Extension of the 300 index growth model – Stage 2

M.O. Kimberley

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EXECUTIVE SUMMARY

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In recent Cooperative projects, a validation of the 300 Index Growth Model revealed a number of biases in the model, and a method of eliminating model bias using 300 Index drift correction was developed. In this study, a modified version of the 300 Index Model is described in which this technique has been used to eliminate the identified shortcomings in the model. In particular, the following model biases have been corrected: under-prediction at ages greater than 30 years; over-prediction when projecting from very young starting values especially on low productivity sites; and over- prediction when the *SI* is either very low or very high. The validation had also indicated a tendency for over-prediction at high stockings but this was not confirmed in this study; detailed analysis of trial data found the model to be unbiased at stockings up to 2,500 stems/ha. Some variation in model performance between site types and regions identified in the validation were confirmed in this study. The new version of the model allows users to enter a 300 Index linear drift parameter which can be used to correct for site-type and/or regional model bias. Tables of drift parameters suitable for use in different regions and site types are given in the main report and a summary table is given below.

Recommended linear drift parameters for regional and site type model adjustment

Drift parameter	Regions
-0.30	Northern coastal sand
-0.20	Auckland
-0.05	Bay of Plenty, West Coast, Canterbury
0.00	Northland, Wanganui/Manawatu, Southern coastal sand
0.05	Waikato, Hawkes Bay, Taranaki, Nelson
0.10	Marlborough
0.15	Gisborne
0.25	Wellington, Otago
0.30	Southland
Except for Sand sites, add 0.05 for Forest sites and subtract 0.05 for Farm sites	

The recommendations in this table can be regarded as a first attempt to establish regional drift parameters, and they are likely to be improved with further data analysis.

INTRODUCTION

Growth rates of radiata pine can vary greatly between sites. For example, the 300 Index, a measure of stem volume mean annual increment, varies between about 10 and 40 m^3/ha/yr on sites where the species is commercially grown in New Zealand (Kimberley et al. 2006), while Site Index (*SI*), the standard index of height growth rate, defined as mean top height (*MTH*) at age 20 years (Goulding 2005), varies between about 15 and 40 m. Forest growth models need to be able to account for such differences in site productivity.

In most growth models, some control of the productivity level is provided intrinsically by the starting values (i.e., the tree height, basal area (*BA*), etc. provided by the user to start the prediction). Alternatively, site productivity can be provided explicitly by a productivity index. For example, most height/age models can be calibrated to a site using either a starting height at a particular age, or the productivity index, *SI*. In either case, sufficient local information on site productivity is provided to enable the model to produce reliable predictions for different site types.

Another approach is to account for variation in growth using site-specific or regional models. Regional models were used when developing an earlier generation of stand-level *BA* and height models for radiata pine in New Zealand (Garcia, 1984; Goulding, 1994). These models also use starting values to modify projected yield, and so in principle can accommodate site differences using both starting value control, and regional model parameterisation. However, only limited analysis was performed to rationalise the necessity for this regional approach to modelling.

The 300 Index Growth Model incorporates explicit productivity indices (both the 300 Index and *SI*) directly into the model formulation (Kimberley et al., 2005), potentially allowing the model to be used on a wide range of site types. The model has been subjected to extensive validation against a nationwide validation dataset, demonstrating that its performance is generally sound across a wide range of sites and regimes (Kimberley & Knowles, 2005; Kimberley & Dean, 2006). In particular, it was found that:

- On average, the model performs well nationwide up to age 30 years, and for final crop stockings below 800 stems/ha.
- The effects of pruning and thinning are accurately modelled.

However, a number of general model shortcomings were identified including:

- Under-prediction in yield above age 30 years.
- An apparent tendency to over-predict yield at stockings above 800 stems/ha.

Some site-type shortcomings were also found including:

- A tendency to over-predict yield for very low productivity sites.
- A tendency to under-predict yield on traditional Forest sites.
- A tendency to over-predict yield on coastal sand sites.

Finally, a number of regional deficiencies in performance were found, including:

- A slight tendency to over-predict yield in Northland, Auckland, the South Island West Coast and Canterbury.
- A slight tendency to under-predict yield in the Bay of Plenty, Nelson and Marlborough.
- Significant under-prediction in Otago and Southland and also in Gisborne and Wellington (based on limited data).

According to Goulding (1979), model validation should be a formal, independent process concerned with evaluating the model as a whole. Validation is not a process of proving whether the model is 'correct' as no model will ever perfectly reflect reality and will always at best only present an approximation of the true situation. Goulding quotes Van Horn (1969) as defining validation as "The process of building an acceptable level of confidence that an inference about a simulated process is a correct or valid inference about the actual process". Thus rather than proving that the model is absolutely correct, the validation step should aim to ensure that forest management decisions made on the basis of model predictions are valid and can be made with confidence. Furthermore, validation can be an iterative process. If the validation identifies clear faults in the model, these should be rectified, and the validation performed again to ensure that the original defects have been eliminated, and that no new problems have emerged.

Thus, following on from the validations of Kimberley & Knowles (2005), and Kimberley & Dean (2006), the correct next step is to eliminate the defects identified by these validations, and where appropriate, to rerun the validation process using the modified model to ensure that the defects have been eliminated. A method of correcting model bias was developed by Kimberley (2006). The purpose of this report is to describe how this method has been applied to eliminate model shortcomings revealed by the validations.

OBJECTIVE

Improve the performance of the 300 Index Growth Model on sites types, or in combinations within the matrix of driving variables, where shortcomings have been identified.

DATA

The data used in this analysis is essentially the same dataset used in the formal validation (Kimberley & Dean, 2006), but with some additional Permanent Sample Plots (PSPs) added from regions poorly represented in that analysis, and slightly different criteria for inclusion of measurements based on measurement date. Except for the correction of prediction bias at ages greater than 30 years which required the use of historic data, only measurements made since 1970 were included in the analysis. A summary of the distribution of the more than 5,200 plots used in the analysis is shown in Table 1. Some 41,576 separate measurements made in these PSPs since 1970 were available, allowing for an extremely rigorous and extensive testing of the model.

Table 1. Distribution of validation plots by region and land use prior to establishment. Only measurements made from 1970 were included in the analysis.

Region	Total	Site Type		
		Farm	Forest	Sand
Northland	606	179	155	272
Auckland	474	21	46	407
Waikato	505	187	167	151
Bay of Plenty	1,072	240	832	0
Gisborne	400	339	61	0
Hawkes Bay	317	192	125	0
Taranaki	37	37	0	0
Wanganui/Manawatu	330	84	11	235
Wellington	166	140	26	0

Nelson	361	143	218	0
Marlborough	200	112	88	0
West Coast	252	2	250	0
Canterbury	189	70	119	0
Otago	252	192	60	0
Southland	111	61	50	0
Total	5,272	1,999	2,208	1,065

300 INDEX DRIFT CHARTS

In this report, extensive use is made of 300 Index drift charts. These were used by Kimberley & Knowles (2005) and Kimberley & Dean (2006) in their validations of the growth model. The technique used was to estimate the 300 Index for each plot measurement and test for any systematic 'drift' in the index over time within each measurement plot. When a systematic drift in the index is absent, it can be concluded that the model is providing unbiased predictions of yield over time. A systematic drift in the index is evidence of model bias. A decreasing drift in the index indicates that the model will over-predict yield, while an increasing drift indicates that the model will under-predict.

300 Index drift charts are generally based on data from numerous PSPs. To simplify interpretation, age is often classified into 5-year classes (5-10 years, 10-15 years, etc.), but when sufficient data is available, annual classes can be used. It is important when analysing the data that corrections are made to account for mean differences in the 300 Index between plots. For example, recently planted stands may have higher 300 Indices than earlier plantings, and because they are over-represented in the younger age classes, an apparent negative drift in the index can occur if the unadjusted mean is plotted against age. To overcome this problem, a linear mixed modelling approach is used. The following mixed model is fitted using the SAS Version 9 procedure PROC MIXED:

[1] $I300_{ijk} = a + p_i + t_j + e_{ijk}$

where $I300_{ijk}$ is the 300 Index estimated for the kth measurement in the jth age class in the ith plot, a is the overall mean, p_i is a random term representing the ith plot, t_j is a fixed effect representing the jth age class, and e_{ijk} is the residual error term. Using this model, the age class fixed effects provide precise measures of any trend or drift in the index over time within plots.

BIAS CORRECTION METHODOLOGY

A number of approaches could be used for rectifying bias in the model, including parameter refitting, and either minor or major changes to the model form and structure. The approach adopted in this study was described by Kimberley (2006) and is based on the 300 Index drift technique used in the model validations. The method involves fitting an empirical function expressing 300 Index drift for the particular site type, regimes or combination within the matrix of driving variables where the model is biased. This function is then incorporated into the model in such a way as to cancel out the drift.

The precise method of achieving as described by Kimberley (2006) is as follows. Firstly note that at the core of the 300 Index Model is a function which predicts *DBH* for an unpruned, unthinned stand as a function of age (T), stocking (N), 300 Index ($I300$), and Site Index (SI). Let us call this function $DBH = F(T, N, I300, SI)$. It is defined so that, when $T = 28.6$ years and $N = 300$ stems/ha, the stem volume MAI corresponding to the predicted *DBH* equals *I300*. Note that because pruning on average results in a loss in growth of 1.4 years, the 300 Index age for an unpruned stand is 28.6 rather than 30 years. Within a run, the variable T will increase resulting in the predicted *DBH* increasing during the run. The parameter N can also vary within a run (although it can never increase) in response to mortality or thinning. In contrast, *I300* and *SI* must remain constant within a run. However, the model can easily be re-coded to allow the *I300* parameter to change within a run. A sudden change in *I300* would cause an instantaneous jump or drop in predicted *DBH*, which would obviously be undesirable. However, a gradual change in *I300* need not result in any undesirable behaviour in predicted *DBH*.

If $g(T)$ is a function expressing the 300 Index over time, then drift in the index can be eliminated by predicting *DBH* using $DBH = F(T, N, I300', SI)$, where $I300' = I300 \times f(T)$, and $f(T) = g(T) / g(28.6)$. This will have the effect of removing the 300 Index drift and hence eliminating model bias. It can be used both to remove general bias in the model, and to produce site-specific versions of the model. It is also possible to simultaneously use more than one drift correction function to eliminate several sources of bias, or to combine corrections for general and site-specific bias.

