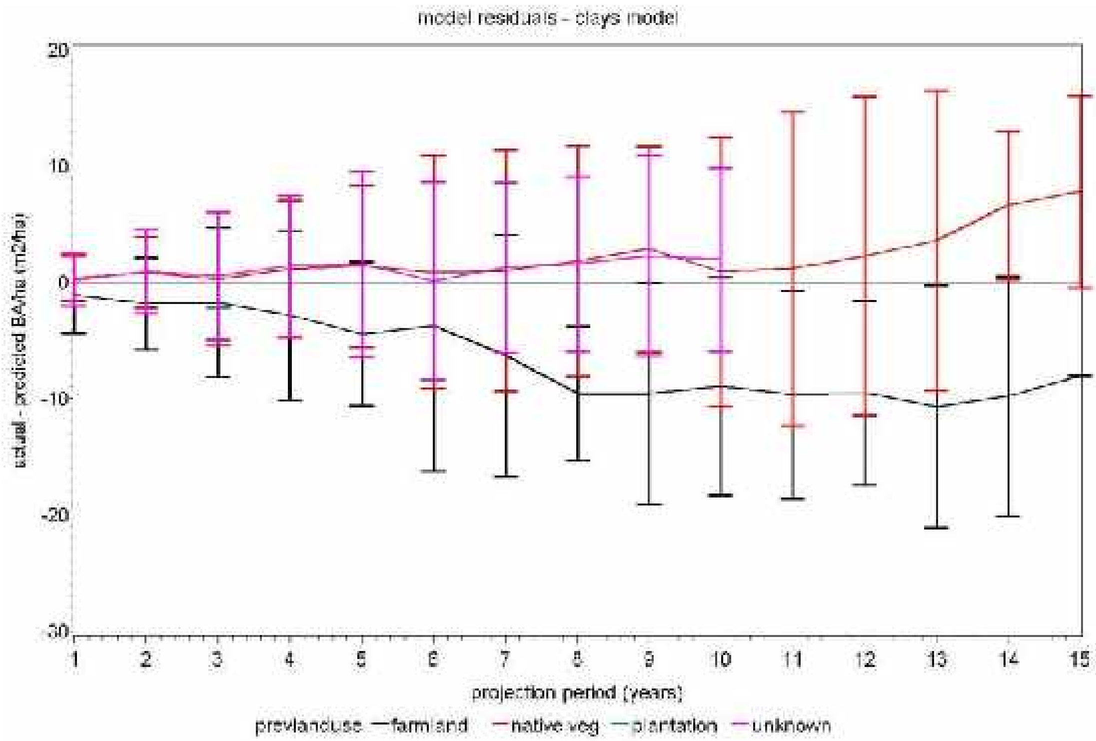


Figure 26. Graph showing mean and two standard deviations for actual – predicted basal area using the Clays model where projection period has been rounded to the nearest integer.

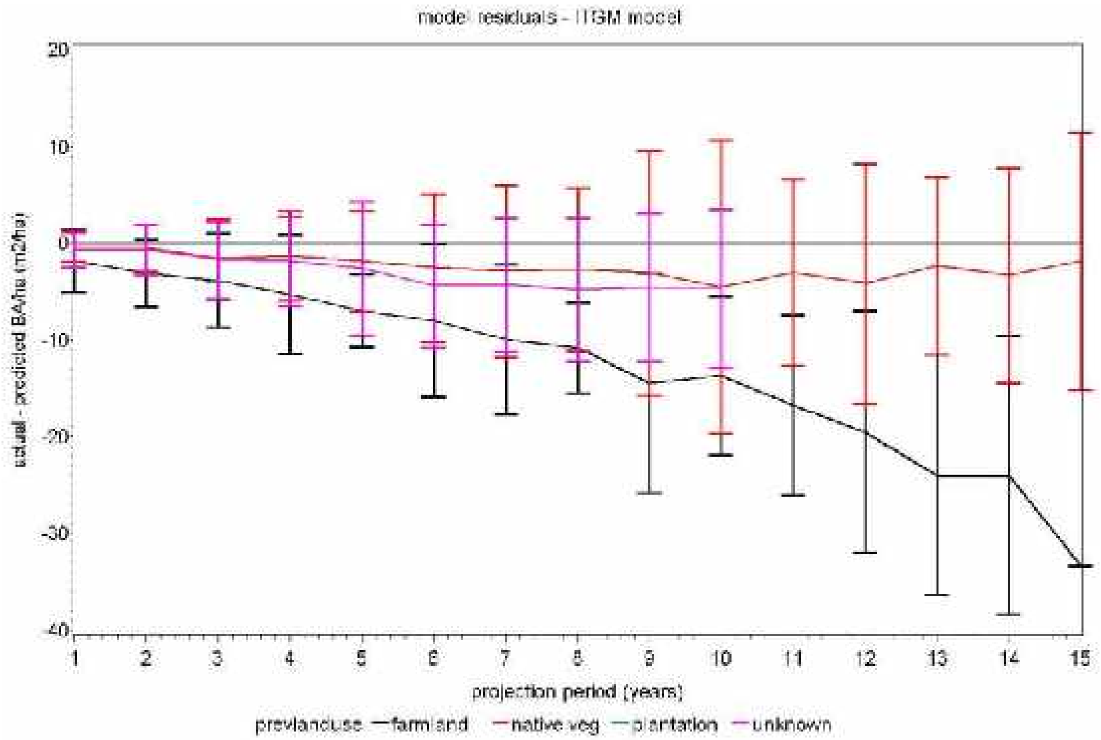


Figure 27. Graph showing mean and two standard deviations for actual – predicted basal area using the ITGM model where projection period has been rounded to the nearest integer.

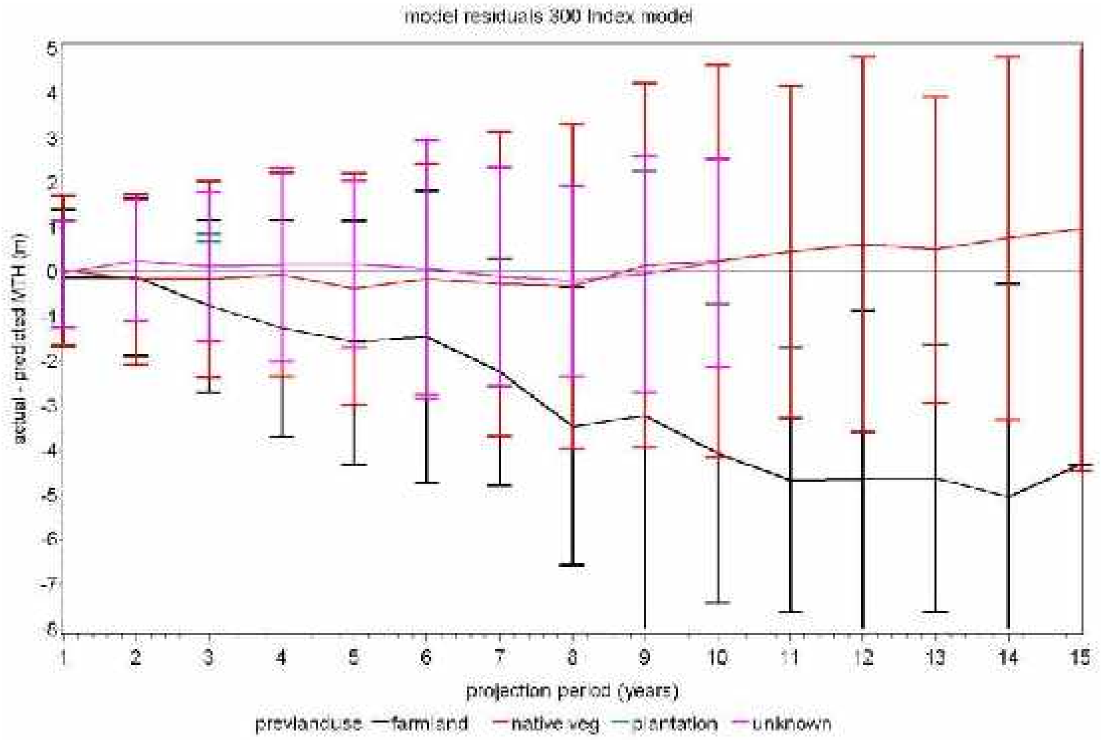


Figure 28. Graph showing mean and two standard deviations for actual – predicted mean top height using the 300 Index model where projection period has been rounded to the nearest integer.

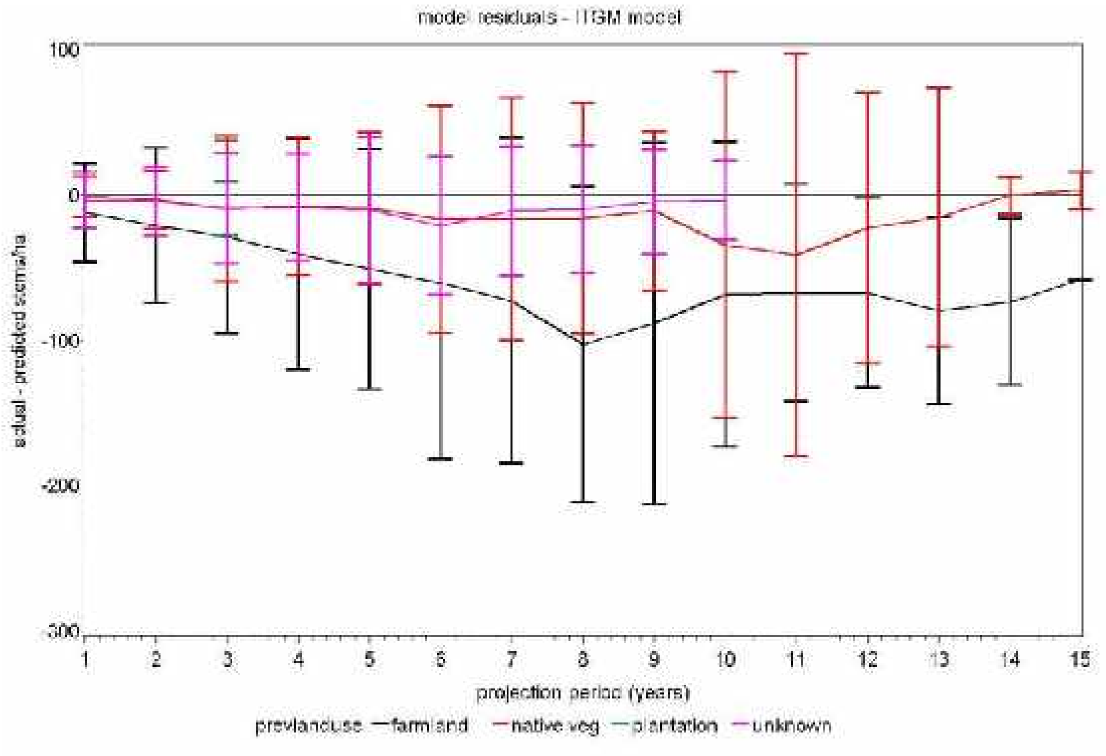


Figure 29. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the ITGM model where projection period has been rounded to the nearest integer.

Silviculture
Knowledge of the silviculture history of the plot may influence the average error for a plot (see above).
Three model – dependent variable combinations are shown to illustrate the influence of silviculture.

Figure 30 shows the mean and two standard deviations for actual – predicted basal area using the Clays growth model.
Figure 31 shows the mean and two standard deviations for actual – predicted stems /ha using the Clays growth model.
Figure 32 shows the mean and two standard deviations for actual – predicted stems /ha using the ITGM growth model.

All three figures indicate that:

- Knowledge of the silviculture history generally results in a slightly smaller mean error for a given projection period.
- The standard deviation is similar, but generally slightly larger when the silvicultural history was unknown.

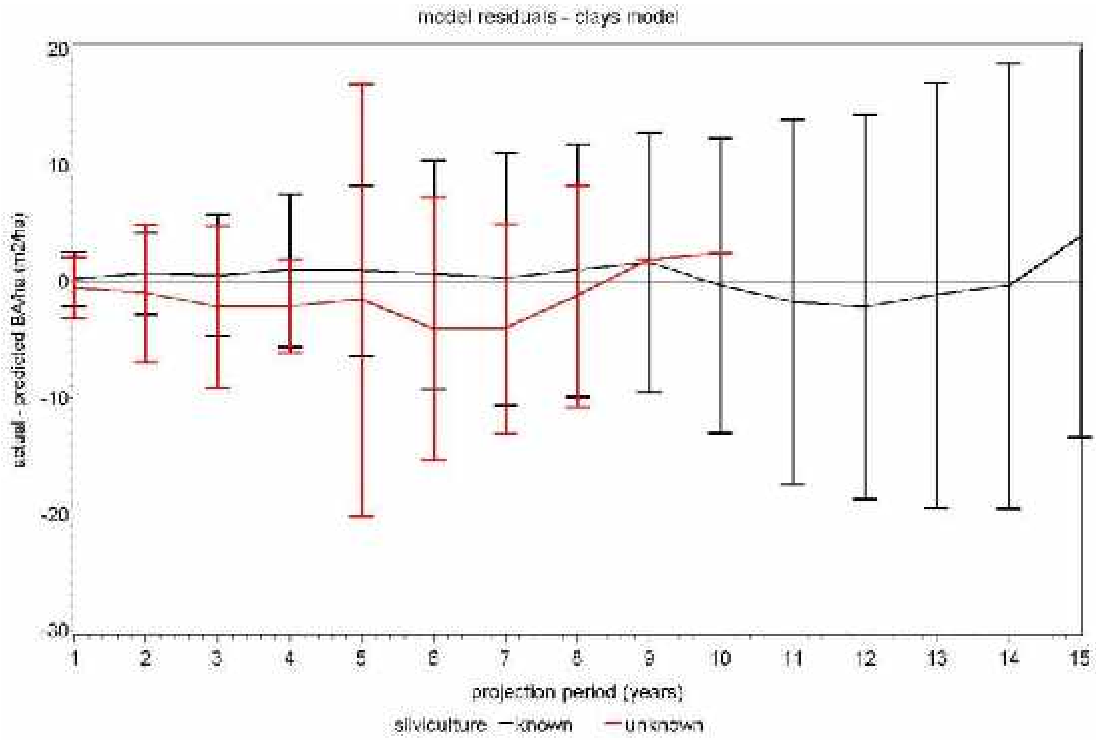


Figure 30. Graph showing mean and two standard deviations for actual – predicted basal area using the Clays model where projection period has been rounded to the nearest integer.

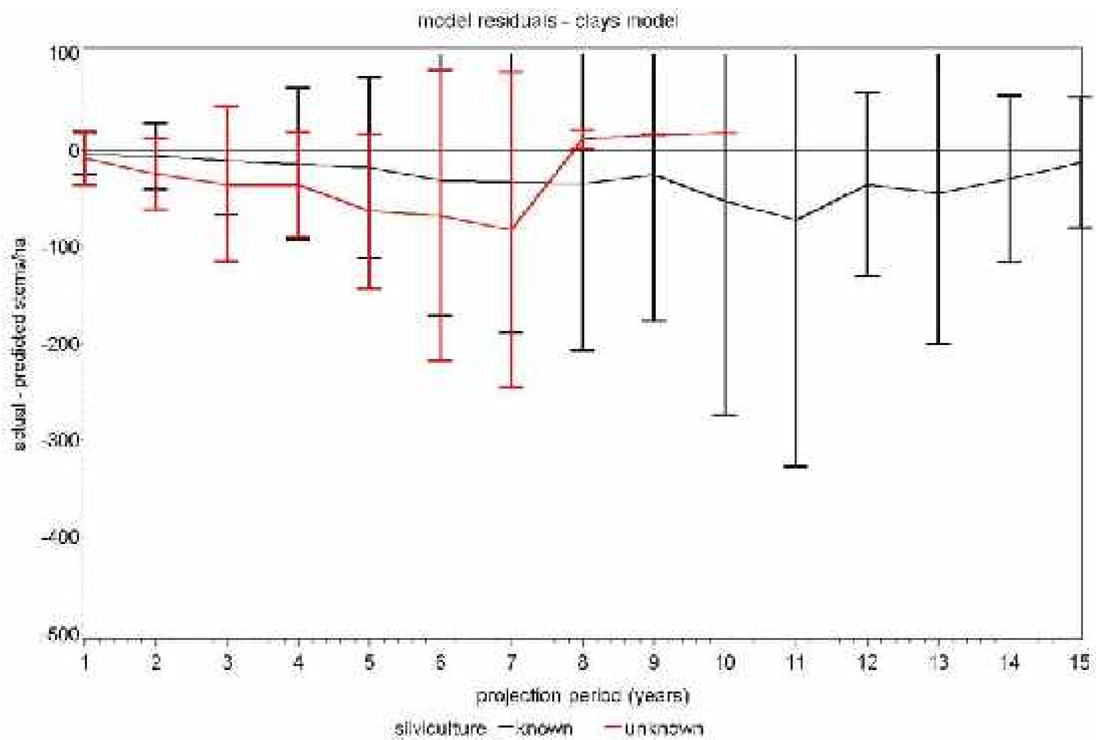


Figure 31. Graph showing mean and two standard deviations for actual – predicted stems/ha using the Clays model where projection period has been rounded to the nearest integer.

