The 300 Index - a volume productivity index for radiata pine

Mark Kimberley, Graham West, Mark Dean, Leith Knowles
Ensis, Rotorua

Abstract

Site Index, defined as dominant height at age 20 years, is the most widely used index of site quality for radiata pine in New Zealand. However, analysis of stocking trials shows that, at a common stocking and age, Site Index is only weakly related to basal area growth, especially at older ages and higher stockings. Site Index, therefore provides only a partial measure of site productivity. We propose a new measure of productivity for radiata pine, the 300 Index, defined as the stem volume mean annual increment at age 30 years for a defined reference regime of 300 stems ha^{-1}. To estimate this index requires the use of several models including a new basal area model, which is briefly described.

Introduction

Knowledge of site quality, and of how tree growth is influenced by environmental factors, is important to forest managers. It plays a major role in regime evaluation, and in calculating probable economic returns from a forest. Two broad methods of characterising site quality are commonly used (Husch *et al.* 2003). The first method is to classify sites directly into site classes on the basis of environmental factors such as climatic variables, soil properties both physical and chemical, or typography. The problem with this approach is that environmental variables have complex and interacting influences, and simple rules based on them can only explain a modest proportion of variation in site productivity.

The second method is to use some characteristic of the trees themselves, or of lesser vegetation, to infer site quality. For example, as proposed by Cajander (1909) and in New Zealand by Ure (1950), the presence or absence of certain indicator species can sometimes be used. However, the best means of assessing site productivity for a particular species is to use a direct measurement of productivity taken from trees of that species. This measurement should ideally be on a numeric scale expressing the site quality in terms of a single figure or productivity index.

Logically, the most direct measure of productivity should be the quantity of wood grown within a given period. However, particularly for regimes of the type commonly used in New Zealand, volume is strongly influenced by stocking, thinning history and mortality. The UK Forestry Commission defines yield classes in terms of maximum volume mean annual increment (MAI) including thinnings, for a set of silvicultural regimes that all have similar maximum volume MAI (Johnson *et al.* 1967).

A more common approach to overcome the effect of stocking is to use the mean height of dominant trees, which is little affected by stocking or thinning, as an index of site productivity for even-aged stands. As discussed by Assmann (1970), this concept originated with F. von Bauer in 19th century Germany, and it came to be widely used internationally. For example, referring to forests in the U.S.A., Belyea (1931) states that, "whereas farm land is classed by actual yield, forest land, because of the effect of density of stocking on yields per acre, must be related by some other factor in which the effect of density or stand crowding is least shown. Such is found in the acceptance of the average height of dominants." This insensitivity of dominant height growth to stocking and thinning has generally been confirmed for *Pinus radiata* (radiata pine) in New Zealand, although a slight tendency for dominant height to increase with stocking has been identified (Maclaren *et al.* 1995).

An index based on height was therefore justified for pragmatic reasons, but it was widely believed that height and stem volume growth were closely related. For example, according to Bruce & Schumacher (1950), "for a single species, variations in height growth due to variations in the site factors are found to be closely and positively correlated with variations in growth in diameter or volume that are similarly caused. It follows from this that height growth may be used as an index of site." A productivity index for even-aged stands was therefore defined as the height attained by the average dominant tree at an arbitrarily chosen age, and the term *Site Index* (SI) was used for this productivity index.

The measure of dominant height most commonly used in New Zealand is mean top height (MTH), and SI for radiata pine is defined as MTH at age 20 years (Goulding 2005). Because height is strongly related to stand age, estimating SI from a height measurement requires a procedure for adjusting this height measurement to the specified base age. This was traditionally achieved using a site index chart, but today a height/age model, an equation for predicting height for any age and SI, is generally used. By inverting the equation, it is possible to obtain SI as a function of age and height.

The purpose of this article is firstly to consider how well SI performs as a productivity index for radiata pine in New Zealand. Secondly, the *300 Index*, a new measure of productivity based on stem volume growth rate is described. Thirdly, a new growth model is described, with emphasis on the BA (basal area) component of the model developed by the senior author. This model, or a model of similar type, is required to estimate the 300 Index from stand measurements.

Performance of SI as a measure site productivity

Although SI has long been used to assess site productivity for radiata pine in New Zealand, there appears to have been few published attempts to justify this on the basis of hard data. To examine this question, we took data from a series of 20 final-crop stocking trials established throughout New Zealand by the then FRI in the 1970s and 1980s (Maclaren *et al.* 1995). All of these trials contain two or more replications of 200 and 400 stems ha^{-1} stocking treatments (other stockings were not analysed in this study), and measurements to, or close to, age 25 years.