The advantage of this approach compared with refitting the parameters or changing the entire structure of the 300 Index model, is that it involves only fitting a function to data that deviates slightly from a constant value, as is generally the case with 300 Index drift. In many cases, a simple linear function is sufficient for $f(T)$ to adequately represent the departure from a constant value.

APPARENT BIAS AT HIGH STOCKINGS

The model validation revealed an apparent tendency for over-prediction at stockings above 800 stems/ha (Kimberley & Dean, 2006). The evidence was based on a tendency for highly stocked plots to have a lower 300 Index on average, compared with lower stocked plots. For example, in the complete validation data set, plots with a stocking greater than 800 stems/ha had an average 300 Index of about 20, while plots at lower stockings had an average index of about 25. Assuming that both high and low stocked stands are on sites of similar average productivity, this suggested that the model over-predicts at high stockings. However, the evidence is not conclusive. An alternative explanation is that highly stocked stands are generally located on less productive sites, and the reduced 300 Index in the validation data set is simply a genuine reflection of site productivity.

To determine which of these explanations is correct, the model was tested against a field trial in Tarawera Forest with a wide range of stockings on the same site (RO 955). This trial was not used originally in developing the model, and thus provided an independent test of the performance of the model across a range of stockings. The 300 Index was predicted for each plot in the trial at ages 10, 15, 20, 25 and 30 years, and plotted against stocking (Figs. 1-5). Because all plots are from the same site, there should be no general trend in the index with stocking if the model is performing correctly.

There is evidence for under-estimation of the 300 Index in several very highly stocked plots of about 4,000 stems/ha at age 10 years (Fig. 1), but no evidence of 300 Index bias at stockings up to 2,500 stems/ha at this age. Between ages 15-30 years, there is no evidence of any clear relationship between stocking and 300 Index (Figs. 2-5). It can thus be concluded from this trial that the model shows no evidence of any bias related to stocking, except for a slight tendency to over-predict at very high stockings at young ages (e.g., 4,000 stems/ha at age 10 years). This is of little practical importance as radiata pine is not grown at such high stockings in normal circumstances. It was therefore decided not to correct this minor defect at this stage. It is concluded that the suggestion by Kimberley & Dean (2006) that the model over-predicts at high stockings was based on an erroneous assumption that stocking is unrelated to site quality.

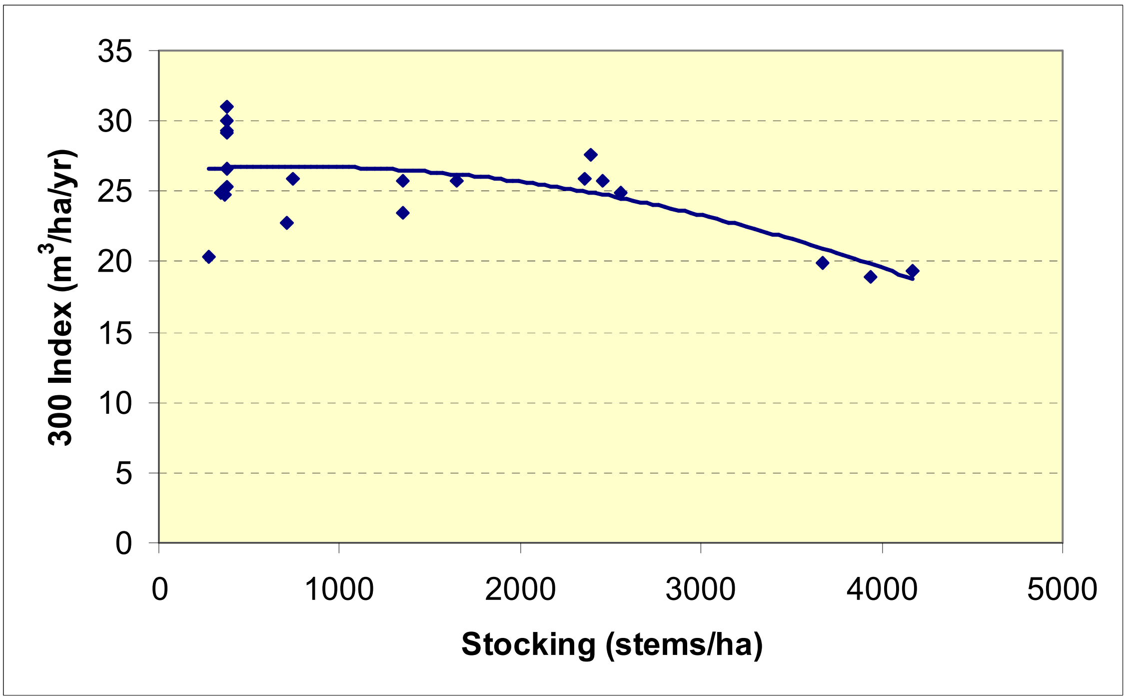

Fig. 1. 300 Index versus stocking for plots from RO 955 at age 10 years.

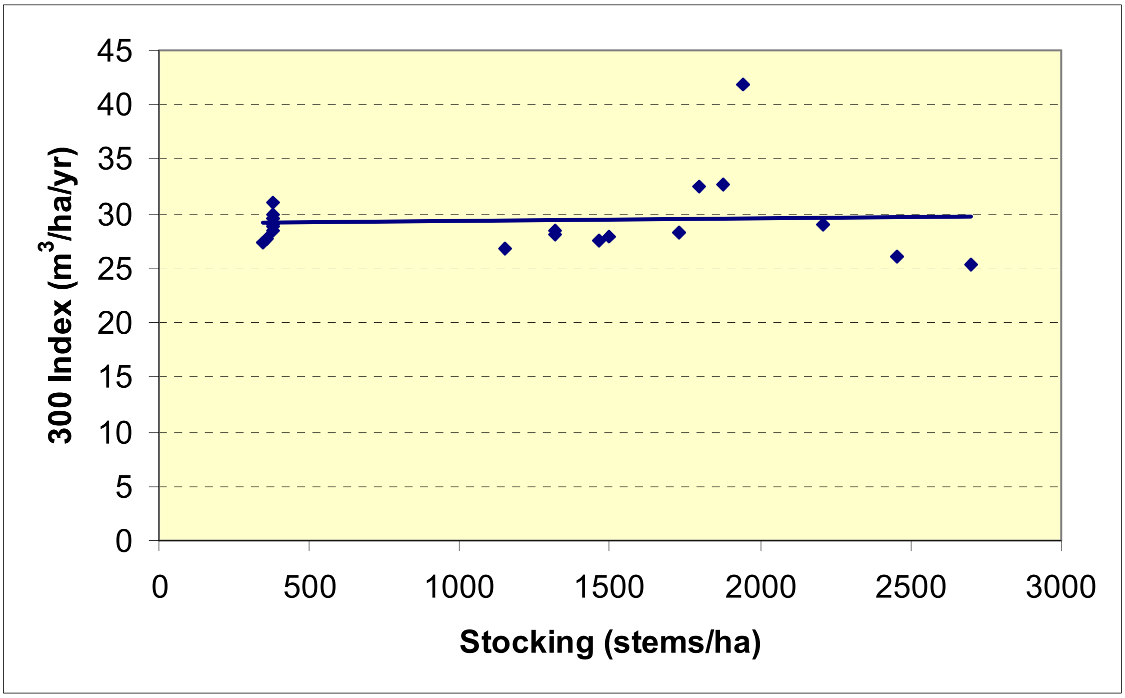

Fig. 2. 300 Index versus stocking for plots from RO 955 at age 15 years.

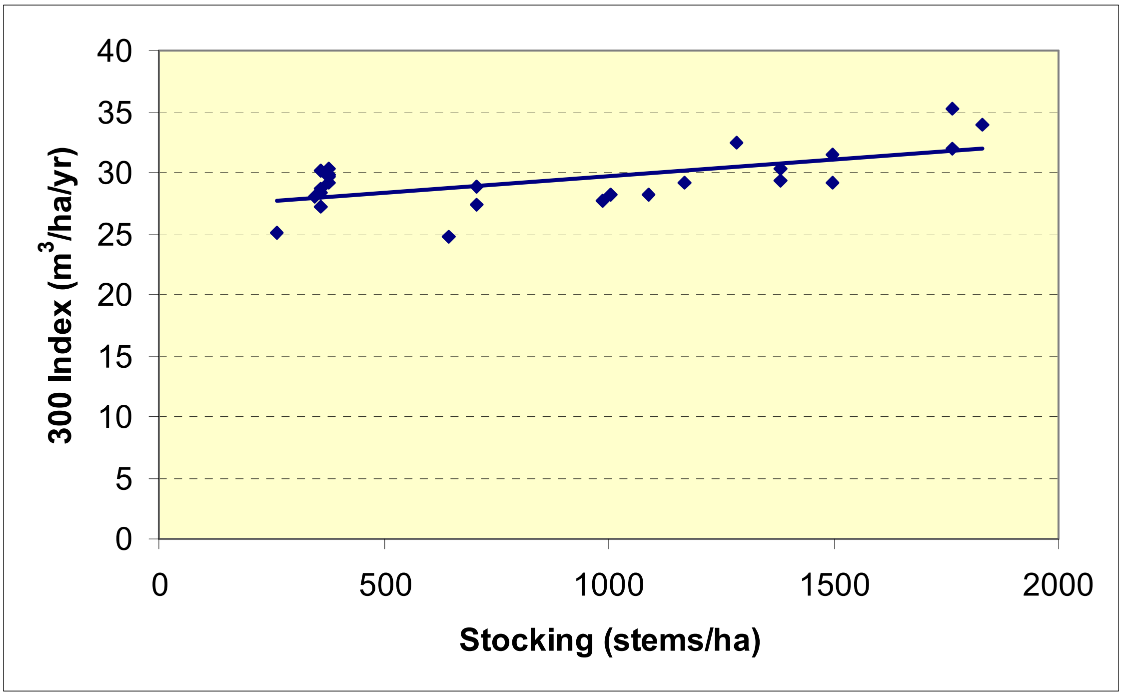

Fig. 3. 300 Index versus stocking for plots from RO 955 at age 20 years.