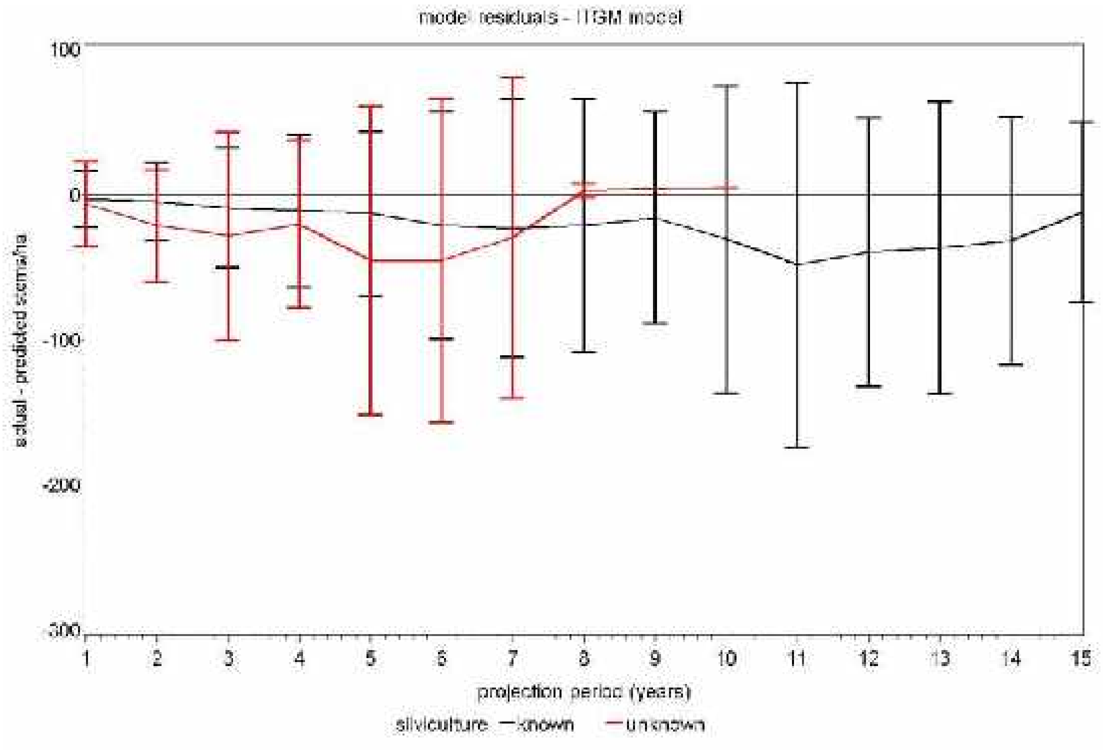


Figure 32. Graph showing mean and two standard deviations for actual – predicted stems/ha using the ITGM model where projection period has been rounded to the nearest integer.

GF rating

Knowledge of the GF rating for the plot appears to be important. The F value was significant ($p < 0.05$) for all 9 model – dependent variable combinations (see above).

Two model – dependent variable combinations are shown to illustrate the influence of genetics.

Figure 33 shows the mean and two standard deviations for the actual – predicted mean top height using the Clays model.

Figure 34 shows the mean and two standard deviations for the actual – predicted mean top height using the ITGM model.

Both figures show that:

- The mean error tends to be most negative where the GF rating is seven or less and most positive when the seedlot rating is greater than 14.
- The standard deviation is similar for all three classes.

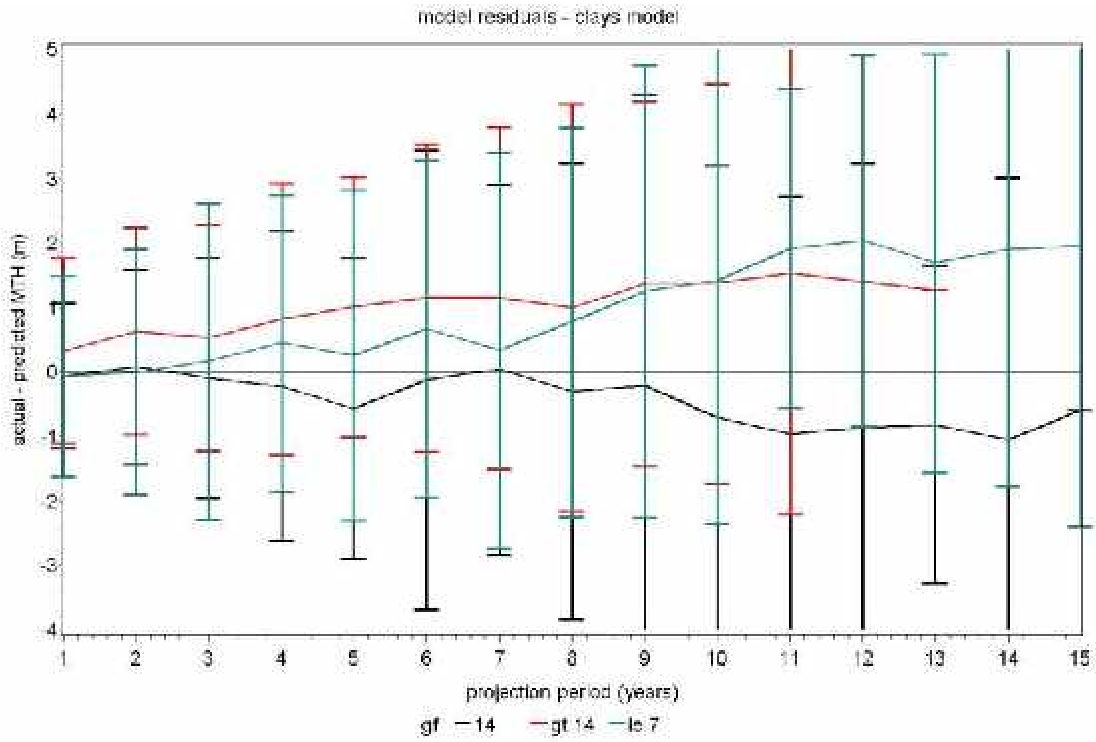


Figure 33. Graph showing mean and two standard deviations for actual – predicted mean top height using the Clays model where projection period has been rounded to the nearest integer.

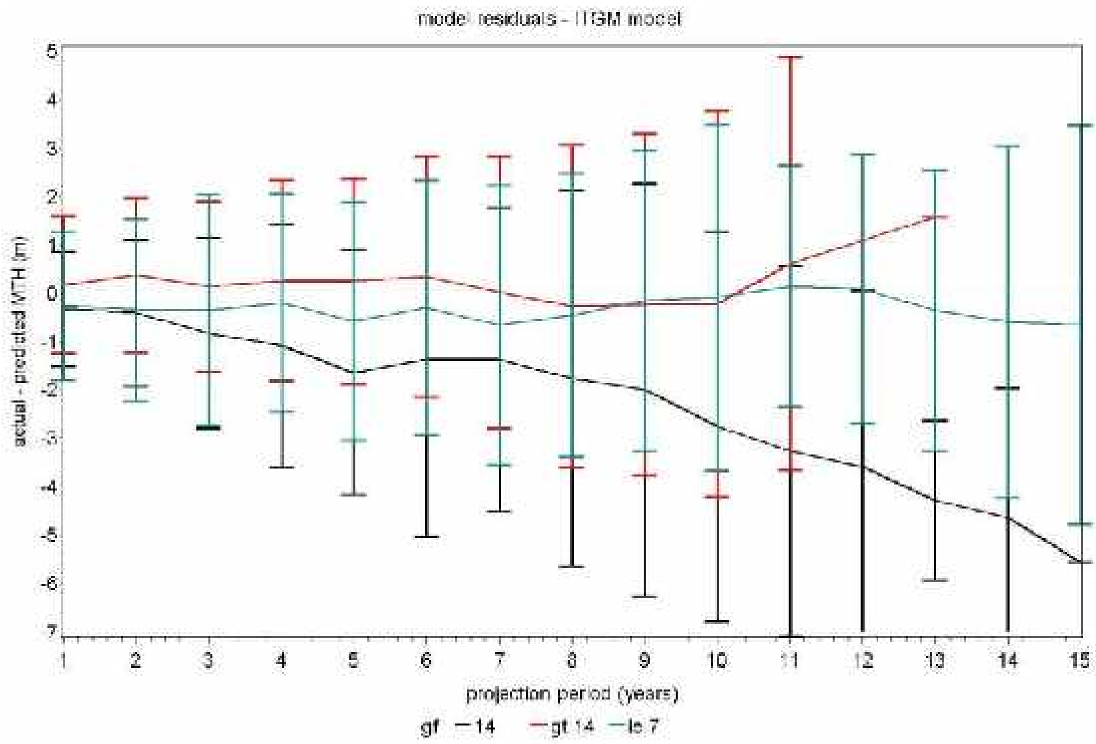


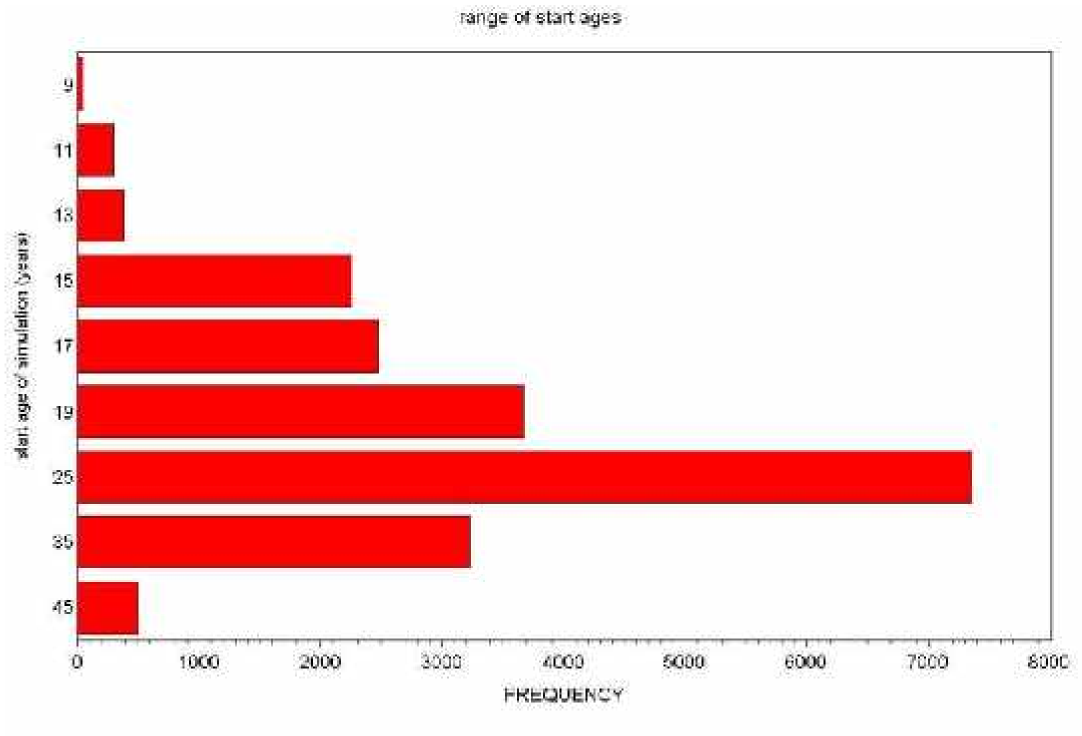
Figure 34. Graph showing mean and two standard deviations for actual – predicted mean top height using the ITGM model where projection period has been rounded to the nearest integer.

Performance of models in CNI Growth Modelling Region

There were 25916 individual simulations where the performance of the three growth models: PPM88, ITGM and 300 Index models could be compared at a stand level.

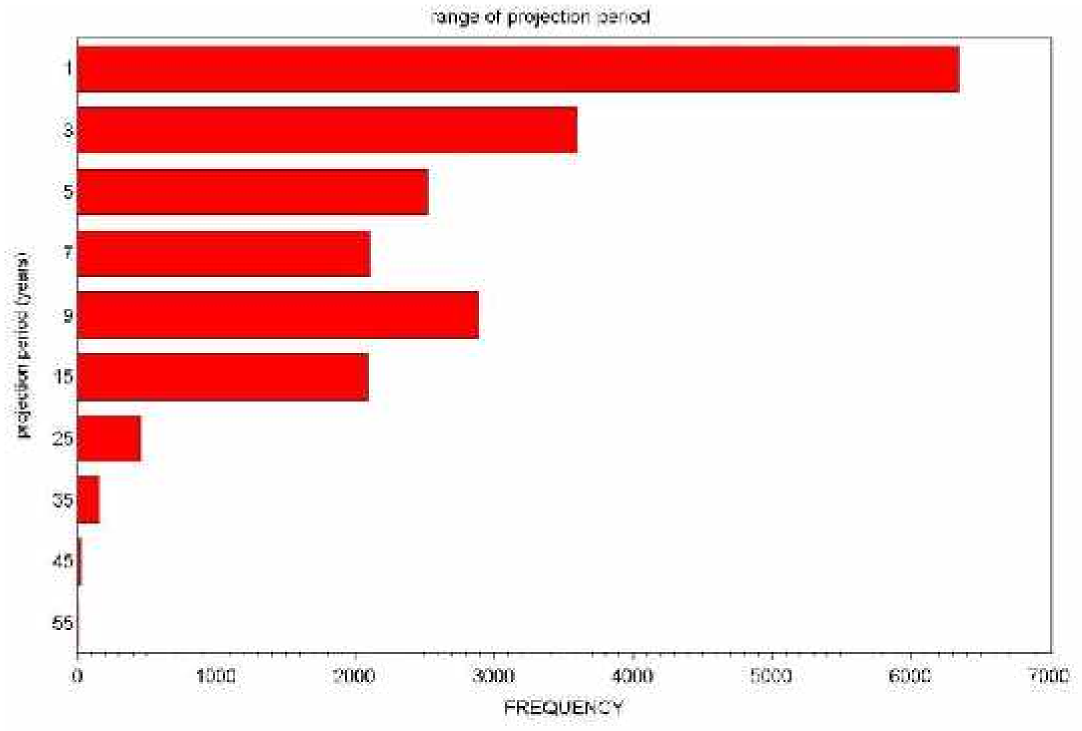
The ITGM model was designed to grow data forward from mid-rotation. Consequently the starting age of the simulations was generally no younger than 13 years. A few simulations started towards the end of the rotation (Figure 35).

The projection period varied from a few months up to 55 years, with shorter projection periods of up to 15 years being more frequent (Figure 36).