Volume MAI of the standing crop (i.e., excluding thinnings or mortality), and BA, were calculated for both stockings at ages 10, 15, 20 and 25 years, using interpolating spline functions when measurements at these precise ages were not available. Volume MAI was calculated by estimating the total stem volume using a standard volume function, and dividing by stand age. Correlations (r) between SI and volume MAI, and SI and BA, were then calculated for each stocking and age. Because the trials were thinned early to their final stocking, and because comparisons were carried out separately for each stocking and age, this allowed for a direct comparison of the relationship between SI, stem volume, and BA productivity, independent of age and stocking.

Table 1 shows a reasonable relationship between volume MAI and SI, especially at younger ages and lower stockings. At 400 stems ha^{-1} and 15 years age, the correlation is 0.88, although this reduces to 0.74 by age 25 years. However, although SI and volume MAI are related, at a fixed SI there is a considerable range in volume MAI. For example, at a SI of approximately 30 m and stocking of 400 stems ha^{-1}, the volume MAI at age 25 ranges from about 22 to 39 m^3 ha^{-1} yr^{-1} (Fig. 1). The relationship between SI and BA is much poorer (Table 1; Fig. 2), and reduces markedly with age and increasing stocking. It can therefore be concluded that dominant height and BA/ha growth are only very weakly related, especially at older ages, and that the relationship between SI and volume is primarily due to the direct effect of height on stem volume rather than to a relationship between dominant height and BA. For this reason, SI as a measure of productivity will be insensitive to environmental variables that affect stem diameter rather than height growth. It can be concluded that SI provides only a partial measure of site quality and that an index more directly related to stem volume should perform better.

Development of a volume-based productivity index

The main problem with using stem volume as an index of productivity is that, with the silvicultural regimes common in New Zealand, it is strongly influenced by stocking. For example, Fig. 3 shows how volume MAI increases with stocking in several of the final-crop stocking trials. However, in principle it should be possible to obtain a productivity index in terms of volume in the same way as SI is calculated from a height measurement, only instead of adjusting the measurement for age only, an adjustment for both age and stocking would be required. To achieve this, an equation for predicting volume in terms of age, stocking, and the volume index would be needed. By inverting this equation,

Fig. 1: Volume MAI at 400 stems ha^{-1} at ages 15 and 25 years plotted against SI. Each point is the mean of two or more plots from one field trial.

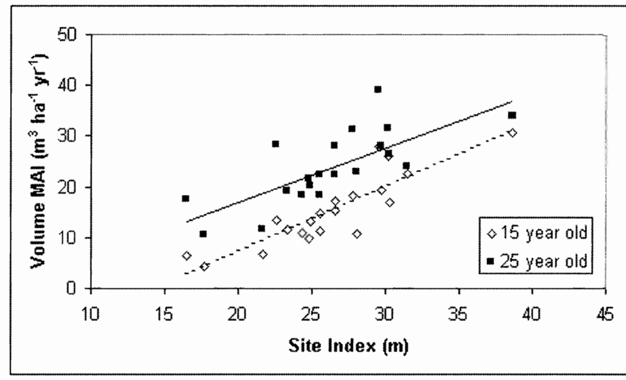


Fig. 2: Basal area at 400 stems ha^{-1} at ages 15 and 25 years plotted against SI. Each point is the mean of two or more plots from one field trial.

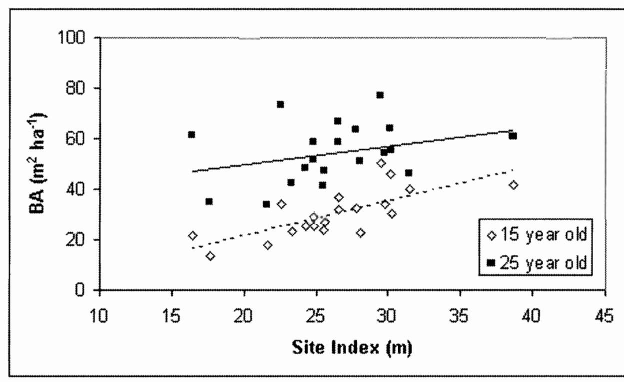
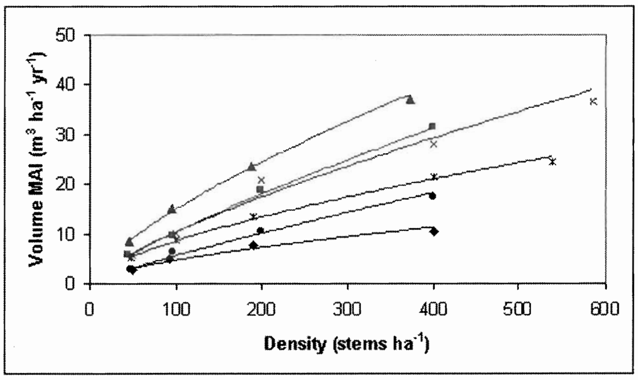