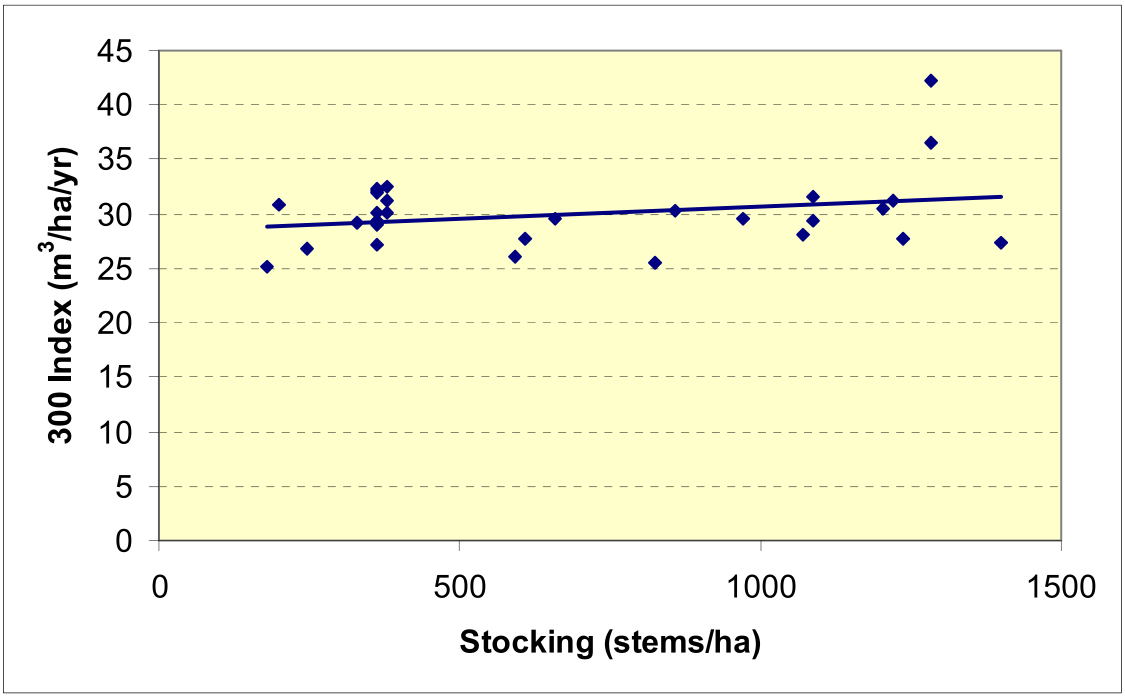

Fig. 4. 300 Index versus stocking for plots from RO 955 at age 25 years.

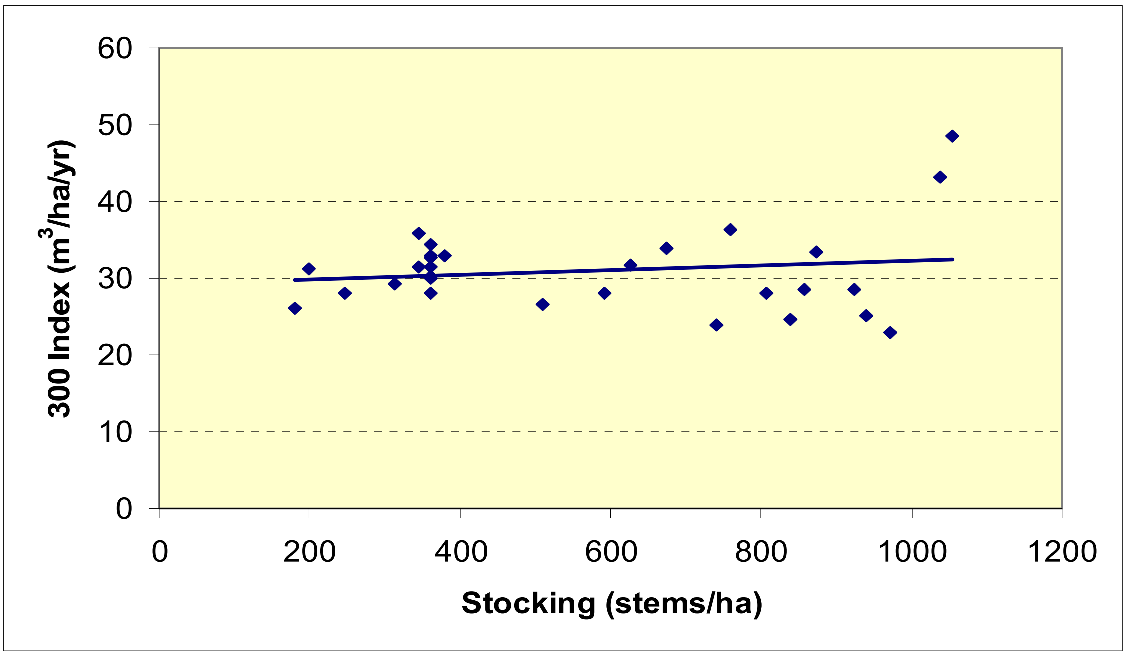

Fig. 5. 300 Index versus stocking for plots from RO 955 at age 30 years.

ELIMINATION OF BIAS AT CERTAIN PREDICTION AGES AND SITE PRODUCTIVITY LEVELS

Using 300 Index drift charts, Kimberley & Dean (2006) showed that there was significant positive drift in the 300 Index beyond age 30 years. They also showed evidence of negative drift in the index on low productivity sites as defined by the 300 Index. In part, the latter was due to the effect of coastal sand sites which showed a pronounced negative drift. Therefore, sand sites have been excluded from Fig. 6 which shows 300 Index drift in the current data set for five productivity classes. This Figure shows the upward drift in the index for older ages, although, as shown later, this effect is better analysed using historic PSPs chosen specifically to cover this age range. Between ages 10 and 30 years, the 300 Index is stable and horizontal in all five site classes indicating no consistent bias in the model for any class. However, at very young ages below 10 years, there is some negative drift, especially in the less productive classes. This means that the model will tend to over-predict yield when projecting from very young starting ages, especially on low-productivity sites.

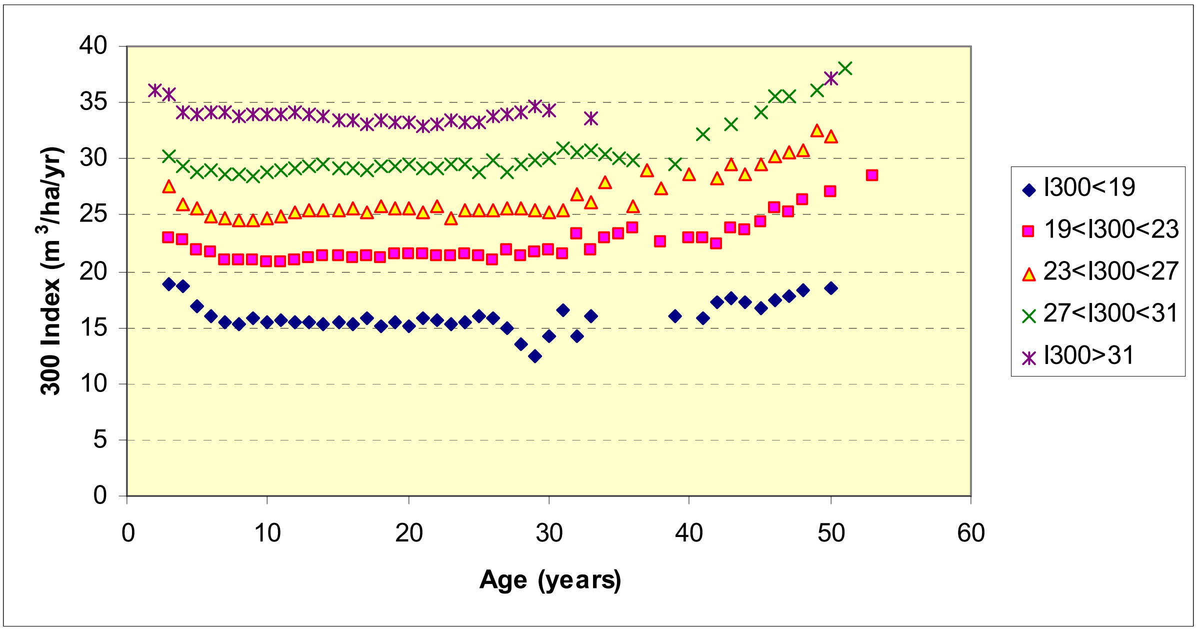

Fig. 6. Chart showing 300 Index drift using original model for five 300 Index productivity classes, excluding coastal sand sites.

A function to correct the bias at ages greater than 30 years was fitted using historic data from older stands by Kimberley (2006). To correct the bias at very young ages, a function was fitted to the age 20 and under data in the drift chart shown in Fig. 6. These two bias correction functions, one accounting for bias at older ages, and the other at very young ages, are given by the following equations, with T being age in years and I the 300 Index:

$$
[2] \quad
\begin{aligned}
f(T) &= 1 + 0.0221 \times (T - 6.77)^2, && \text{when } T < 6.77 \;\&\; I \leq 15.9 \\
f(T) &= 1 + I^{-3.256} \times 180.5 \times (T - 6.77)^2, && \text{when } T \leq 6.77 \;\&\; I > 15.9 \\
f(T) &= 1, && \text{when } 6.77 < T \leq 25 \\
f(T) &= 1 + 0.000420 \times (T - 25)^2, && \text{when } 25 < T \leq 60 \\
f(T) &= -0.255 + 0.0295 \times T, && \text{when } T > 60
\end{aligned}
$$

Up to age 6.77 years, this function is a decreasing quadratic equation, with a more extreme slope for less productive stands. This transitions smoothly into a constant of 1 between ages 6.77 and 25 years (i.e., no bias correction is required between these ages). Between ages 25 and 60 years the function is an increasing quadratic equation which transitions to a linear function above age 60 years. This function is shown plotted against a drift chart for the entire data set excluding sand sites in Fig. 7. The function was incorporated into the 300 Index Model using the bias correction procedure described above. In the 300 Index drift chart comparing the five productivity classes produced using this age-bias corrected model (Fig. 8), the consistent patterns of drift visible in Fig. 6 have been largely eliminated, and the trends are horizontal in all productivity classes.