Note: values on the vertical axis are the mid-point value for each bar.

Figure 35. Bar chart showing the starting age of simulations in years.



Note: values on the vertical axis are the mid-point value for each bar.

Figure 36. Bar chart showing the distribution of projection period in years.

For each simulation the difference (actual – predicted) was calculated for three variables: mean top height (MTH), basal area per ha, and stems per hectare.

The performance of the three models in predicting the above three variables was examined visually by plotting the differences against projection period.

Figure 37 shows the errors in predicting MTH using the three models. The following points may be noted:

- The performance of all three models is similar.
- While MTH is generally predicted to within 5 m, all three models produce large errors in some instances.

Figure 38 shows the errors in predicting MTH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean error is very similar for projection periods of up to 10 years.
- For projection periods between 10 and 40 years, the mean error is smaller for the 300 Index model
- For projection period greater than 40 years, PPM88 or ITGM generally have the smaller mean error.
- Twice the standard deviation is similar for all three models.

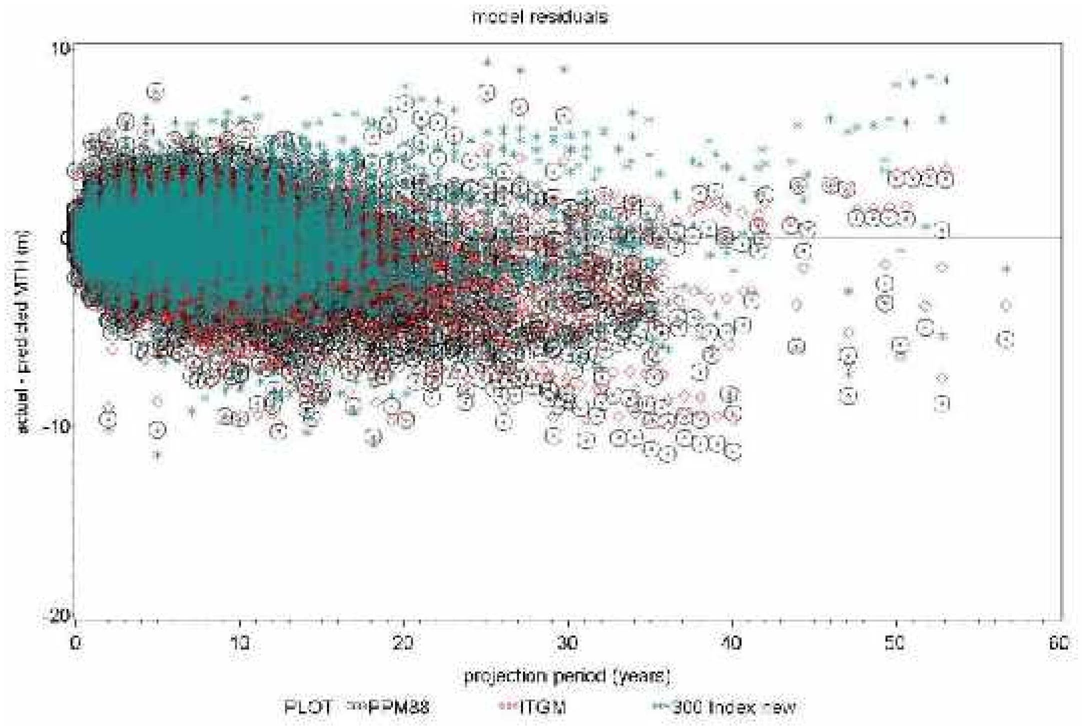


Figure 37. Graph showing actual – predicted mean top height from the PPM88, ITGM and 300 Index growth models.

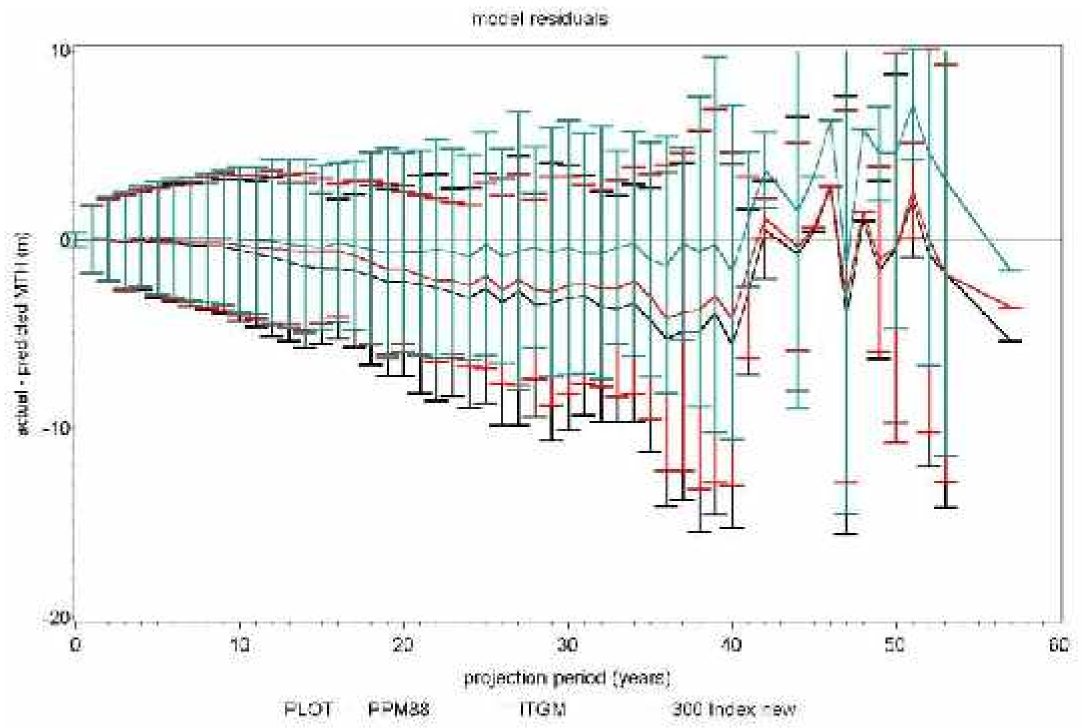


Figure 38. Graph showing mean and two standard deviations for actual – predicted mean top height where projection period has been rounded to the nearest integer.

Figure 39 shows the errors in predicting basal area per hectare (BA/ha) using the three models.

The following points may be noted:

- In general the prediction from the three models is similar. This is shown by the large block of colour.
- While BA/ha is generally predicted to within 20 m^2/ha, there are larger errors for all three models.

- In some instances, the 300 Index predicts less basal area than observed (actual – predicted basal area is positive). This is indicated by blue points above the zero reference line
- In some instances PPM88 and ITGM predict more basal area than observed (actual – predicted basal area is negative). This is indicated by black and red points below the zero reference line.

Figure 40 shows the errors in predicting BA/ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- It shows that the mean error tends to be positive for the 300 Index model, and similar but negative for the PPM88 and ITGM models.
- The standard deviation is similar for all three models and tends to increase with increasing projection period.

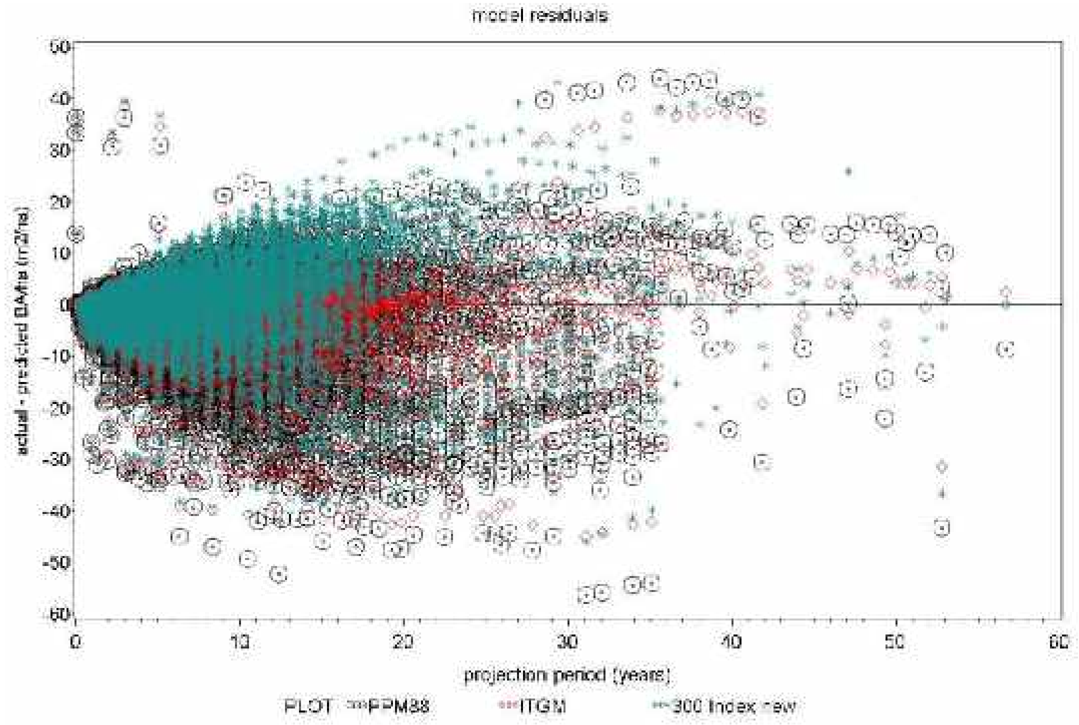


Figure 39. Graph showing actual – predicted basal area from the PPM88, ITGM and 300 Index growth models.

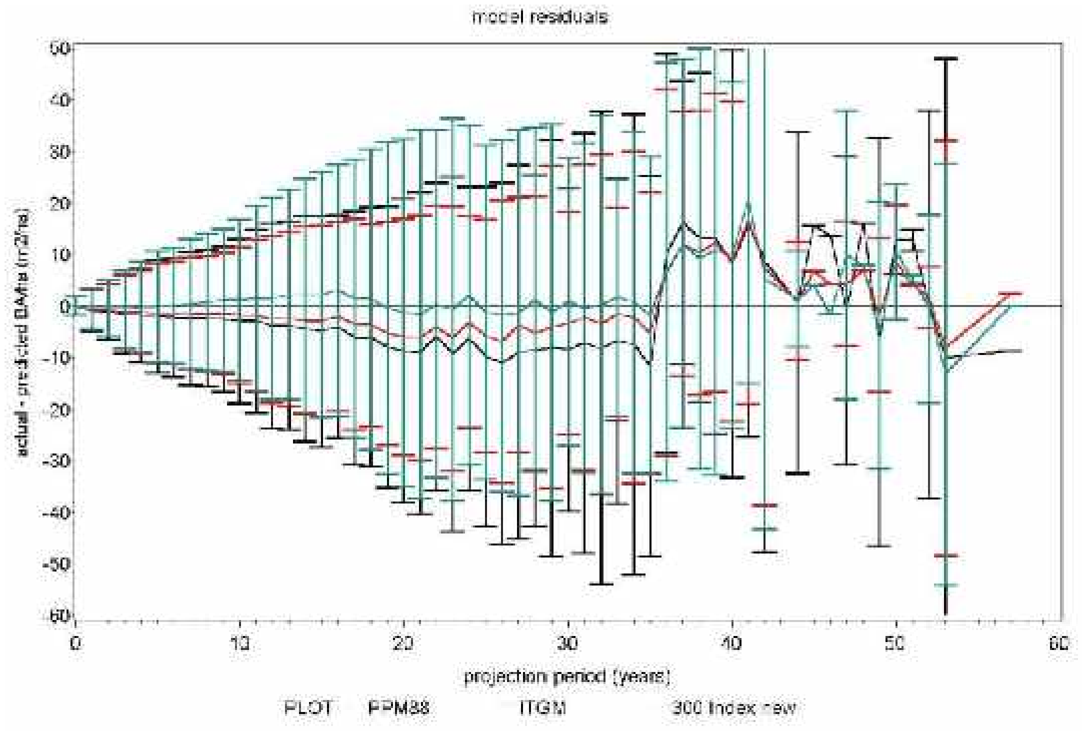


Figure 40. Graph showing mean and two standard deviations for actual – predicted basal area where projection period has been rounded to the nearest integer.

Figure 41 shows the errors in predicting stems per hectare (SPH) using the three models. The following points may be noted:

- All three models over-predict stocking, with most estimates being within 100 SPH.
- There are some large errors using all three models and, especially for the PPM88 model.

Figure 42 shows the errors in predicting SPH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean is similar and below zero for all three models with the ITGM model being closest to zero and the PPM88 model over-predicting the most.
- The standard deviation tends to increase with increasing projection period.

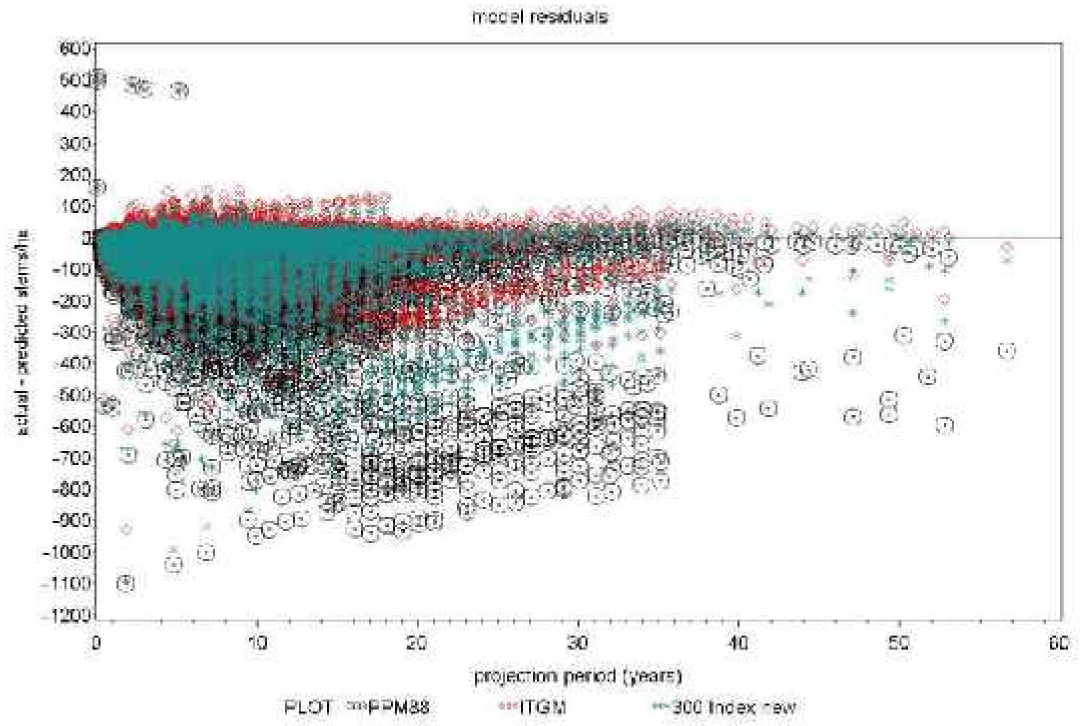


Figure 41. Graph showing actual – predicted stems/ha (SPH) from the PPM88, ITGM and 300 Index growth models.

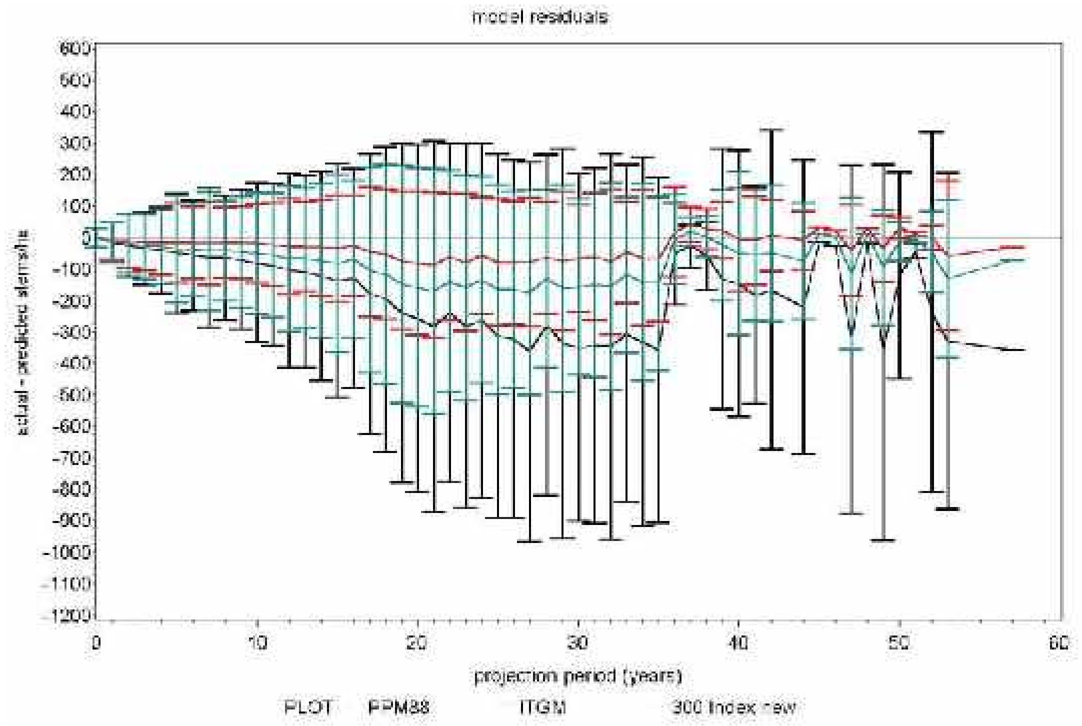


Figure 42. Graph showing mean and two standard deviations for actual – predicted stems/ha where projection period has been rounded to the nearest integer.

For this study in the Central North Island only three variables were examined:

- Number of height trees used to estimate site index
- Knowledge of silvicultural history
- Genetic rating for the planted trees

The height trees were split into two categories:

- Less than 10 height trees
- 10 or more height trees

Knowledge of silvicultural history was divided into two categories:

- Information on silvicultural history stored in PSP system
- No information on silvicultural history stored in PSP system

The genetic (GF) rating was divided into three categories:

- Less than or equal to 7 (i.e. unimproved to climbing select seedlot)
- 14 (i.e. 1st generation of seed orchard improvement)
- greater than 14 (i.e. later generations of improvement)

There were multiple simulations for most plots due to different start age and different projection period. To account for the varying projection period, the residual (actual – predicted value) was divided by the length of the projection period, then an "average" error was calculated for each plot, and then an "average" error was calculated for each plot.

The significance of the above four variables was tested using the "average" error in the SAS Proc Mixed procedure. The tables below show the significance of these factors for the different models and the different predicted variables (basal area (BA), mean top height (MTH) and stocking (SPH)). The number reported is the probability of being greater than the calculated F value. Low probabilities indicate a significant effect.

Previous land use

Not applicable as nearly 100% of the plots are ex-plantation forests.

Height trees

	PPM88	ITGM	300Index
BA	0.0324	0.0815	0.0031
MTH	0.0151	0.7874	0.0800
SPH	0.0313	0.1104	0.0345

Silviculture

	PPM88	ITGM	300Index
BA	0.0001	0.0055	< 0.0001
MTH	0.0002	0.3736	0.6319
SPH	0.1309	0.3077	0.0742

GF rating

	PPM88	ITGM	300Index
BA	0.0013	0.0002	0.0296
MTH	0.6385	< 0.0001	0.1740
SPH	< 0.0001	0.0543	0.0017

Graphs were plotted to illustrate the more significant differences (highlighted in tables above). Each graph shows the mean value and two standard deviations when the projection period is rounded to the nearest integer.

For these graphs, it was decided to allow SAS to choose the scale automatically so that no data points are missed when using the same generic code for different regions.

Height trees

Figure 43 shows the mean and two standard deviations for actual – predicted basal area using the 300 Index model. Points to note:

- For most projection periods, the means are generally similar regardless of the number of height trees.

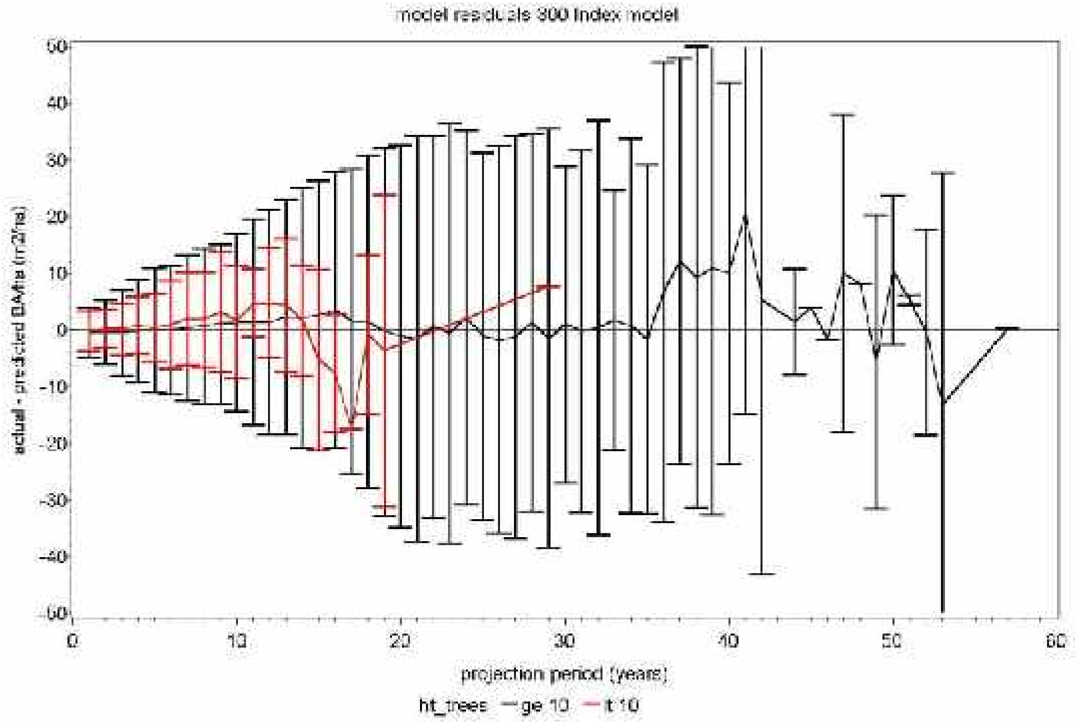


Figure 43. Graph showing mean and two standard deviations for actual – predicted basal area using the 300 Index model where projection period has been rounded to the nearest integer.

Silviculture

Figure 44 shows the mean and two standard deviations for actual – predicted mean top height using the PPM88 (CNI) model. Points to note:

- The means and standard deviations are similar regardless of whether the silvicultural history was known or not.

Figure 45 shows the mean and two standard deviations for actual – predicted basal area using the PPM88 (CNI) model. Points to note:

- The mean and standard deviation are similar regardless of whether the silvicultural history was known or not.

Figure 46 shows the mean and two standard deviations for actual – predicted basal area using the 300 Index model. Points to note:

- The means and standard deviations are similar regardless of whether the silvicultural history was known or not.

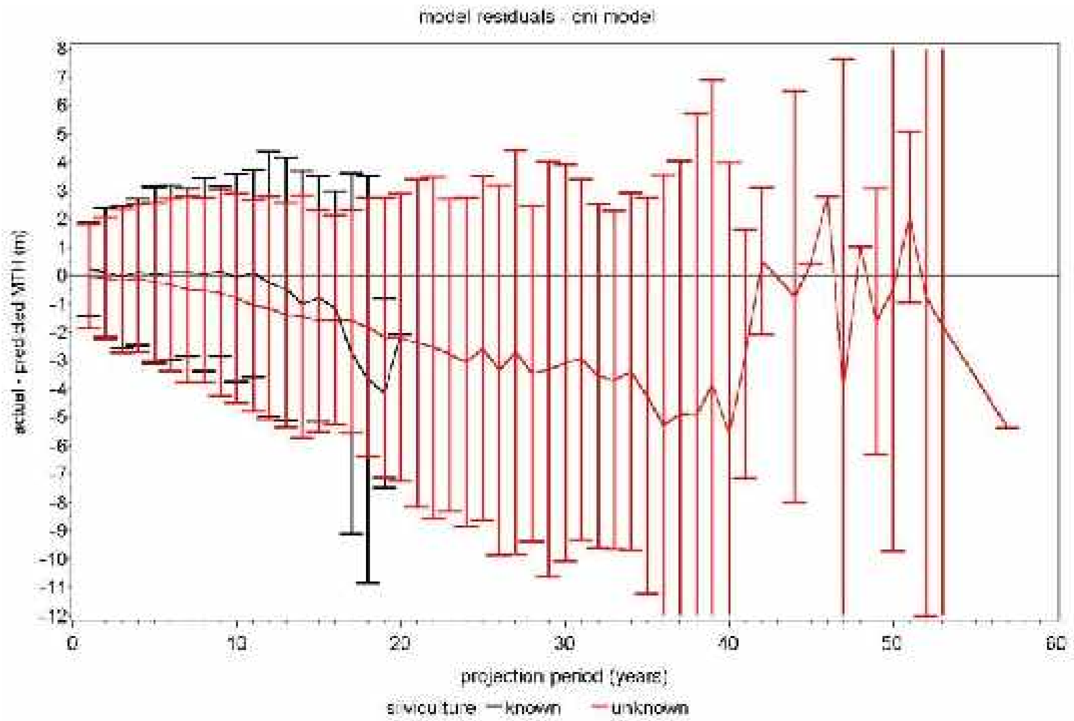


Figure 44. Graph showing mean and two standard deviations for actual – predicted mean top height using the CNI model PPM88 where projection period has been rounded to the nearest integer.

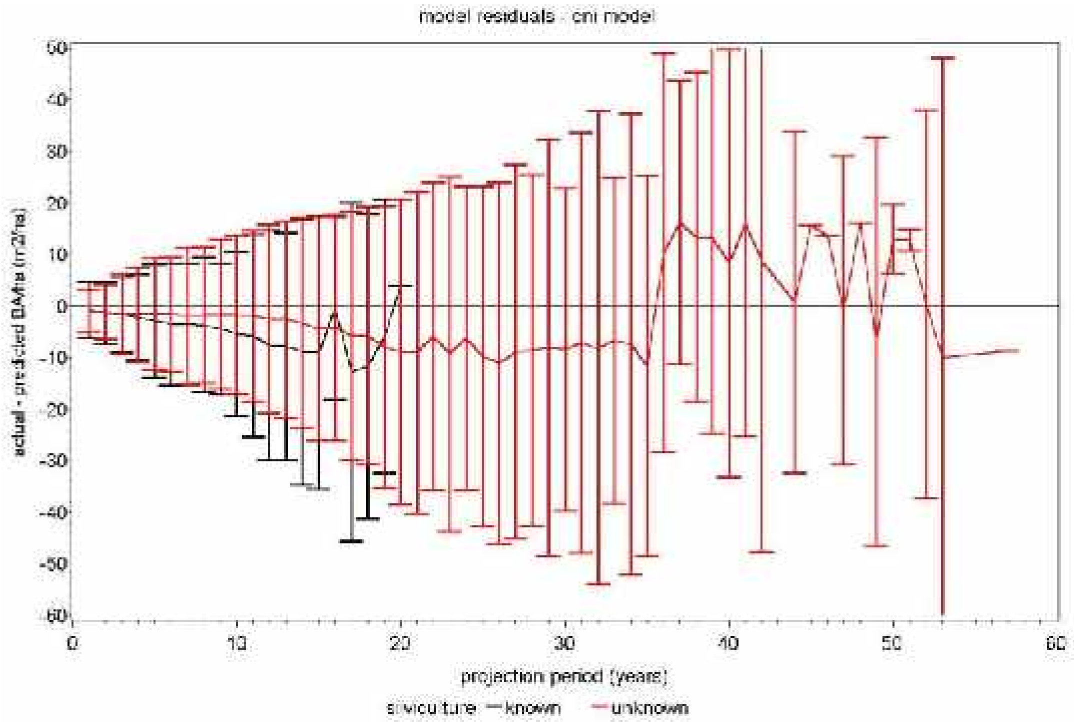


Figure 45. Graph showing mean and two standard deviations for actual – predicted basal area using the CNI model PPM88 where projection period has been rounded to the nearest integer.

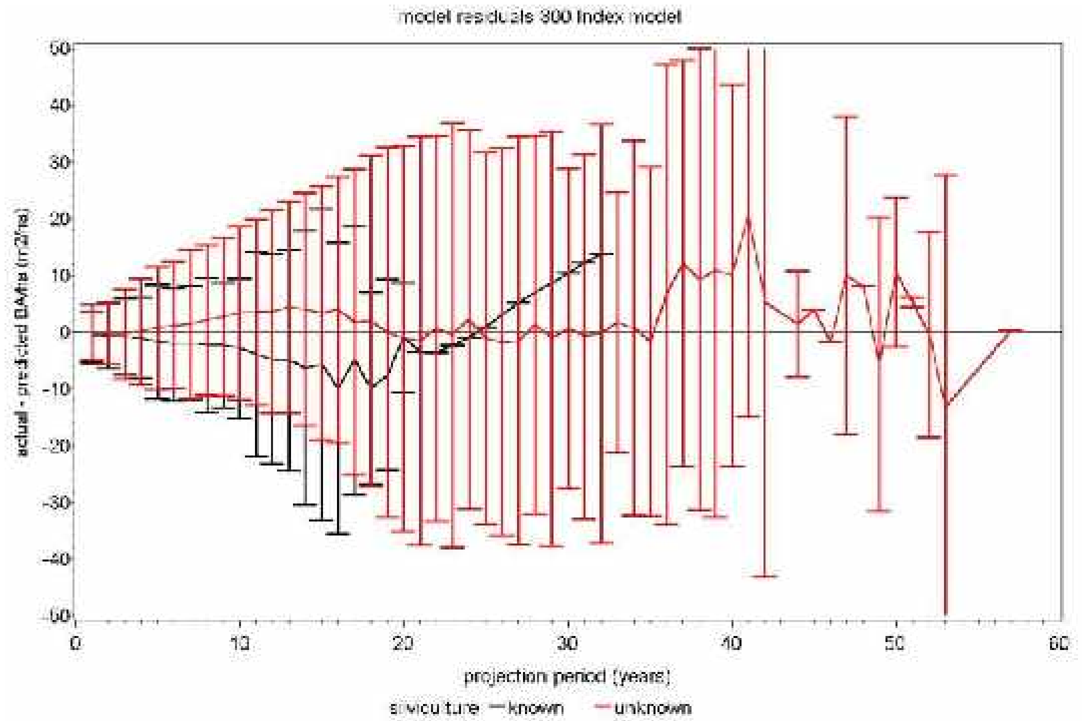


Figure 46. Graph showing mean and two standard deviations for actual – predicted basal area using the CNI model PPM88 where projection period has been rounded to the nearest integer.

GF rating

Figure 47 shows the mean and two standard deviations for “actual – predicted mean top height” for different seedlots with the ITGM model. Points to note:

- The mean error is generally negative, but is least for the GF7 seedlots, and poorer for the more improved seedlots.

Figure 48 shows the mean and two standard deviations for “actual – predicted basal area” for different seedlots with the ITGM model. Points to note:

- The mean difference is similar for small projection periods where there is data for the three different classes.

Figure 49 shows the mean and two standard deviations for “actual – predicted basal area” for different seedlots with the 300 Index model. Points to note:

- The mean difference is similar for small projection periods where there are data available for the three different classes.

Figure 50 shows the mean and two standard deviations for “actual – predicted stems per hectare using the PPM88 (CNI) model.