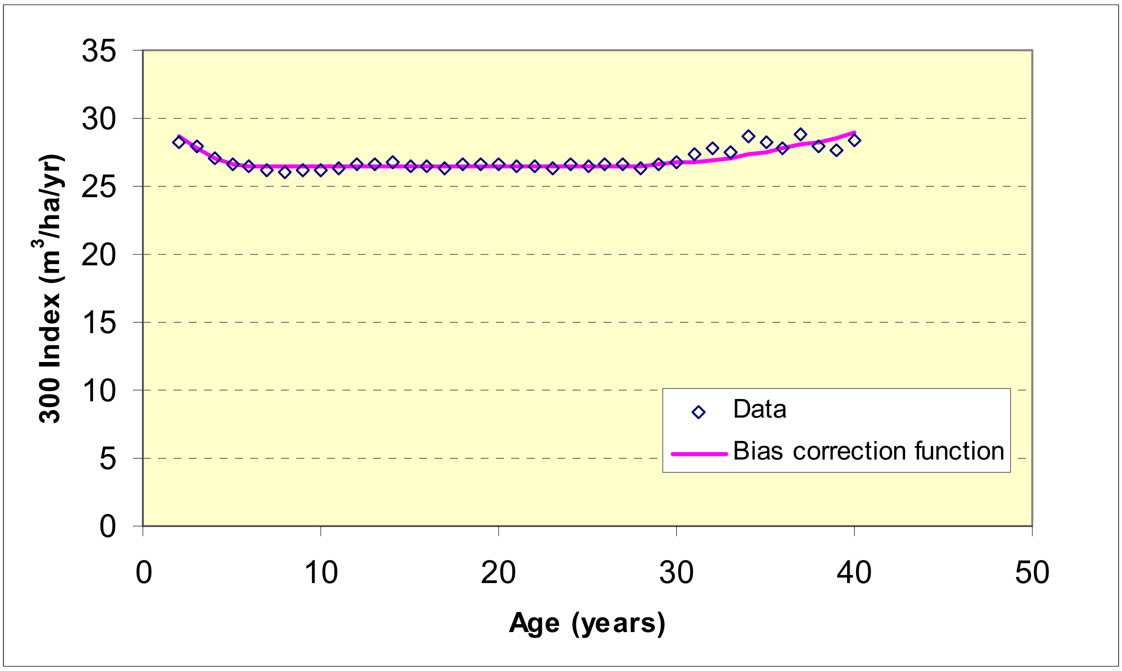

Fig. 7. 300 Index dift chart for the complete data set excluding coastal sand sites. Also shown is the bias correction function (Equation [2]), standardised to the mean 300 Index of 26.4 as appropriate for this data.

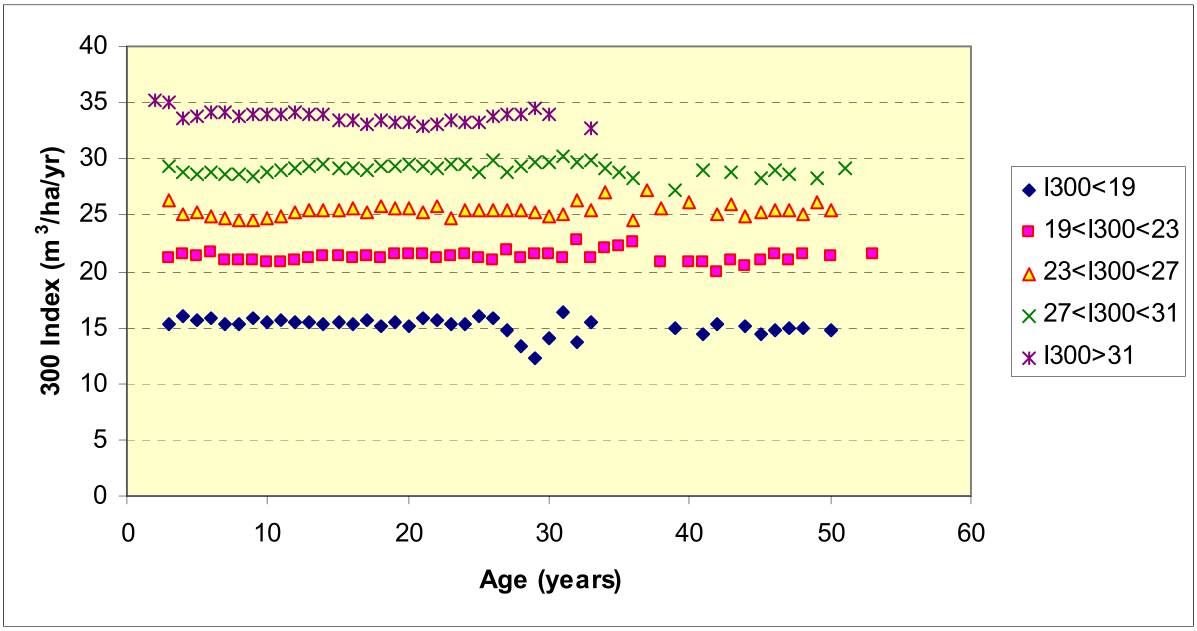

Fig. 8. Chart showing 300 Index drift using the age-bias corrected model for five 300 Index productivity classes, excluding coastal sand sites.

The validation also suggested a tendency for negative 300 Index drift at low *SI*, and analysis of the current data gives some indication of a negative drift for *SI* below 25 m, and also a slight suggestion of negative drift for *SI* above 35 m (Figs. 9 & 10). To correct these minor biases, a linear drift of -0.02 $m^3/ha/yr^2$ has been introduced into the model for every metre of *SI* below 25 m,and for every metre aove 35 m, with a maximum negative drift of -0.2.

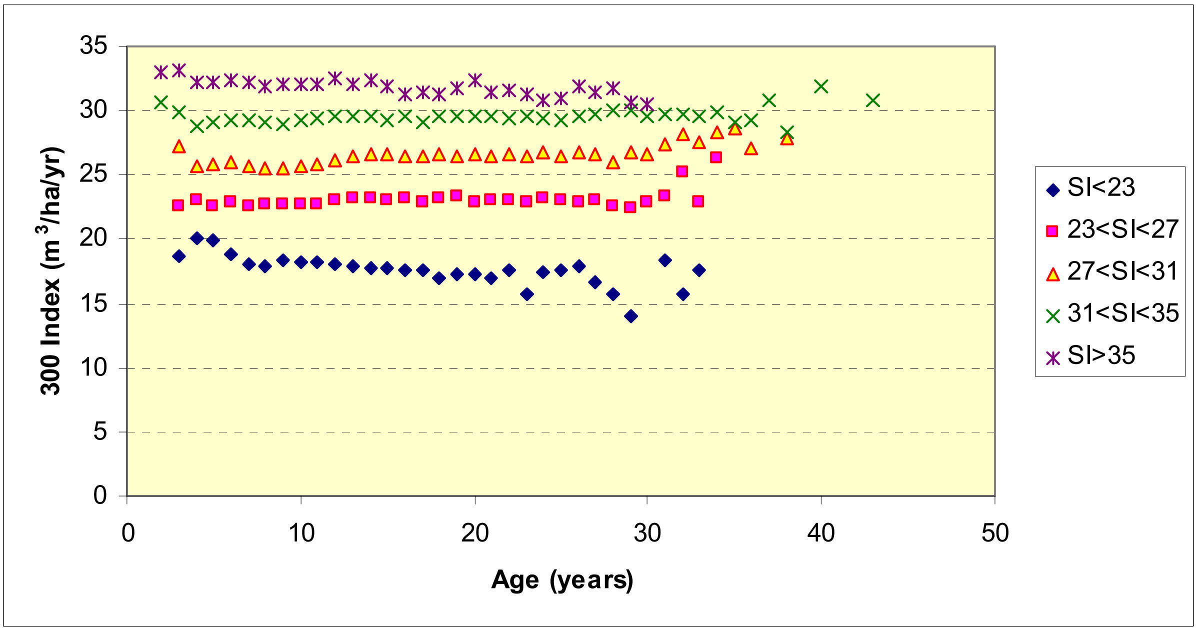

Fig. 9. 300 Index drift chart using the age-bias corrected model for five *SI* productivity classes, excluding coastal sand sites.

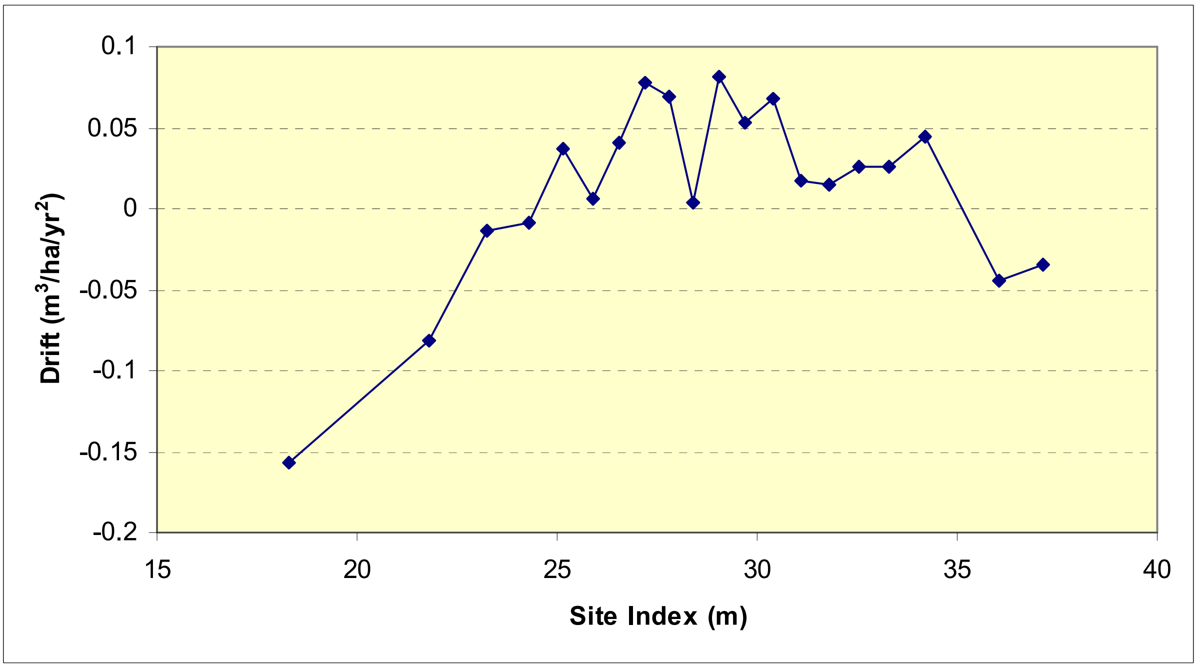

Fig. 10. Chart showing mean 300 Index drift using the age-bias corrected model in each of 20 *SI* classes (based on the 5th, 10th, etc. *SI* percentiles), excluding coastal sand sites.