Figure 51 shows the mean and two standard deviations for “actual – predicted stems per hectare using the 300 Index model.

Points to note:

- For both models, the mean is similar for small projection periods where there is data for the three different classes

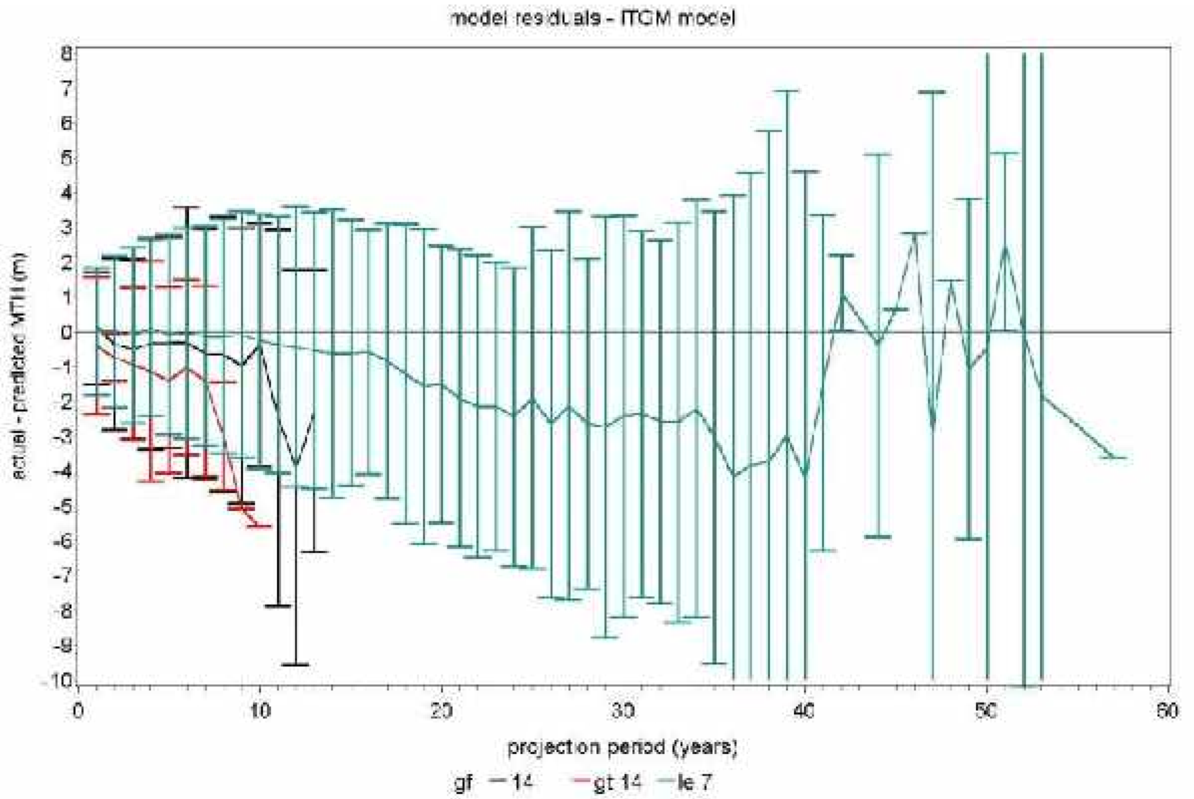


Figure 47. Graph showing mean and two standard deviations for actual – predicted mean top height using the ITGM model where projection period has been rounded to the nearest integer.

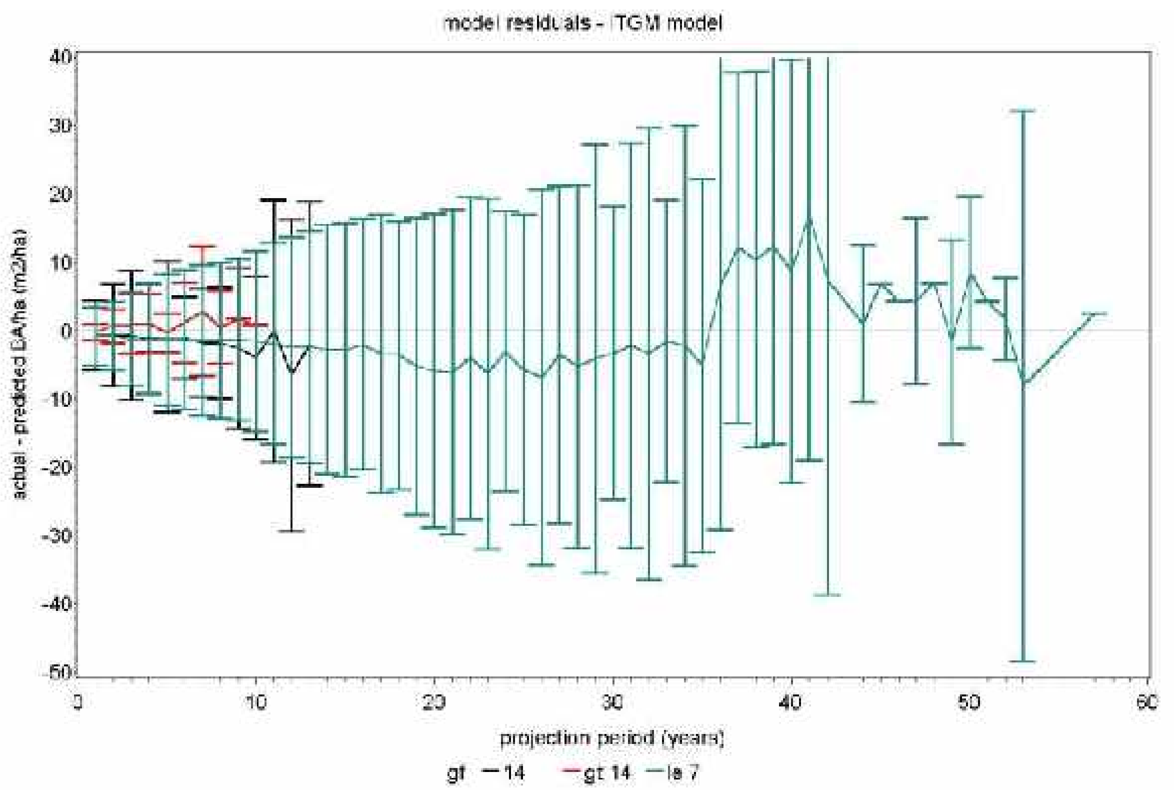


Figure 48. Graph showing mean and two standard deviations for actual – predicted basal area using the ITGM model where projection period has been rounded to the nearest integer.

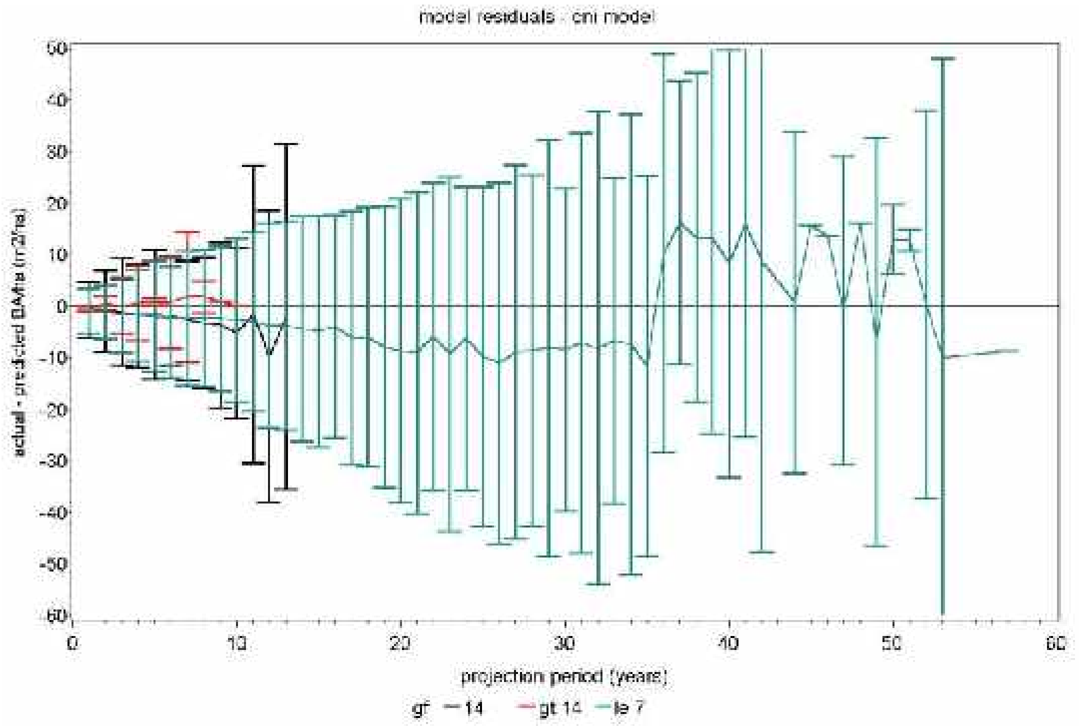


Figure 49. Graph showing mean and two standard deviations for actual – predicted basal area using the CNI model PPM88 where projection period has been rounded to the nearest integer.

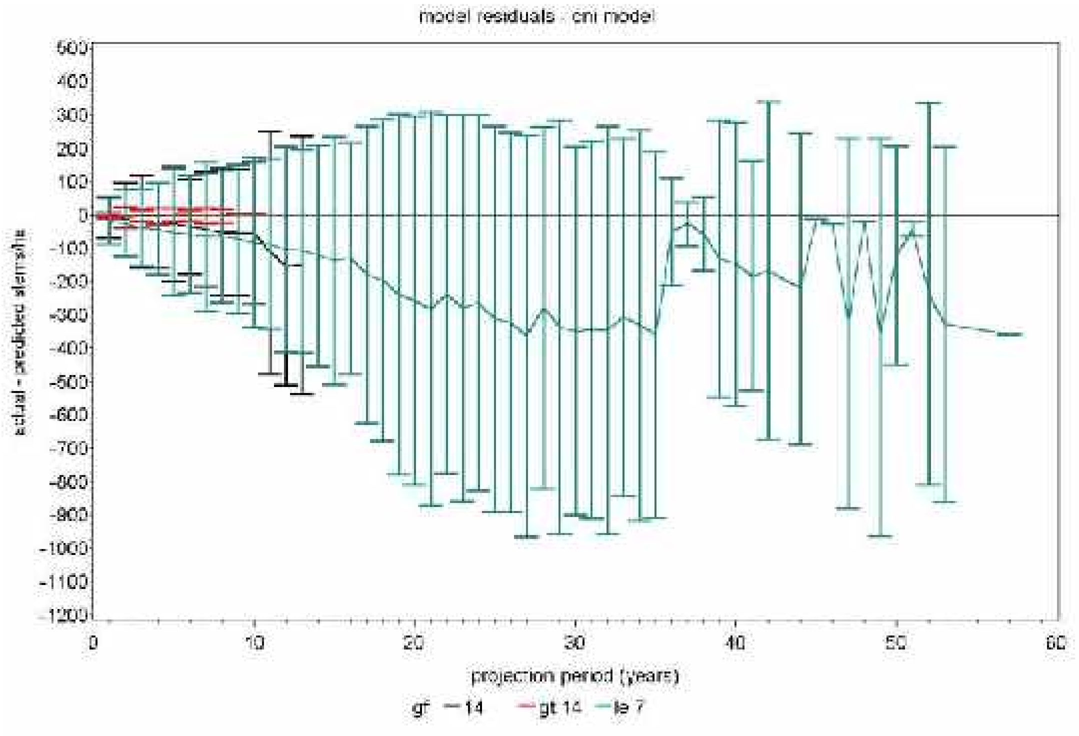


Figure 50. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the CNI model PPM88 where projection period has been rounded to the nearest integer.

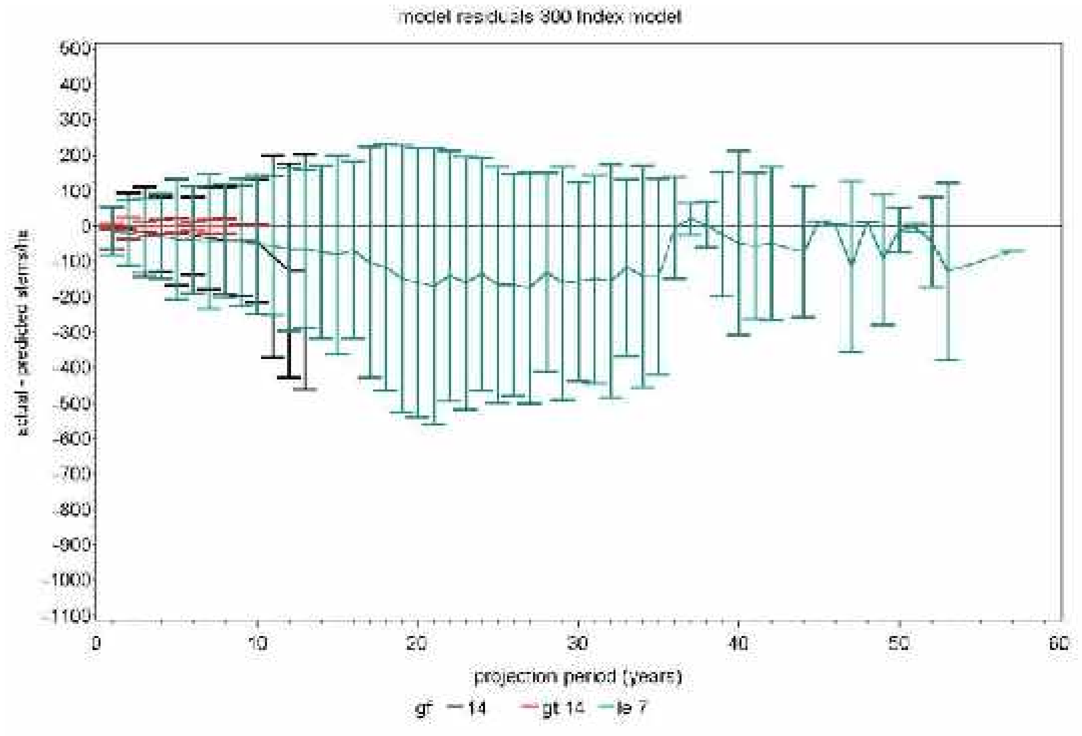


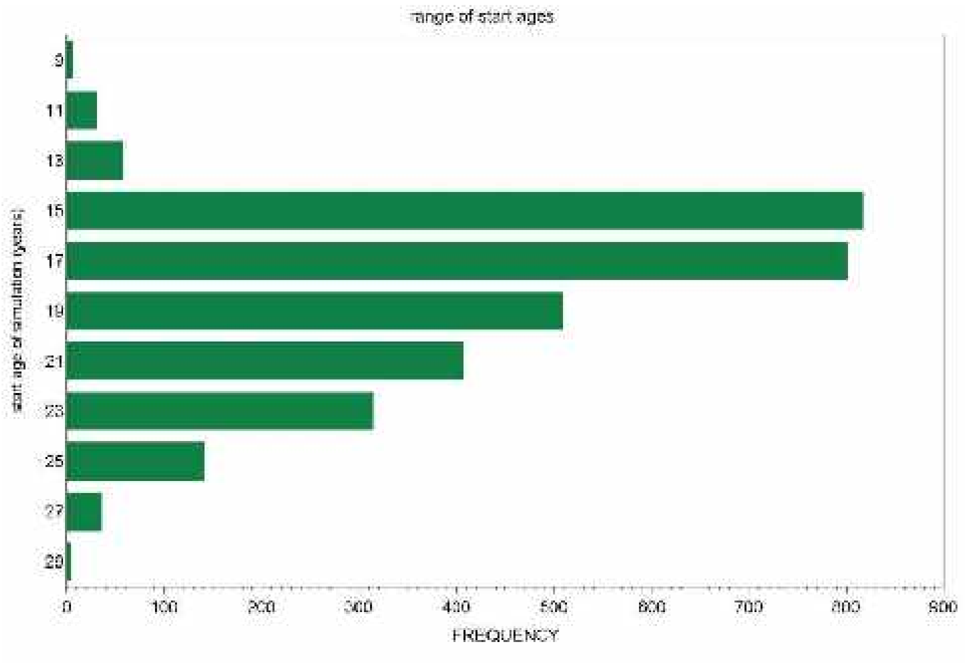
Figure 51. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the 300 Index model where projection period has been rounded to the nearest integer.