The model adjustments described above to remove age and site productivity related biases are mostly minor in nature. In most situations they leave the model either unchanged or only very subtly altered. They only affect model predictions significantly on extreme sites (e.g., very low *SI*), and extreme ages. The most important change is the older-age bias correction which introduces an increase in the growth trajectory at ages greater than 25 years, and begins having a pronounced effect above 30 years. But as radiata pine rotation lengths are generally less than 30 years, this is mostly of only academic interest. The performance of this modification was tested using data from 45 historic PSPs, chosen because they had one or more measurement at an age greater than 45 years. These PSPs were widely distributed including plots from Northland, Auckland, Bay of Plenty, Waikato, Otago and Southland. The 300 Index drift in these PSPs is shown for the original model, and for the modified model in Fig. 11. The strong positive drift in the index above age 30 years is clearly apparent for the original model, but is largely eliminated in the bias-corrected version of the model.

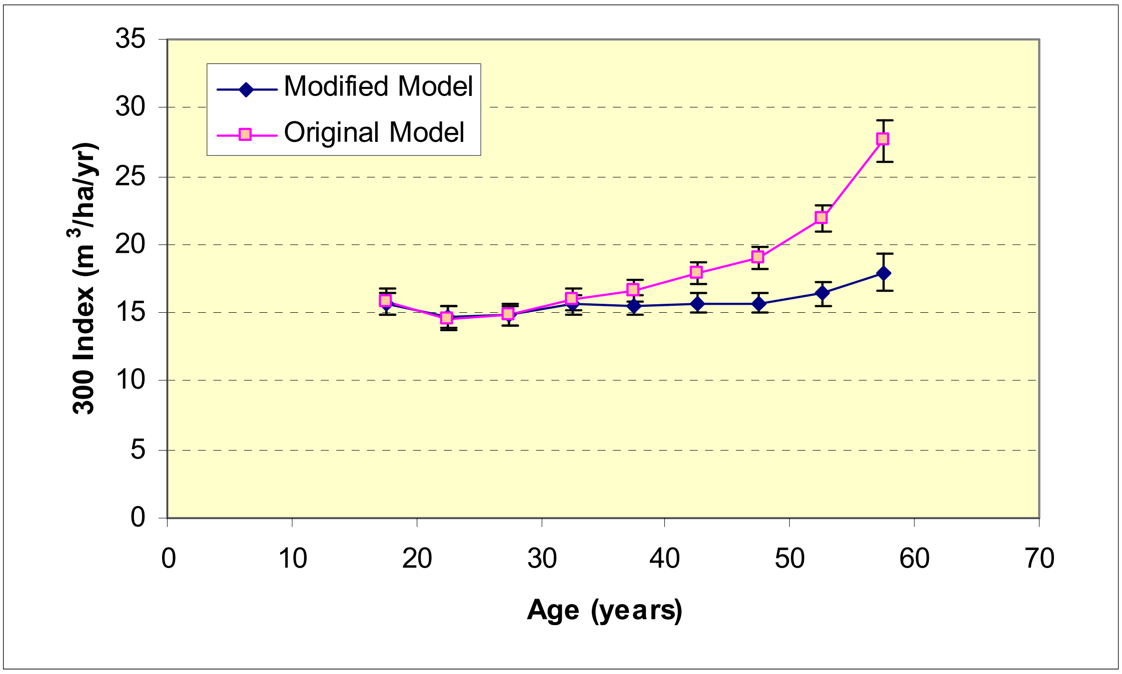

Fig. 11. 300 Index drift chart based on data from 45 PSPs for the original 300 Index model, and the age-bias corrected model.

SITE TYPE BIAS

In the validation of Kimberley & Dean (2006), plots were classified according to previous vegetation cover into ex-pasture 'Farm' sites, traditional 'Forest' sites, and also into coastal 'Sand' sites. The validation revealed a marked tendency for the 300 Index Model to over-predict yield on North Island coastal sand sites. There was a slight tendency to under-predict on traditional Forest sites, but the model appeared unbiased on Farm sites. Similar results are evident in this study, with a strong negative drift for Sand sites, and a slight tendency for the productivity gap between Farm and Forest sites to converge over time (Fig. 12).

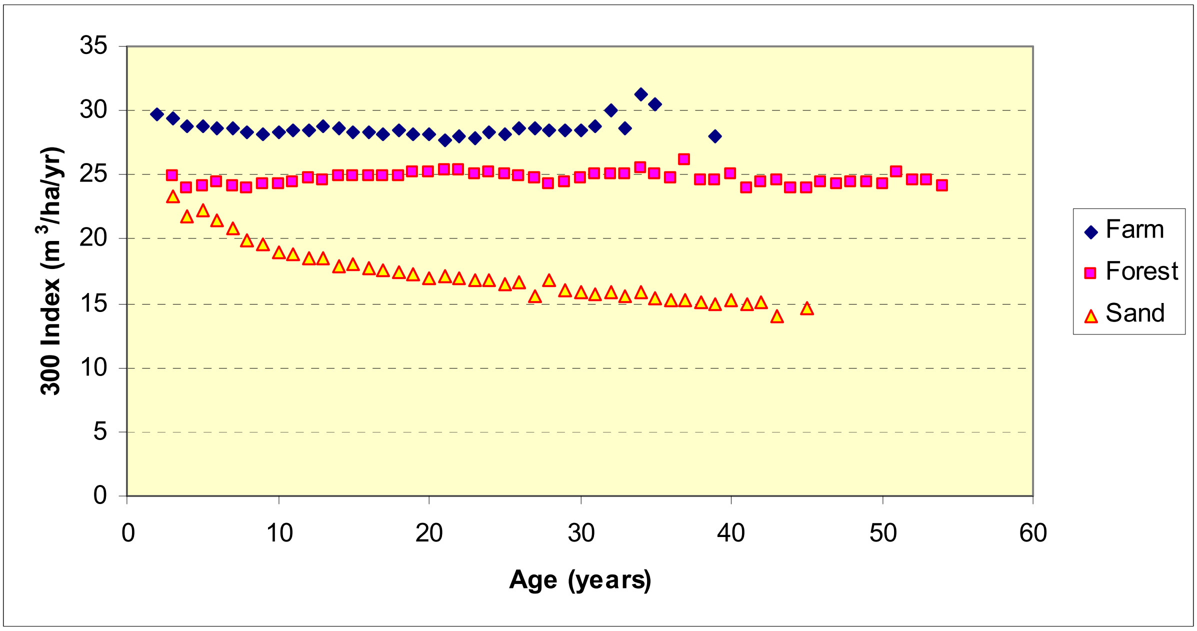

Fig. 12. 300 Index drift chart for three site types using the age-bias corrected model.

To overcome these site type biases, linear drift parameters for each site type were estimated from the data using measurements between ages 5 and 35 years, by the following random coefficient regression model fitted using the SAS Version 9 procedure PROC MIXED:

[3] $$I300_{ikl} = s_i + p_k + sd_i \times Age + e_{ikl}$$

where $I300_{ikl}$ is the 300 Index estimated for the lth measurement in the kth plot of site type i, s_i is a fixed effect term for site type i, p_k is a random effect term for the kth plot, sd_i is a fixed drift slope term for site type i, Age is the age of the measurement, and e_{ikl} is the residual error term.

The drift parameters estimated using this model, are shown in Table 2. These imply, for example, that when projecting a stand measurement forward for 10 years on Forest sites, the model will on average slightly under-predict volume MAI by 0.5 m^3/ha/yr, while average bias on Farm sites will be positive but negligible at 0.1 m^3/ha/yr. On coastal sand sites, the bias will be more substantial with MAI over-prediction over the ten years of 2.1 m^3/ha/yr.

Table 2. Drift parameters to correct site type bias in the 300 Index Model.

Site Type	Drift Parameter ($m^3/ha/yr^2$)
Coastal Sand	-0.21
Farm	-0.01
Forest	0.05

To test the use of linear drift correction for removing site type bias, a test version of the 300 Index model was programmed in Visual Basic for Applications (VBA) which allows the user to enter a linear drift correction parameter for each model run. This programme was then used to estimate 300 Index values from each PSP measurement using the appropriate site type linear drift correction parameter from Table 2. The 300 Index drift chart produced from these runs (Fig. 13) shows that drift in the 300 Index is on average largely eliminated for each site type when linear drift corrections are applied. There is still some negative drift for coastal sand forests below age 10 years, and the model will therefore tend to over-estimate yield on these sites when run from a very young age. However, beyond age 10 years, the drift-corrected model is unbiased for Sand sites.

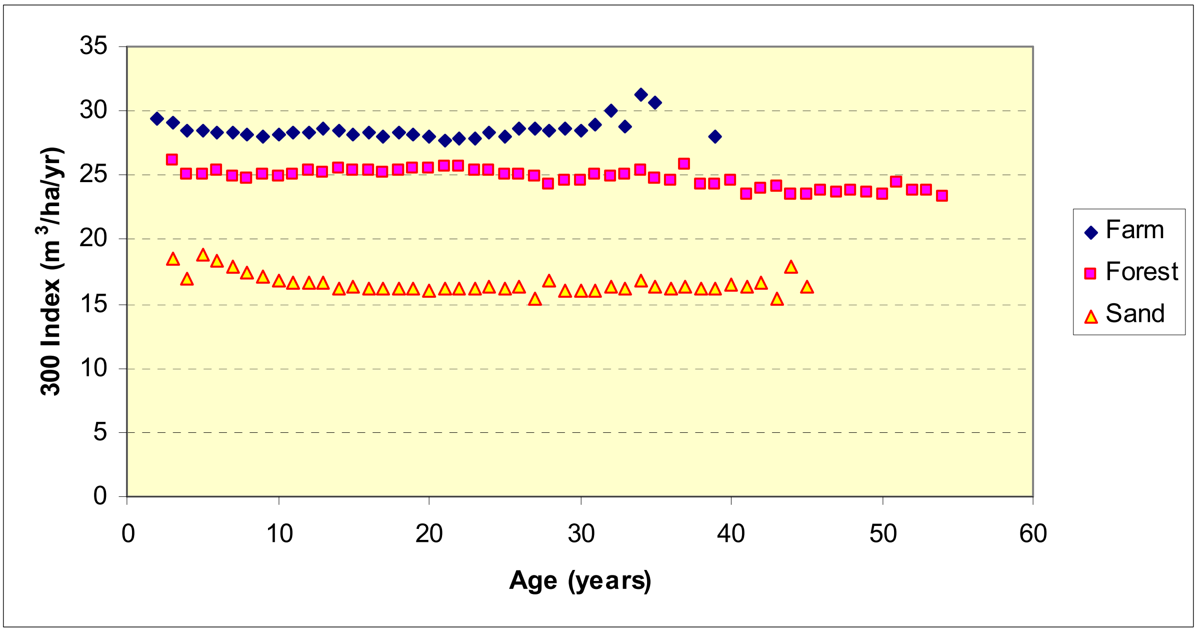

Fig. 13. 300 Index drift chart for three site types using the drift parameters given in Table 2.