Performance of models in Nelson Growth Modelling Region

There were 3120 individual simulations where the performance of the three growth models: NM90, ITGM and 300 Index models could be compared at a stand level.

The ITGM models were designed to grow data forward from mid-rotation. For the Nelson region, the majority of the simulations started between ages 14 and 20 years. A few simulations started towards the end of the rotation (Figure 52).

The projection period varied from a few months to nearly 20 years, with shorter projection periods being more frequent (Figure 53).



Note: values on the vertical axis are the mid-point value for each bar.

Figure 52. Bar chart showing the starting age of simulations in years.

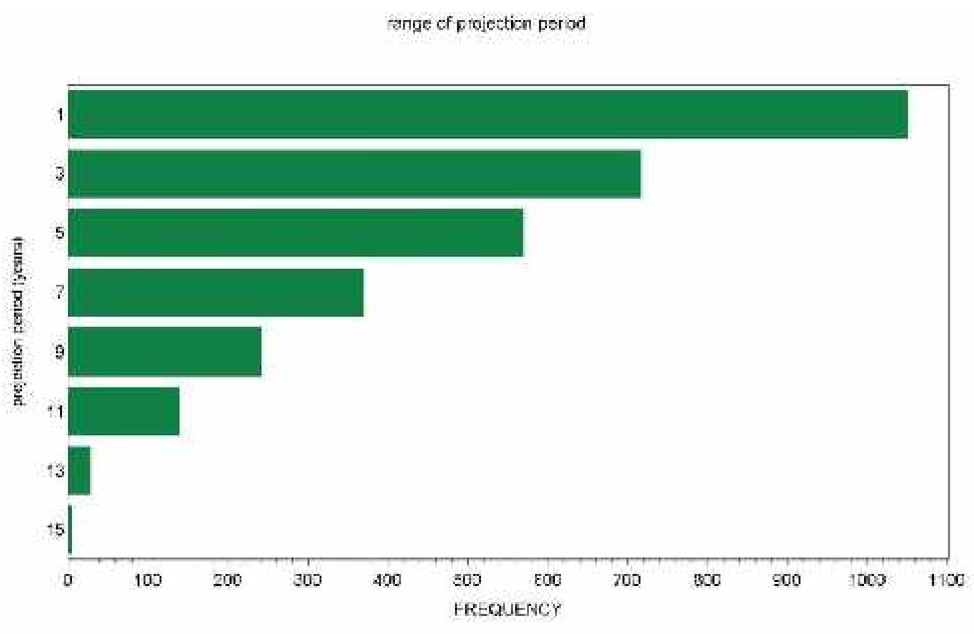


Figure 53. Bar chart showing the distribution of projection period in years.

Figure 54 shows the errors in predicting MTH using the three models. The following points may be noted:

- The performance of all three models is similar.
- There are a few simulations where all three models produce large but similar errors.
- The range in errors for any projection period tends to be similar.

Figure 55 shows the errors in predicting MTH in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean error and the trend with increasing projection period are similar for all three models.
- Twice the standard deviation is similar for all three models.

Figure 56 shows the mean and two standard deviations for the absolute error in MTH predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean absolute error is similar for all three models.
- The mean absolute error tends to increase with increasing projection period.
- The standard deviations are similar for all three models.

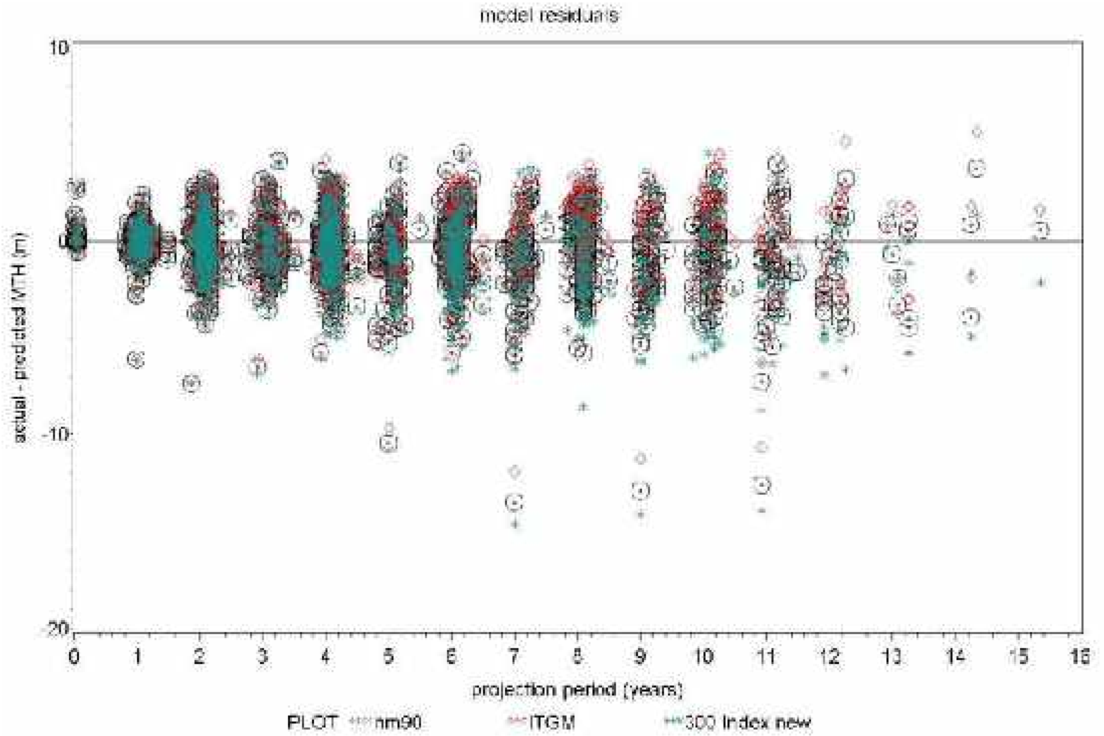


Figure 54. Graph showing actual – predicted mean top height from the NM90, ITGM and 300 Index growth models.

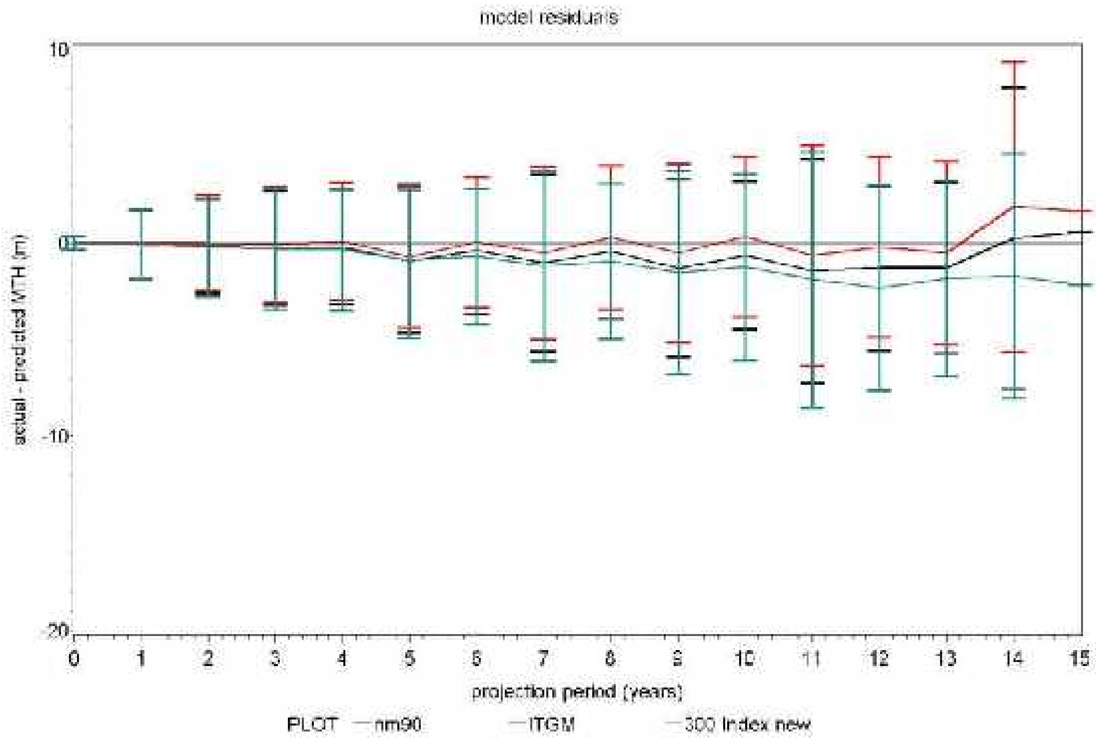


Figure 55. Graph showing mean and two standard deviations for actual – predicted mean top height where projection period has been rounded to the nearest integer.

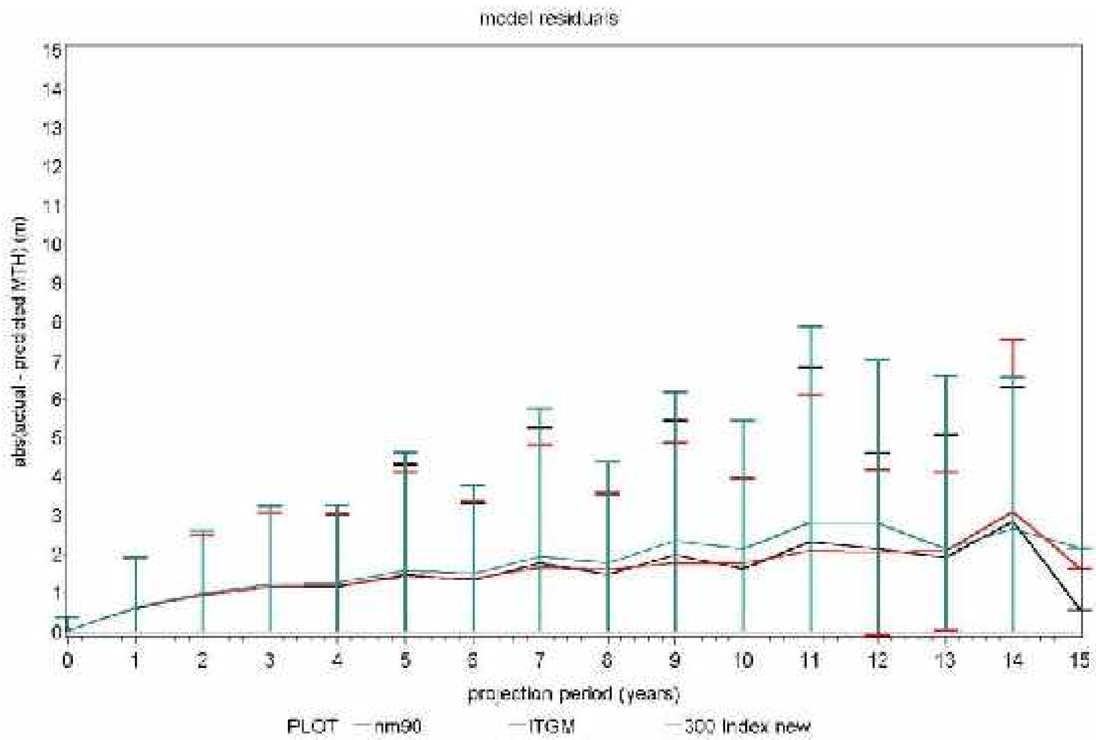


Figure 56. Graph showing mean and two standard deviations for the absolute value of actual – predicted mean top height where projection period has been rounded to the nearest integer.

Figure 57 shows the errors in predicting basal area per hectare using the three models. The following points may be noted:

- All three models produce similar results.

- Of particular note are the plots where “actual –predicted basal area” has large positive values. All three models perform similarly.

Figure 58 shows the errors in predicting basal area per ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean error is similar for all three models
- The standard deviation is similar for all three models

Figure 59 shows the mean and two standard deviations for the absolute error in stems per ha predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean absolute error is similar for all three models, but increases with increasing projection period.
- Twice the standard deviation is similar for all three models, but increases with increasing projection period.

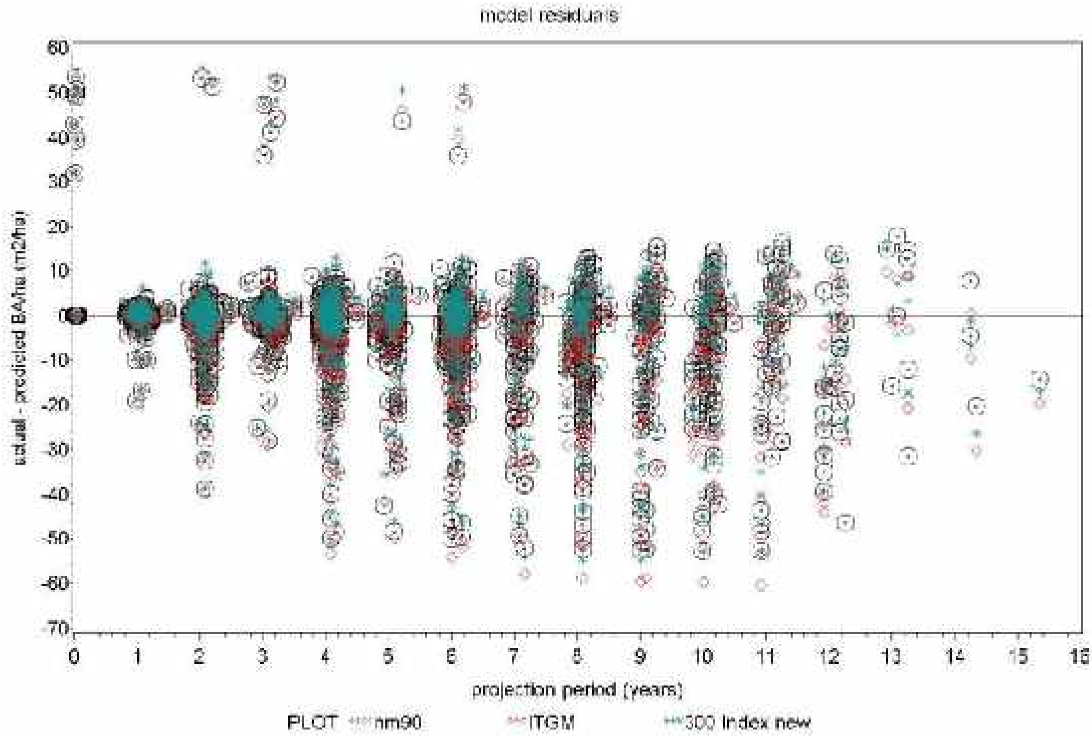


Figure 57. Graph showing actual – predicted basal area from the NM90, ITGM and 300 Index growth models.