REGIONAL MODEL BIAS

The validation showed some regional variation in model performance. There was a slight tendency to over-predict yield in Northland, Auckland, the South Island West Coast and Canterbury, a slight tendency to under-predict yield in the Bay of Plenty, Nelson and Marlborough, and a marked tendency to under-predict in Otago and Southland and also in Gisborne and Wellington (based on limited data). The somewhat more extensive data used in the current study gave generally similar results as shown by the 300 Index drift charts in Fig. 14 (North Island), and Fig. 15 (South Island). An earlier validation (Kimberley & Knowles, 2005) indicated that the strong tendency to over-predict on coastal sand sites was confined to forests north of Auckland, and was absent in the southern North Island. A similar result was obtained in this study, when coastal sand plots were separated into the Northland/Auckland regions, and the Waikato/Wanganui/Manawatu regions (Fig. 16).

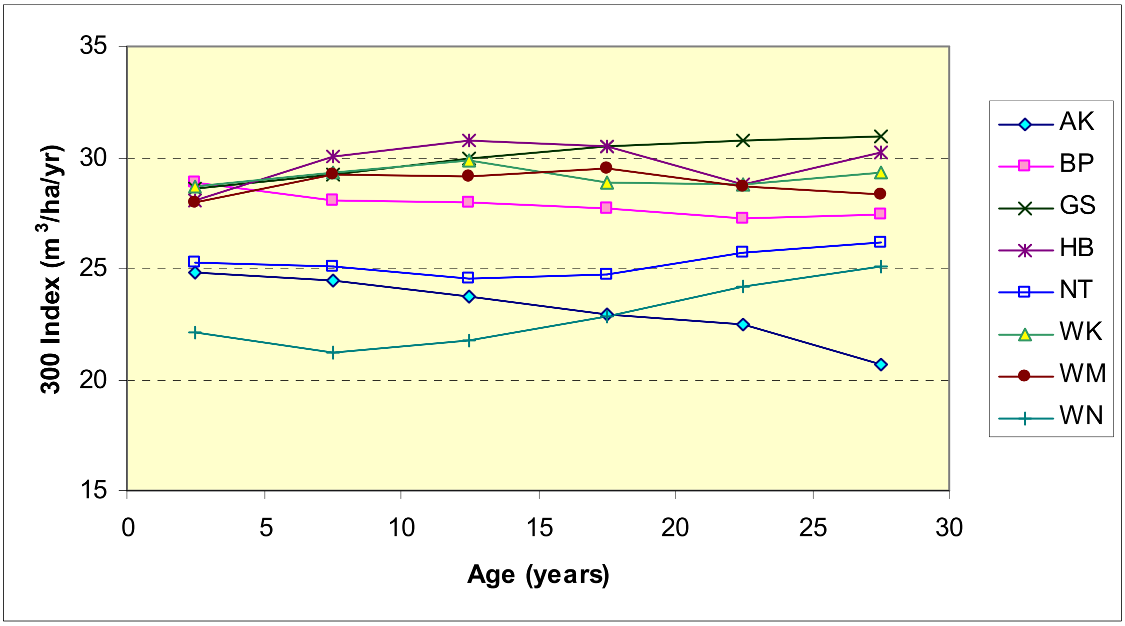

Fig. 14. 300 Index drift chart for North Island regions using the age-bias corrected model. Coastal sand sites are excluded. Taranaki region had insufficient data to provide reliable estimates.

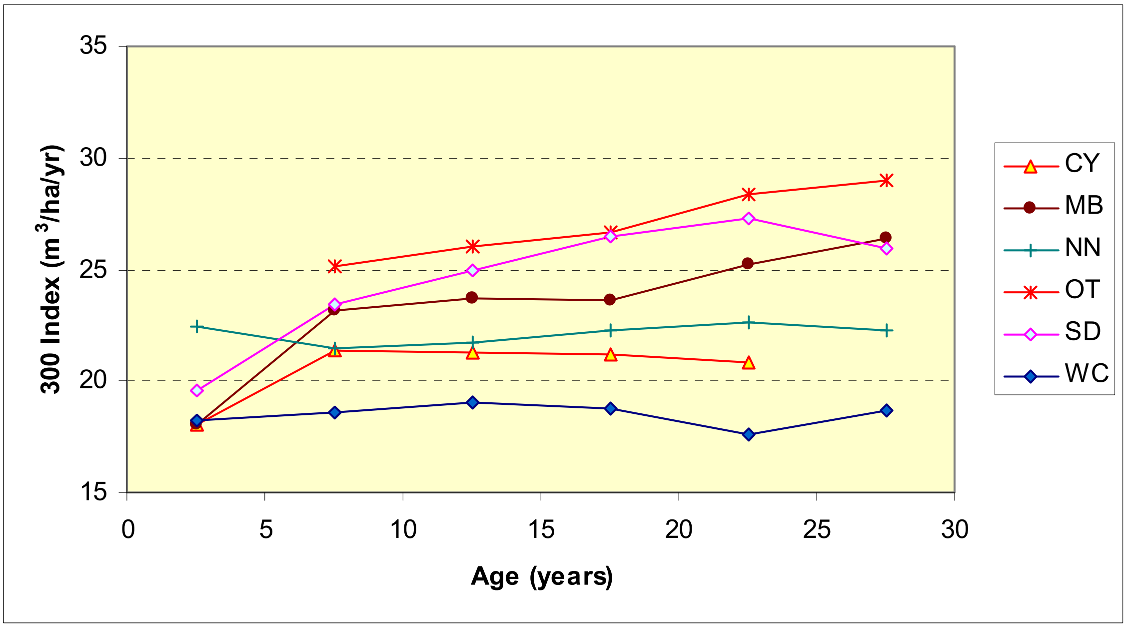

Fig. 15. 300 Index drift chart for South Island regions using the age-bias corrected model.

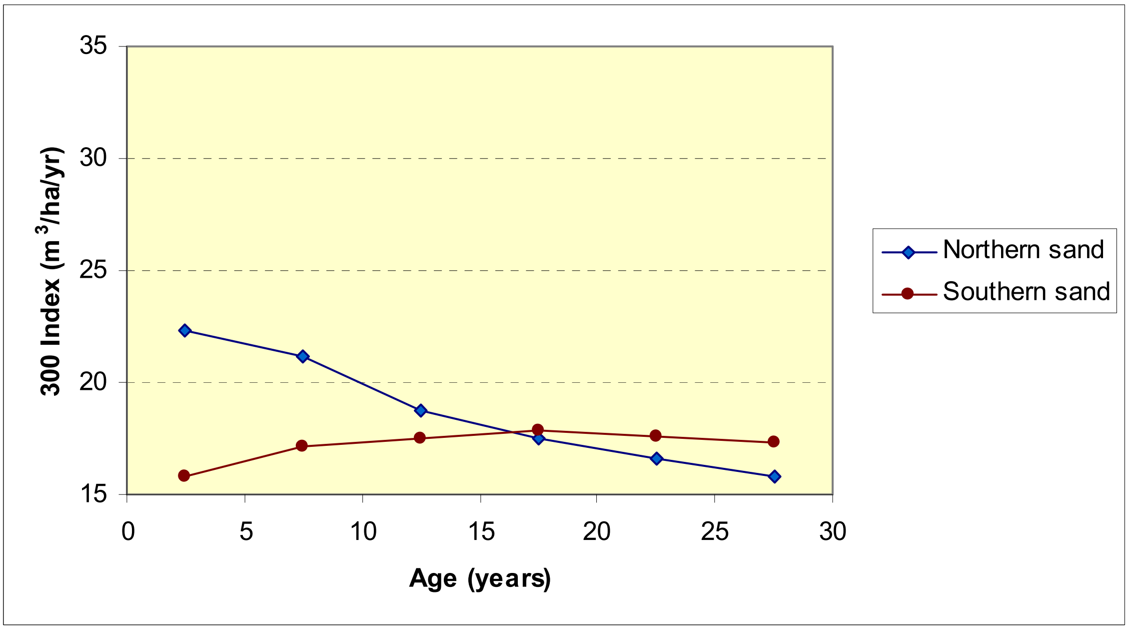

Fig. 16. 300 Index drift chart for coastal sand forests in northern and southern North Island using the age-bias corrected model.

To overcome these regional biases, linear drift parameters for each region were obtained using a model similar to Model [3], with region replacing site type. Site type and regional drift parameters were also estimated simultaneously using the following random coefficient regression model fitted using PROC MIXED:

[4] $$I300_{ijkl} = s_i + r_j + p_k + sd_i \times Age + rd_j \times Age + e_{ijkl}$$

where $I300_{ijkl}$ is the 300 Index estimated for the lth measurement in the kth plot, of site type i, and region j, s_i is a fixed effect term for site type i, r_j is a fixed effect term for region j, p_k is a effect term for the kth plot, sd_i is a fixed drift slope term for site type i, rd_i is a fixed drift slope term for region j, Age is the age of the measurement, and e_{ijkl} is the residual error term. This model was only fitted to the Farm and Forest site types, with Sand forests being treated separately.

The estimated drift parameters from the above models are shown in Table 3. There was strong positive drift (implying model under-prediction) in Southland, Otago, Wellington, and to a lesser extent, Gisborne. There was strong negative drift in northern coastal sand forests and in the Auckland region. Other regions showed only minor positive or negative trends. When the regional and site-type linear drift parameters in Table 3 were applied to each PSP in the dataset using the linear drift version of the model, 300 Index drift in each region was largely eliminated (Figs. 17-19). Linear drift correction appeared to be generally effective in removing regional biases in the model.

Table 3. Drift parameters fitted to each region, and fitted in combination to site type and region.

Region	Drift Parameter ($m^3/ha/yr^2$)	
	Fitted separately for each region	Regional and site-type parameters fitted in combination
Northland	0.02	0.02
Auckland	-0.18	-0.21
Waikato	-0.01	0.04
Bay of Plenty	-0.03	-0.03
Gisborne	0.09	0.15
Hawkes Bay	0.02	0.05
Taranaki	-0.04	0.03
Wanganui/Manawatu	-0.03	0.02
Wellington	0.22	0.27
Nelson	0.06	0.05
Marlborough	0.12	0.12
West Coast	0.01	-0.04
Canterbury	-0.06	-0.07
Otago	0.21	0.27
Southland	0.28	0.29
Forest sites		0.05
Farm sites		-0.05
Northern N.I. coastal sand	-0.28	
Southern N.I. coastal sand	-0.00	

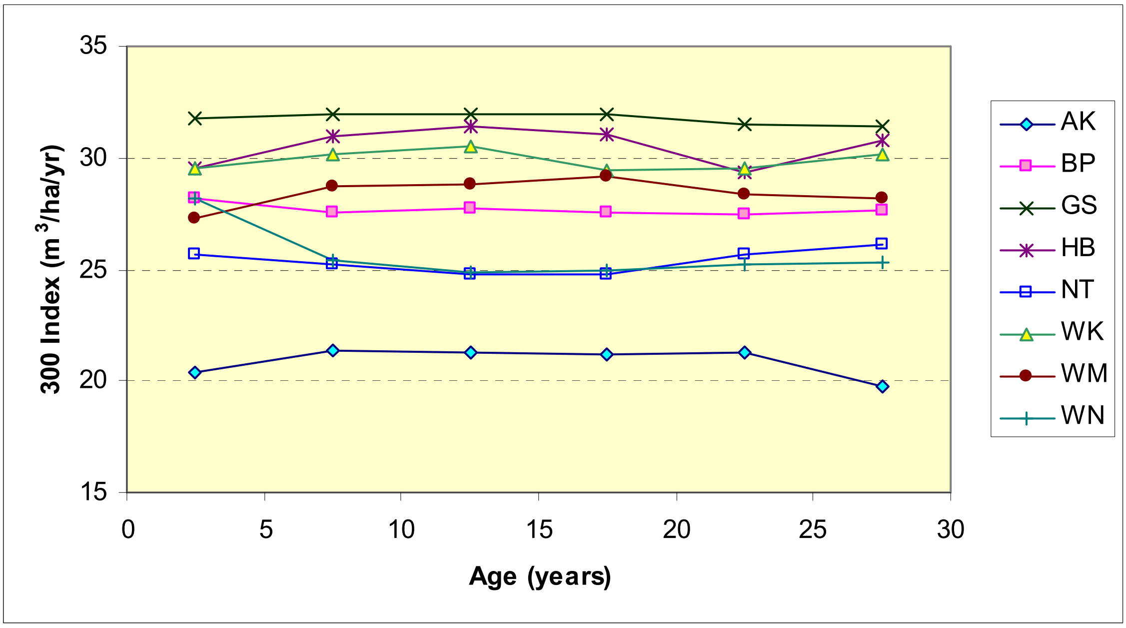

Fig. 17. 300 Index drift chart for North Island regions using linear drift correction for site-type and region. Coastal sand sites are and Taranaki region are excluded.

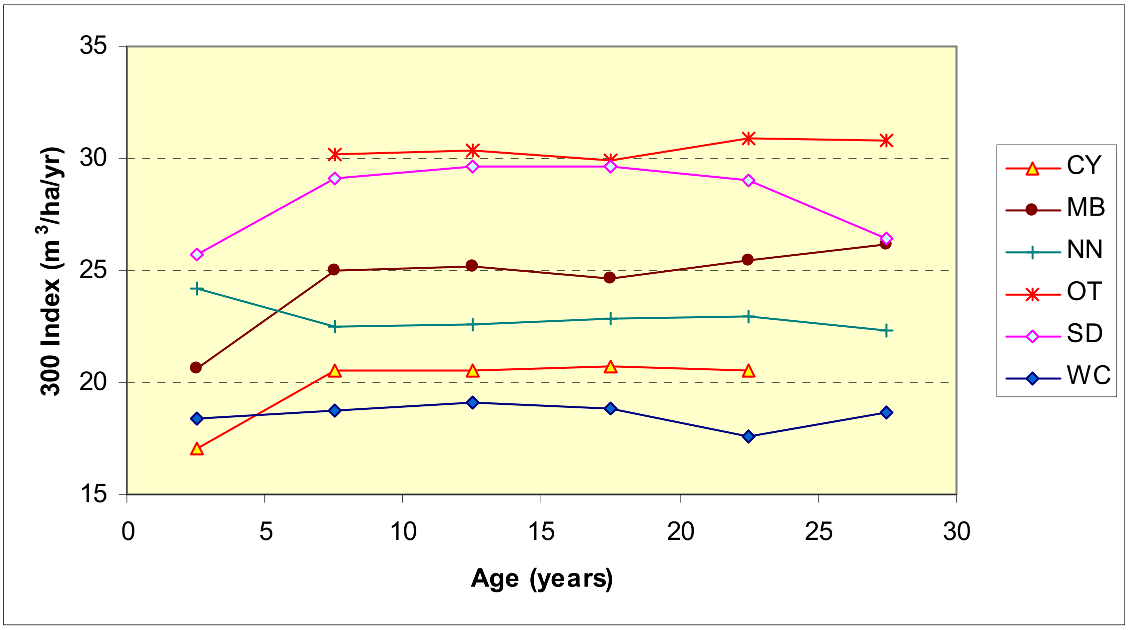

Fig. 18. 300 Index drift chart for South Island regions using linear drift correction for site-type and region.

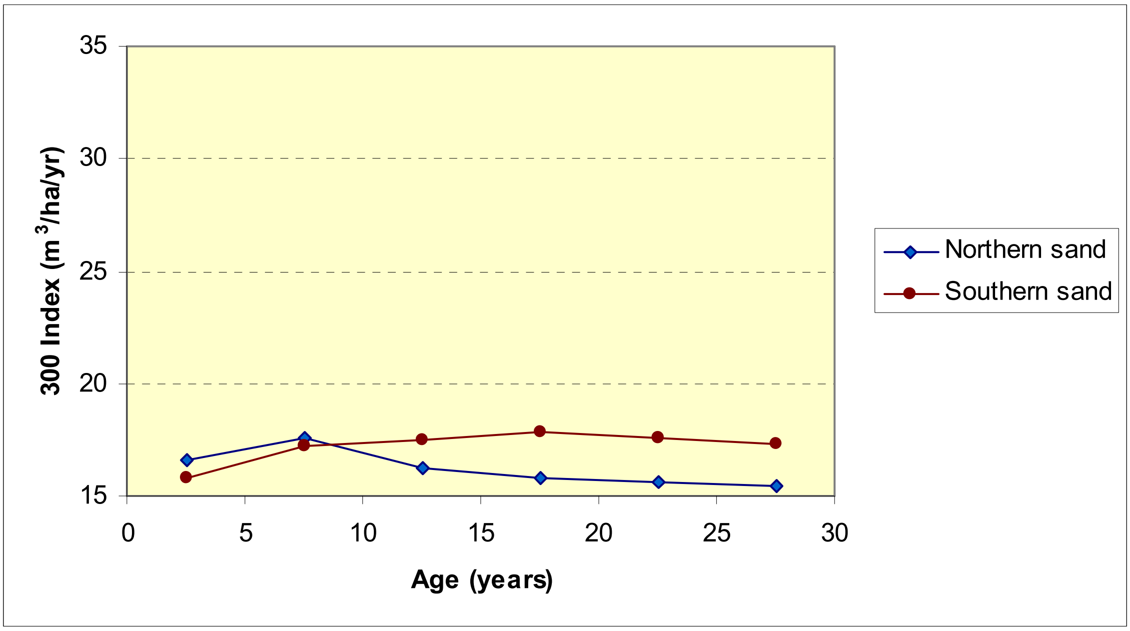

Fig. 19. 300 Index drift chart for coastal sand forests in Northland and Auckland regions, and in southern North Island regions using linear drift correction for site-type and region.

DISCUSSION

Productivity Index drift charts were shown to be useful tools for identifying model bias by Kimberley & Knowles (2005), and were used extensively by Kimberley & Dean (2006). The resultant drift correction methodology developed by Kimberley (2006) and utilised in this study, has proved to be a powerful and effective technique for eliminating model bias. Although drift parameters may be somewhat disparagingly referred to as 'fudge factors', they provide a practical and elegant means of correcting model bias without having to resort to a complete model refit. Furthermore, no parametric nonlinear growth function can perfectly reflect the growth trajectory of a forest stand, especially in a multidimensional model like the 300 Index Model which incorporates both age and stocking as driving variables, and drift correction methodology provides a means of eliminating deficiencies in otherwise well-performing models. The use of this technique is not confined to the 300 Index Model. For example, the generally good performance of the National Height Model used in this study is shown using *SI* drift charts (Figs. 20 & 21), but these also reveal that some subtle improvements in this model may be possible (e.g., a slight negative drift is evident, especially on Sand and low *SI* sites).