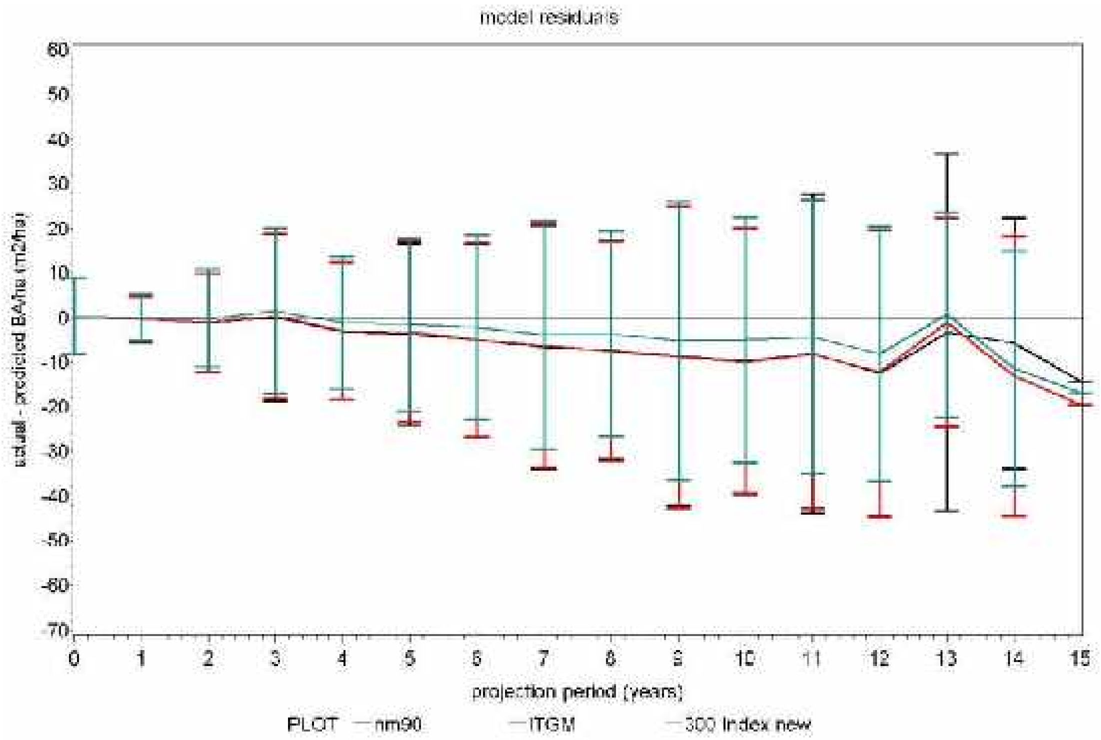


Figure 58. Graph showing mean and two standard deviations for actual – predicted basal area where projection period has been rounded to the nearest integer.

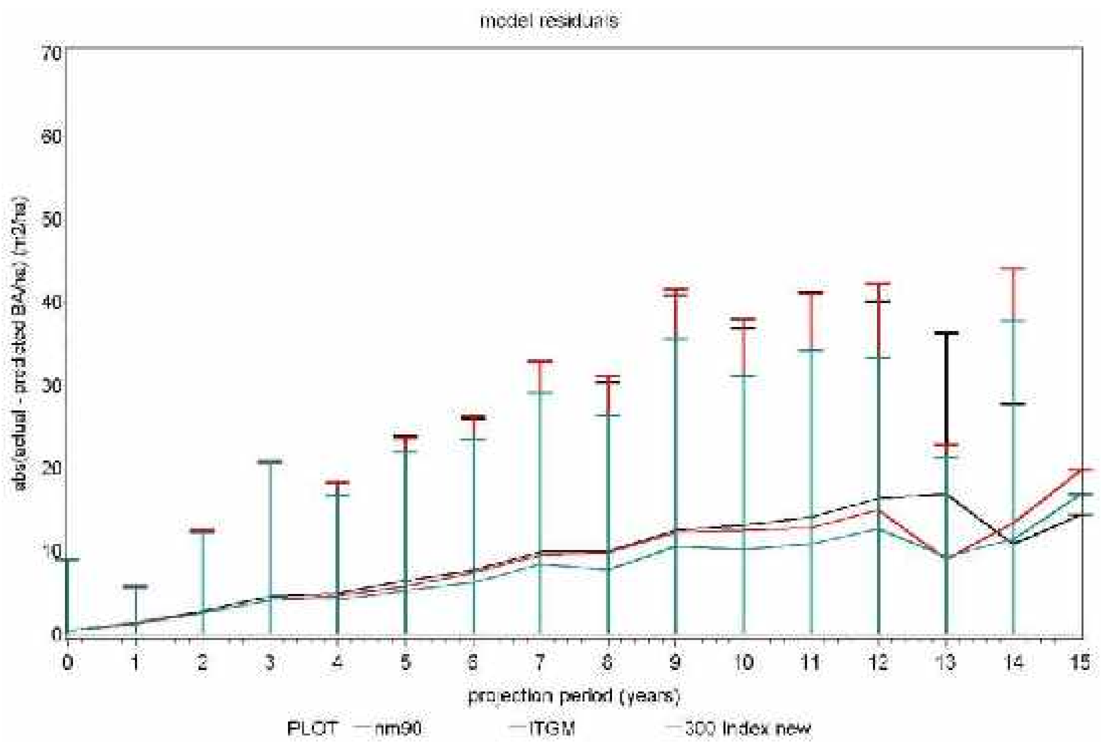


Figure 59. Graph showing mean and two standard deviations for the absolute value of actual – predicted basal area per ha where projection period has been rounded to the nearest integer.

Figure 60 shows the errors in predicting stems per hectare using the three models. The following points may be noted:

- The errors are similar for all three models.
- The ITGM model tends to show slightly more positive residuals (more red colour visible above the zero line)

Figure 61 shows the errors in predicting stems per ha in an alternative way. It shows the mean and two standard deviations when the projection period is rounded to the nearest integer. The following points may be noted:

- For short projection periods, the mean error is similar for all three models.
- The difference in mean error between the three model increases with increasing projection period.
- Two times the standard deviation is similar for all models, but tends to increase with increasing projection period.

Figure 62 shows the mean and two standard deviations for the absolute error in stems per ha predictions when the projection period is rounded to the nearest integer. The following points may be noted:

- The mean absolute error tends to increase with increasing projection period.
- For short projection period, the means are similar for all three models.
- The standard deviation is similar for all three models, but increases with increasing projection period.

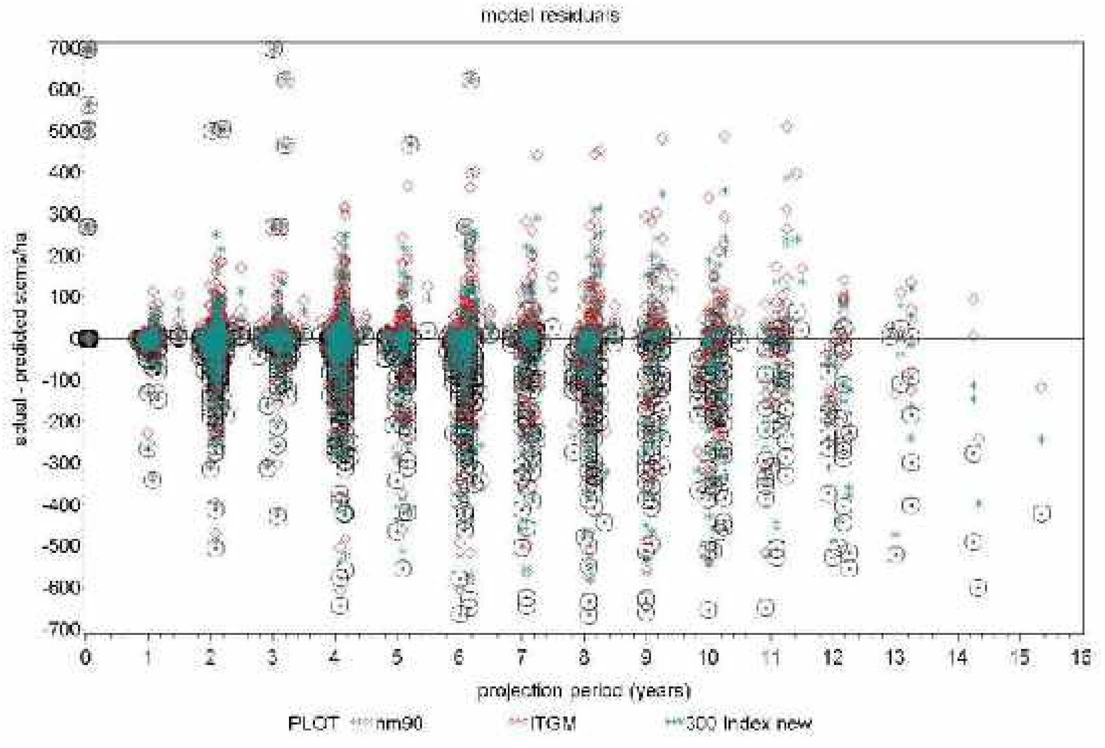


Figure 60. Graph showing actual – predicted stems/ha (SPH) from the NM90, ITGM and 300 Index growth models.

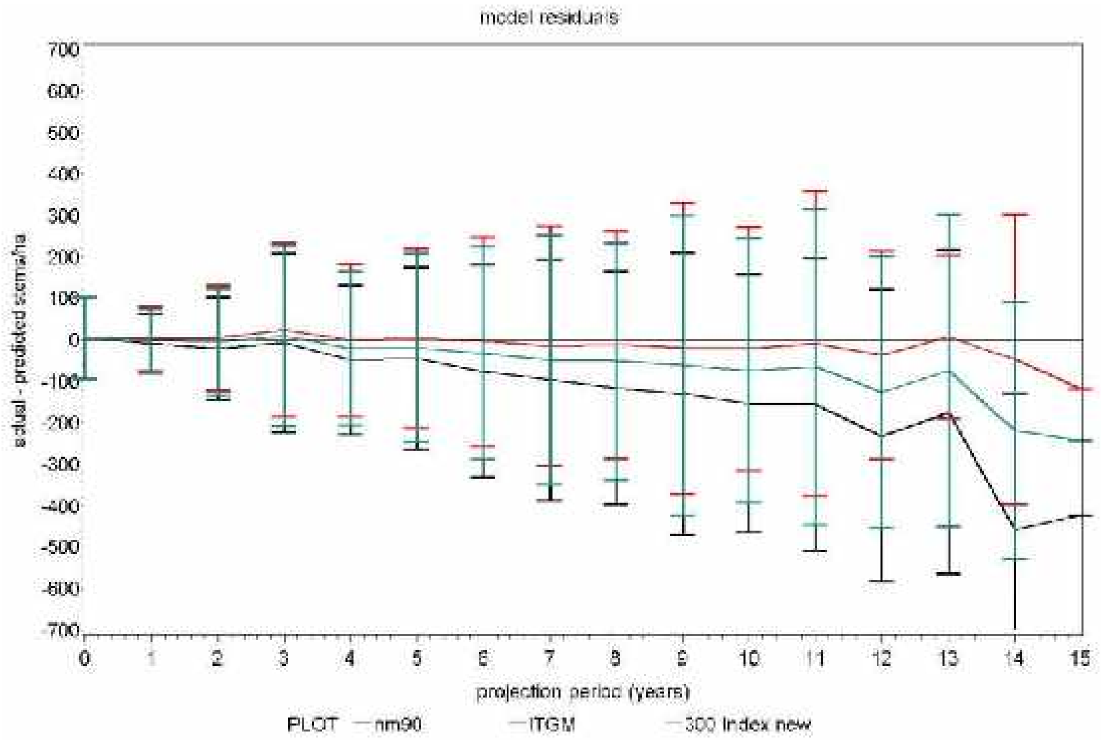


Figure 61. Graph showing mean and two standard deviations for actual – predicted stems/ha where projection period has been rounded to the nearest integer.

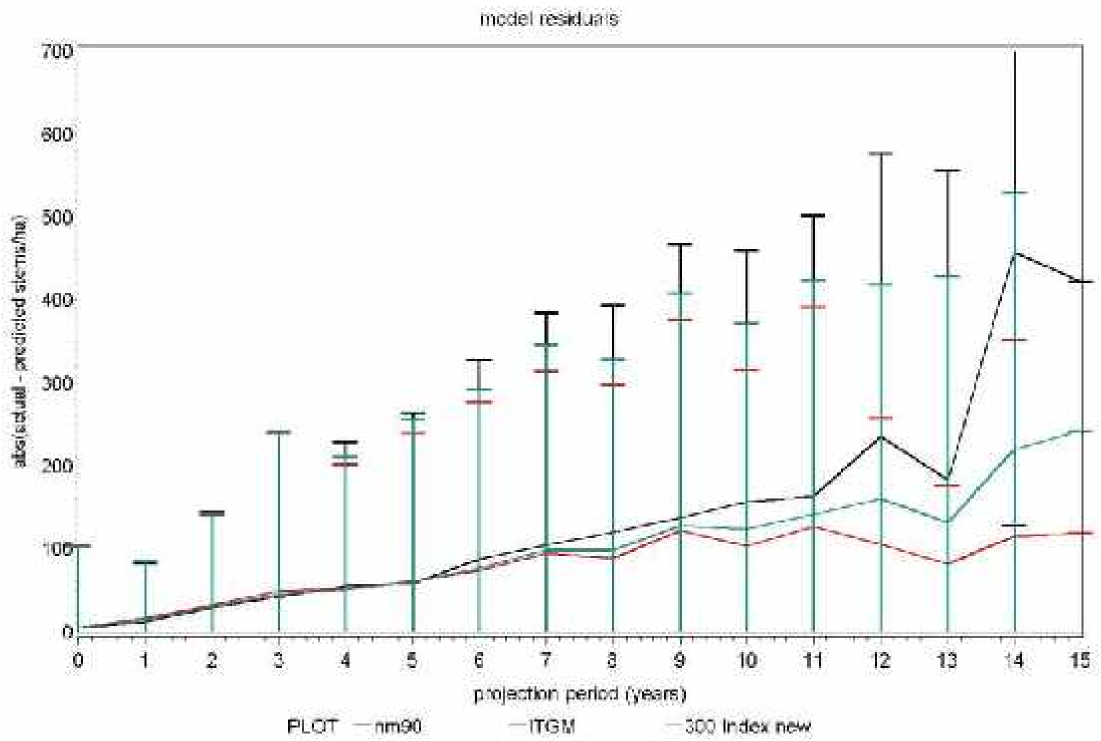


Figure 62. Graph showing mean and two standard deviations for the absolute value of actual – predicted stems/ha where projection period has been rounded to the nearest integer.

It is also important to identify whether there are any independent variables that may influence the model results. Any such variables that are shown to be important may be considered for inclusion in future model development if required.

For this study four variables were examined:

- Previous land use
- Number of height trees used to estimate site index
- Knowledge of silvicultural history
- Genetic rating for the planted trees

In the PSP system, many different descriptors have been used for previous land use. They have been summarised into five categories for this analysis (see below).

Previous land use for analysis	Previous land use from PSP system
Exotic scrub	Exotic scrub
Plantation	Exotic plantation
Unknown	Gully side Not recorded
Native vegetation	Indigenous grassland Indigenous scrub
Farmland	Old pasture

The number of height trees was divided into two categories:

- Less than 10 height trees
- 10 or more height trees

Knowledge of silvicultural history was divided into two categories:

- Information on silvicultural history stored in PSP system
- No information on silvicultural history stored in PSP system.

The genetic (GF) rating was divided into three categories:

- Less than or equal to 7 (i.e. unimproved to climbing select seedlot)
- 14 (i.e. 1st generation of seed orchard improvement)
- greater than 14 (i.e. later generations of improvement)

There were multiple simulations for most plots due to different start age and different projection period. To account for the varying projection period, the residual (actual – predicted value) was divided by the length of the projection period, then an "average" error was calculated for each plot, and then an "average" error was calculated for each plot.

The significance of the above four variables was tested using the "average" error in the SAS Proc Mixed procedure. The tables below show the significance of these factors for the different models and the different predicted variables (basal area (BA), mean top height (MTH) and stocking (SPH)). The number reported is the probability of being greater than the calculated F value. Low probabilities indicate a significant effect.