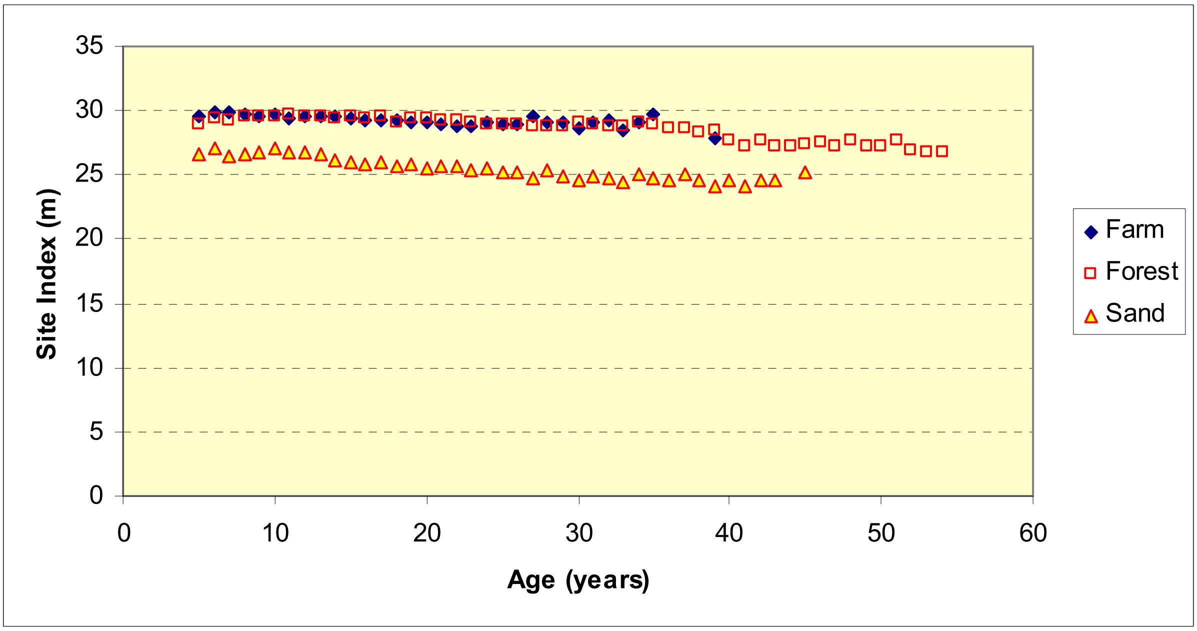

Fig. 20. Site Index drift chart for three site types.

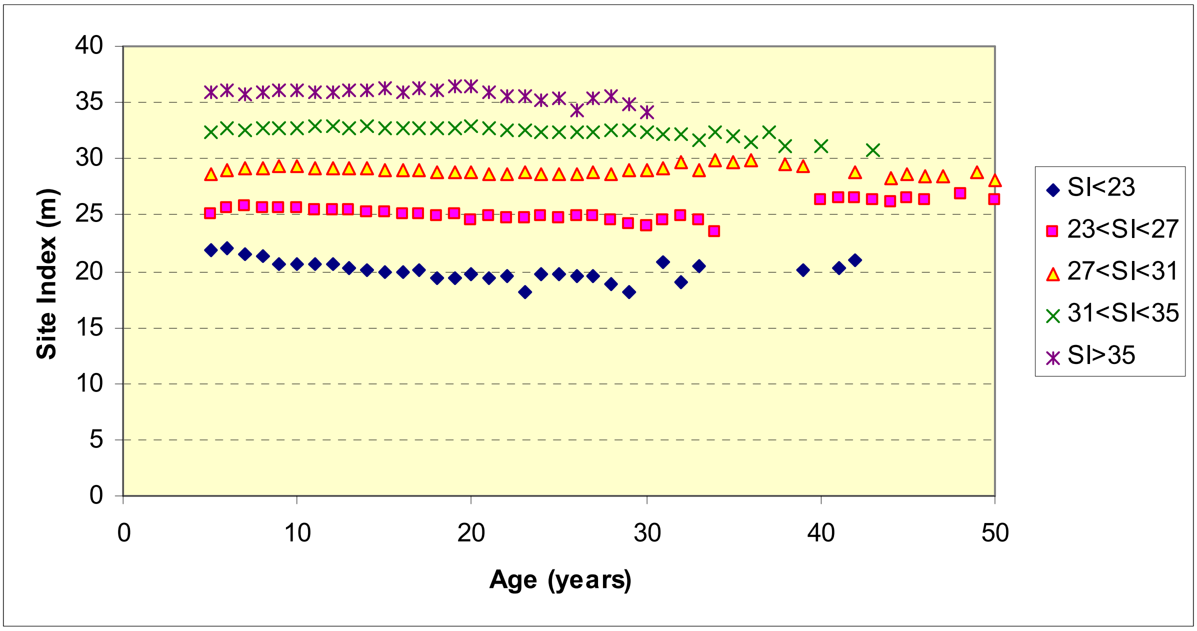

Fig. 21. Site Index drift chart for five *SI* productivity classes.

The validations of the radiata pine 300 Index Growth Model (Kimberley & Knowles, 2005; Kimberley & Dean, 2006) revealed that it performs well nationally across a wide range of site types and regimes. The most significant weakness, a tendency to under-predict yield at ages greater than 30 years, is not surprising in hindsight. The underlying form of the 300 Index *BA* model is the Chapman-Richards function, which has a tendency to reach its asymptote (maximum value) at an earlier age than actually occurs in practice. For this reason, some modellers prefer other functions which display a more gradual asymptotic behaviour (R. Woollons, pers. com.). However, many studies have shown that the Chapman-Richards model represents the behaviour of forest growth over the rotation length of a typical commercial plantation extremely well, arguably better than any other 3-parameter growth function. Nevertheless, because of this asymptotic behaviour, and because the original model dataset included minimal data older than 30 years (Kimberley et al., 2005), the bias at older ages is not surprising. Although the age-bias correction has considerably improved model performance between ages 30 and 50 years (Fig. 11), it has done so at the expense of eliminating the asymptotic nature of the model. It can thus be assumed that at some extreme age, the modified model will over-predict growth.

The causes of site-type and regional variations in 300 Index drift are not entirely clear. They imply that stands in different regions or site types can produce different yields at maturity even when they have identical stand parameters (i.e., stocking, height and *BA*) at an early age. The negative drift in coastal sand sites was interpreted by Kimberley & Dean (2006) as being due to deterioration in nitrogen status of the growing trees during the course of a rotation on these sites. The gradual convergence of Farm and Forest sites was interpreted as reflecting decline in fertility of Farm compared with otherwise similar Forest sites following the cessation of regular fertilisation. However, this convergence is so slow that the initial greater fertility on typical on Farm sites will most likely persist for several rotations. Annual convergence in MAI was quantified as 0.05 $m^3/ha/yr^2$ using Model [2] (Table 2), and 0.10 $m^3/ha/yr^2$ using Model [4] (Table 3). The convergence estimate of Table 3 is probably more precise as it was established by comparing the two site types matched within each region. However, both estimates imply that convergence is almost negligible from a practical viewpoint. Note that the Farm and Forest adjustments in Table 3 should always only be used in conjunction with the corresponding regional adjustments. Also note that the drift parameters for northern and southern coastal sand sites should be used independently of other adjustments, and should not be combined with either the regional or the Farm/Forest adjustments.

Regional model biases are generally only minor, with linear drift within 0.1 $m^3/ha/yr^2$ either side of zero in most regions (Table 3). In fact, for perhaps 90% of the country the unadjusted model will perform well. Regional variation in 300 Index drift presumably reflects regional differences in the way growth limiting factors (e.g., soil fertility, moisture, temperature, exposure, weed competition, disease, etc.) assert themselves as radiata pine stands develop. The most pronounced differences are between those in generally northerly regions (Auckland region and northern coastal sand sites in particular), and those in the most southerly regions (Otago and Southland), and may therefore in part be related to temperature. They imply that, compared to the national average yield curve, and adjusted to the appropriate productivity level using the productivity indices, early growth is slower on cooler sites and faster on warmer sites. However, the trends are not wholly related to latitude - e.g., the Wellington and Gisborne regions have strong positive drift; Canterbury and West Coast have slight negative drift.

It may be inadvisable to assume that drift parameters established between ages 5 and 35 years will be maintained beyond this age range. In fact, by definition, this is impossible. Negative drift if carried on indefinitely will eventually lead to a prediction of zero volume, while positive drift will eventually produce an infinite volume. There is limited information on trends beyond 30 years at the regional level, but the available data suggests that the trends do not continue. For example, older plots in Otago and Bay of Plenty show very similar long-term index trends. Therefore, when the user specifies a regional or site-type drift parameter during a model run, and predictions beyond 30 years are required, the drift parameter is gradually reduced to zero between ages 30 and 45 years, and is set to zero beyond age 45 years.

Although regional drift differences clearly exist, linear drift correction offers a means of adjusting the 300 Index Model to accommodate them. In practice, drift correction could be applied in several ways. If a forest manager has access to high-quality PSP data, testing the model against the data, and deriving customised drift parameters using the techniques described above will be the best solution. If required, parameters could be developed for particular forests, sub-regions, or management units, especially where there are known climatic or soil type differences. If customised drift parameterisation is not possible, the values tabulated in Table 3, or as simplified in Table 4, could be used. Ultimately, if we can gain an understanding of the factors which influence 300 Index drift, it may be possible to link drift directly to environmental variables.

Table 4. Recommended linear drift parameters for regional and site type model adjustment

Drift parameter	Regions
-0.30	Northern coastal sand
-0.20	Auckland
-0.05	Bay of Plenty, West Coast, Canterbury
0.00	Northland, Wanganui/Manawatu, Southern coastal sand
0.05	Waikato, Hawkes Bay, Taranaki, Nelson
0.10	Marlborough
0.15	Gisborne
0.25	Wellington, Otago
0.30	Southland
Except for Sand sites, add 0.05 for Forest sites and subtract 0.05 for Farm sites	

The recommendations in Table 4 can be regarded as a first attempt to establish regional drift parameters, and they are likely to be improved with further data analysis. The extensive nature of the data used in this study means that, even though all plots were individually checked, it is likely that some plots should have been culled, e.g., because of inadequate early history data. Also, in this study, only a little attempt was made to exclude field trial data that may reflect atypical treatments, and no attempt was made to down-weight the data from the multiple plots in replicated field trials. In a few regions, the data is dominated by a few large trials which may not be representative of the region as a whole. Finally, additional PSP data is still available for some regions and could be incorporated into more detailed analyses.

CONCLUSIONS

A number of model biases identified in a recent validation of the 300 Index Growth Model have been corrected. In particular, the model has been modified using the 300 Index drift technique to eliminate: under-prediction at ages greater than 30 years; a tendency to over predict when projecting from very young starting values especially on low productivity sites; a tendency to over predict when the *SI* is either very low or very high. The apparent over-prediction at high stockings has not been confirmed and the model was found to be unbiased at stockings up to 2,500 stems/ha. The new version of the model allows users to enter a 300 Index linear drift parameter that can be used to correct for site-type and/or regional model bias. Generally, continued validation confirms the robustness of the model for different regimes and site types, especially if drift-correction is applied when required.

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