Previous land use

	NM90	ITGM	300Index
BA	0.0792	0.0326	0.0289
MTH	0.0015	< 0.0001	< 0.0001
SPH	0.0004	0.0756	0.0297

Height trees

	NM90	ITGM	300Index
BA	0.3377	0.6324	0.7380
MTH	0.2283	0.0445	0.0517
SPH	0.2653	0.4426	0.4787

Silviculture

	NM90	ITGM	300Index
BA	0.0759	0.0070	0.0172
MTH	0.0250	0.0017	0.0087
SPH	0.5771	0.0318	0.1779

GF rating

	NM90	ITGM	300Index
BA	0.0042	0.0047	0.0012
MTH	0.3544	0.0084	0.3648
SPH	< 0.0001	0.0011	0.0003

Graphs were plotted to illustrate the more significant differences. Each graph shows the mean value and two standard deviations when the projection period is rounded to the nearest integer.

For these graphs, it was decided to allow SAS to choose the scale automatically so that no data points are missed in when using the same generic code for different regions.

Figure 63 shows the variation in “actual – predicted mean top height” for different land uses with the ITGM model. Points to note:

- The “actual – predicted mean top height tends to be positive when the previous land use was plantation, but negative for other land uses.
- The standard deviations are similar for all land uses.

Figure 64 shows the variation in “actual – predicted mean top height” for different land uses with the 300 Index model. Points to note:

- The “actual – predicted mean top height tends to be positive when the previous land use was plantation, but negative for other land uses.
- The standard deviations are similar for all land uses.

Figure 65 shows the variation in “actual – predicted stems/ha” for different land uses with the NM90 model. Points to note:

- The mean value for “actual – predicted stems/ha deceases with increasing projection period.
- The mean value tends to be most negative for the plots that were previously under plantation.

Figure 66 shows the variation in “actual – predicted stems/ha” for different GF ratings with the NM90 model. Points to note:

- The mean value for actual – predicted stems/ha tends to be positive for seedlots with a GF rating of greater than 14, but negative for a GF rating of seven and less.

Figure 67 shows the variation in “actual – predicted stems/ha” for different GF ratings with the 300 Index model. Points to note:

- The mean value for actual – predicted stems/ha tends to be positive for seedlots with a GF rating of greater than 14, but negative for a GF rating of seven and less.
- The result is comparable to that for the NM90 model.

Previous land use

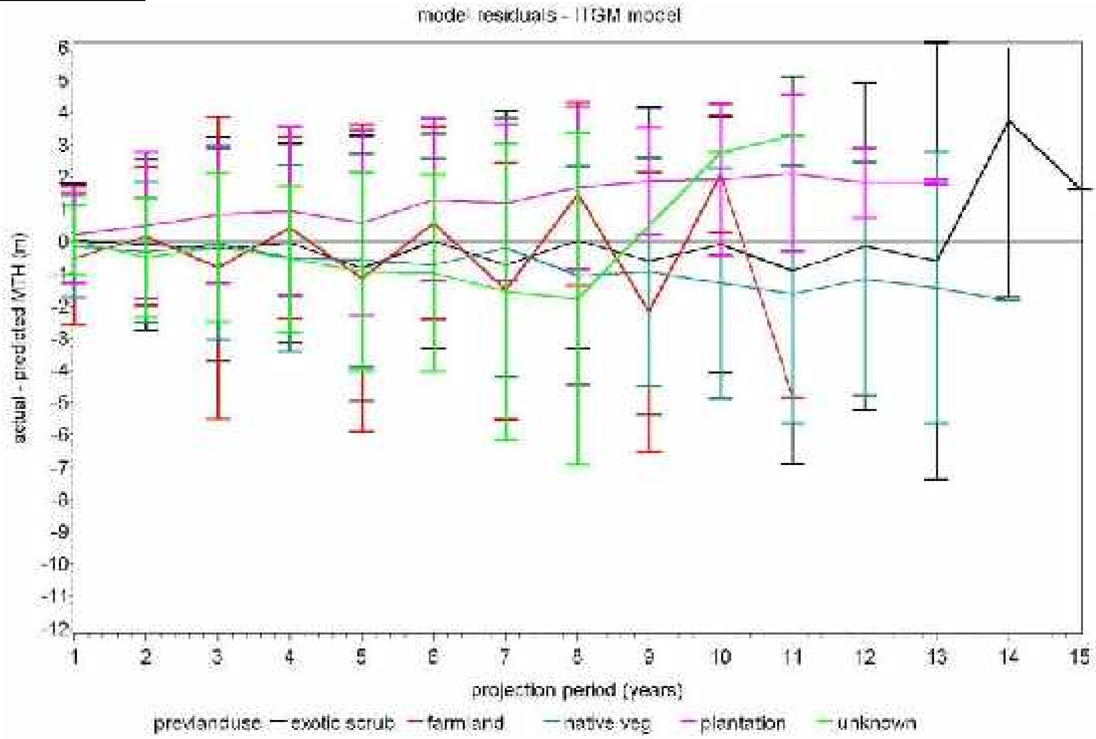


Figure 63. Graph showing mean and two standard deviations for actual – predicted mean top height using the ITGM model where projection period has been rounded to the nearest integer.

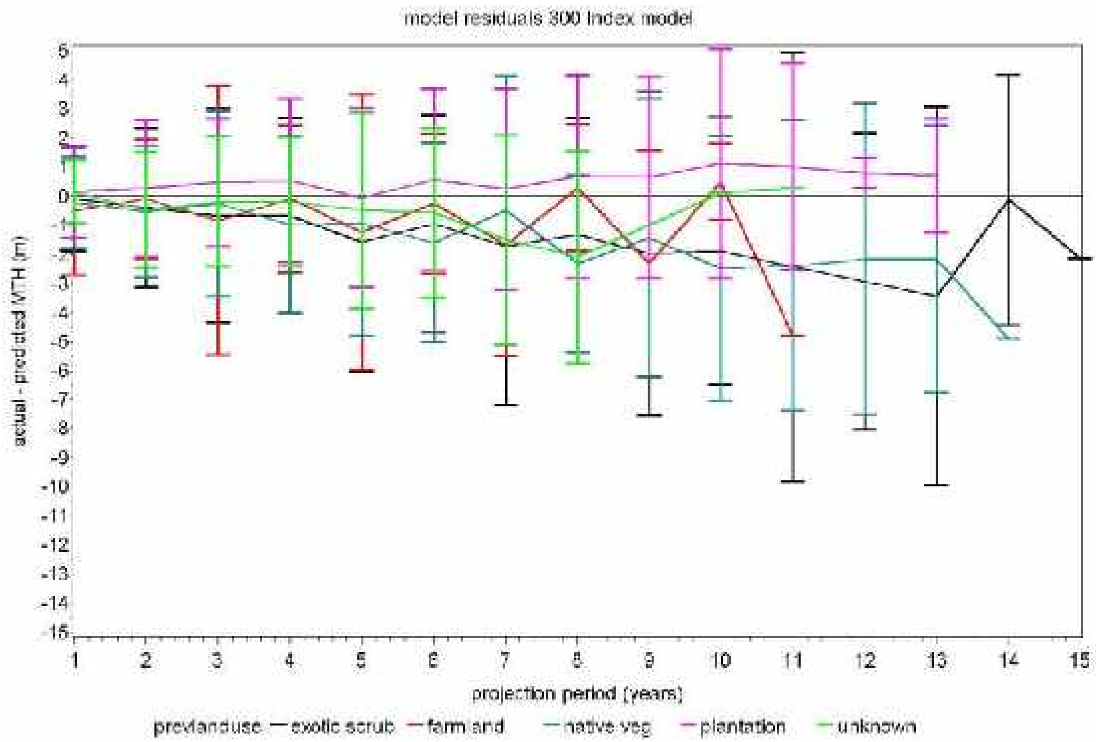


Figure 64. Graph showing mean and two standard deviations for actual – predicted mean top height using the 300 index model where projection period has been rounded to the nearest integer.

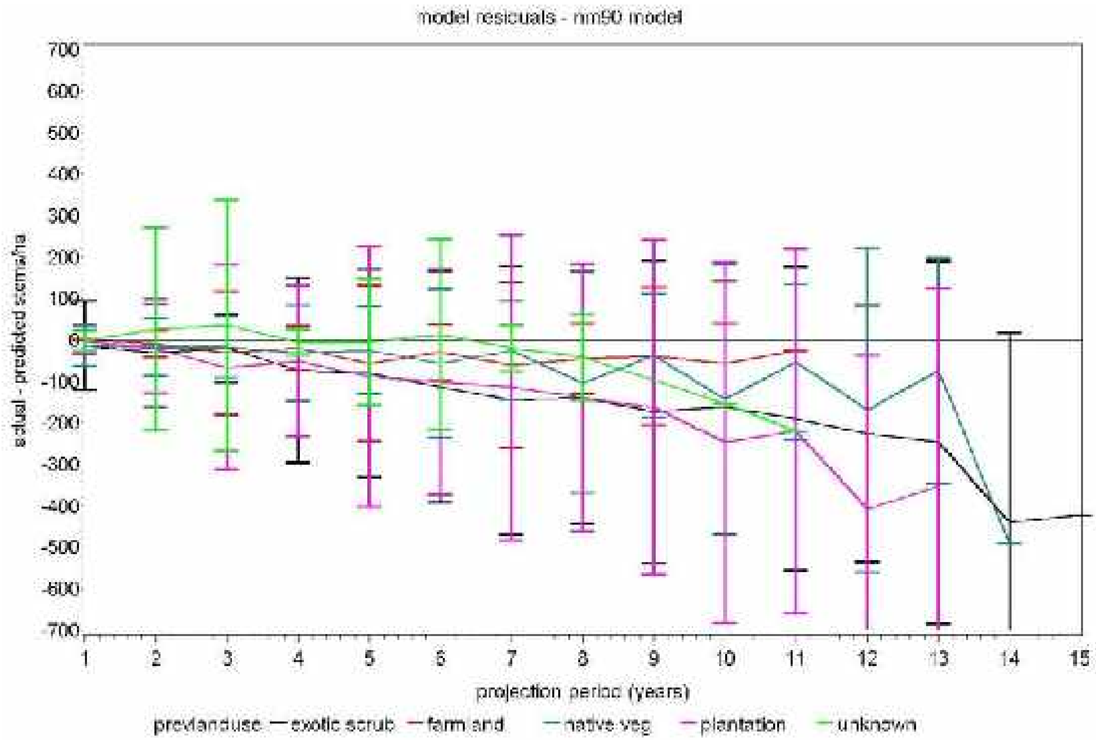


Figure 65. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the NM90 model where projection period has been rounded to the nearest integer.

Genetic rating

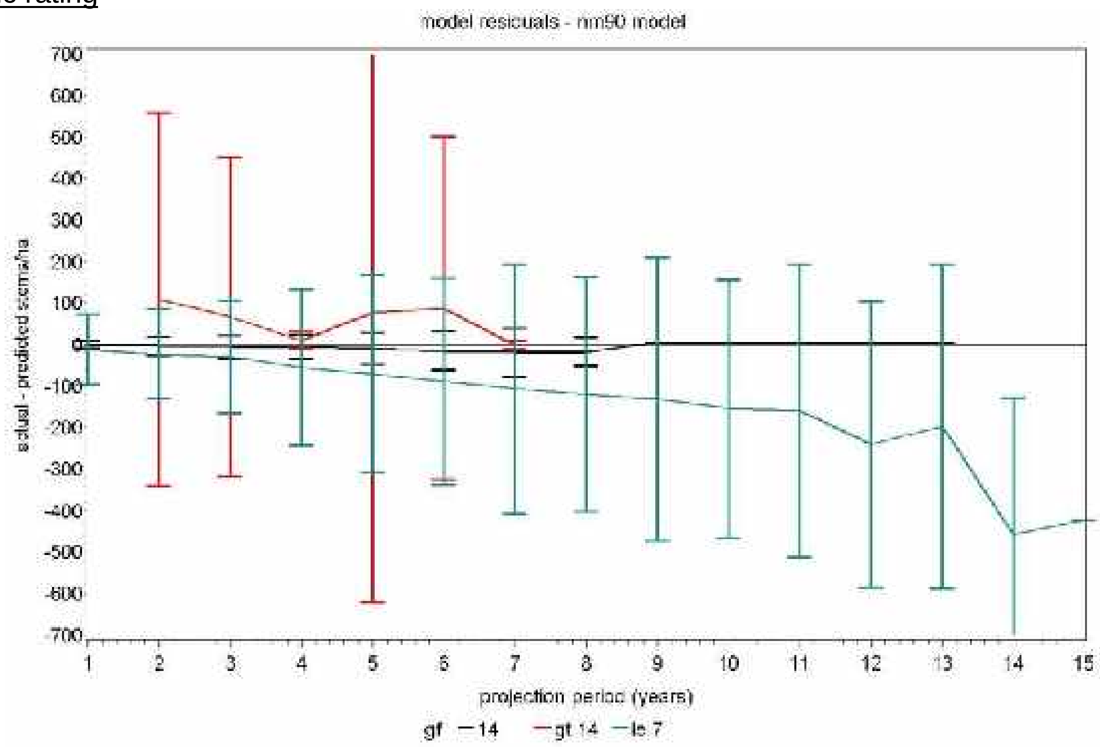


Figure 66. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the NM90 model where projection period has been rounded to the nearest integer.

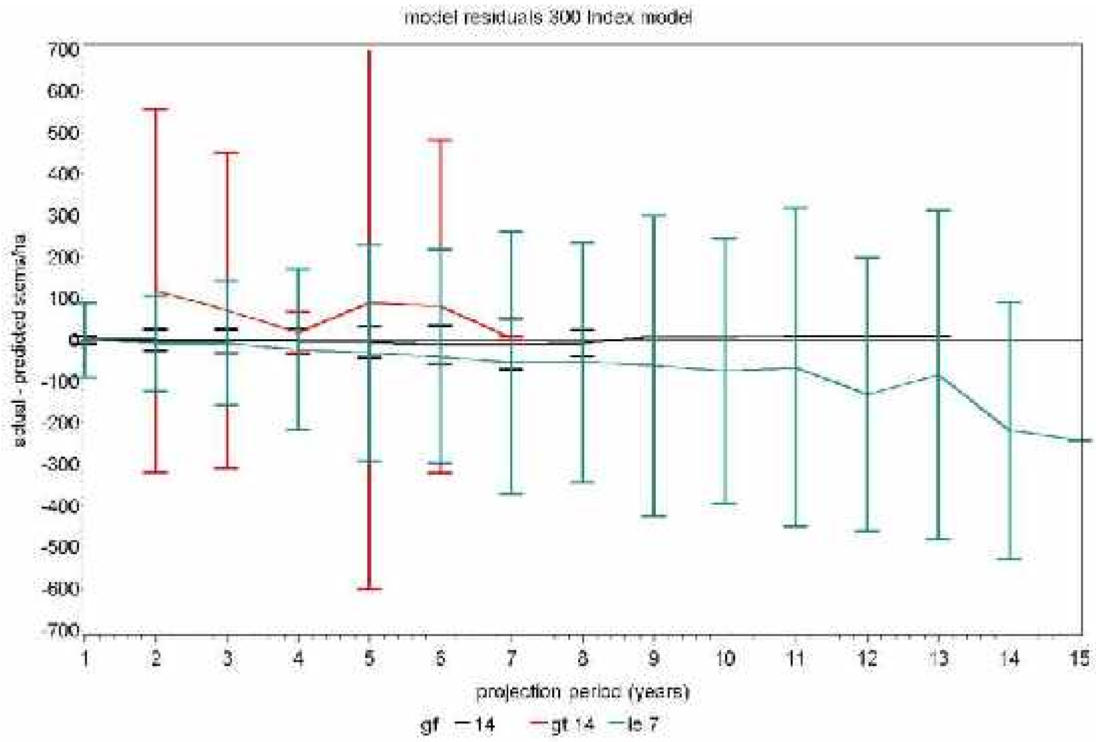


Figure 67. Graph showing mean and two standard deviations for actual – predicted stems per hectare using the 300 Index model where projection period has been rounded to the nearest integer.