Table 1: Correlations between SI and Volume MAI, and SI and BA for a range of ages and two stockings. Analysis is based on means of two or more plots from each of 20 field trials.

Age	Volume MAI (m^3 ha^{-1} yr^{-1})		Basal Area (m^2 ha^{-1})	
	200 stems ha^{-1}	400 stems ha^{-1}	200 stems ha^{-1}	400 stems ha^{-1}
10	0.84**	0.87**	0.84**	0.80**
15	0.88**	0.88**	0.81**	0.74**
20	0.90**	0.84**	0.72**	0.55*
25	0.87**	0.74**	0.60**	0.31

**statistically significant at the 5% level; **statistically significant at the 1% level* the volume index, which would need to be defined as volume at a specified age and stocking, could then be estimated from a stand measurement of volume, age and stocking.

Fig. 3: Volume MAI at age 25 years for a range of densities at six sites.



Several years ago, we developed such a model for the Plantation Management Cooperative. As an index of productivity, volume MAI at a reference stocking of 300 stems ha-1 and a reference age of 30 years was used, and referred to as the 300 Index. The reference stocking and age were chosen as being representative of a fairly typical New Zealand radiata pine regime. The model was essentially a standard growth function, which predicted volume MAI as a function of age, stocking and the 300 Index.

This early version of the 300 Index model was quite limited in that it could only be used in stands that were either unthinned, or thinned at a very early age, and did not account for pruning, which can significantly reduce growth. It was therefore decided to develop a new version of the model incorporating thinning over a wide age range, and pruning. It was also decided to model BA directly rather than volume MAI, so that different volume functions could be used without having to refit the growth model.

With the new system, calculation of the 300 Index involves the use of several models, including a stand-level BA model, a height/age model, a mortality function, a stand-level volume function, and a thinning function that predicts BA following a thinning. Most of these models are either pre-existing, or similar to existing models, and are not further described in this article. However, the BA model is quite new and of a form somewhat different to any existing radiata pine BA growth model. It is therefore briefly described in this article; a more comprehensive description is currently being prepared for publication.

The addition of thinning and pruning variables meant that the 300 Index had to be redefined more precisely. The index is now defined as the total standing stem volume MAI at age 30 years, excluding the volume of any mortality or thinnings, for the following reference regime:

- All crop trees pruned to six metres using pruning lifts performed in a timely fashion.
- Thinned to final stocking at the completion of the final pruning lift (before about 11 m height).
- A final crop stocking of 300 stems ha^{-1} at 30 years of age.

The final thinning should thus be to about 340 stems ha^{-1} to provide the required stocking at age 30 years after allowing for mortality. It is assumed that standard good practice management in terms of establishment and silviculture is performed. The pruning operation in terms of number of lifts and crown lengths, and the initial stocking, number of thinnings, and thinning intensity are not defined precisely, although most of these factors have only a minor effect on volume at age 30 years.

A new BA growth model

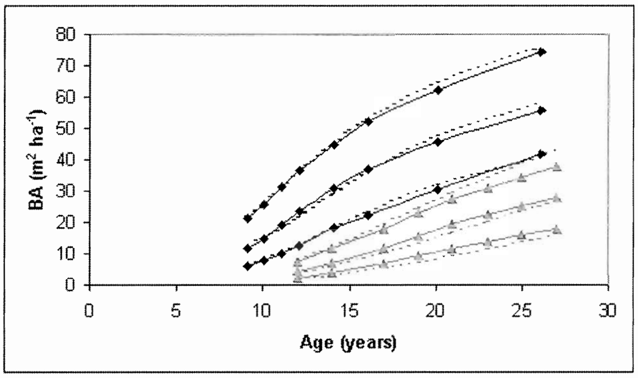
Although the BA model was originally intended as a means of predicting the 300 Index, it can be used in the same way as existing growth models. Development of a new stand-level BA growth model was timely, because of the large quantity of additional data that has become available since the last major generation of stand-level models developed in the 1980s (West *et al.* 1982; Garcia 1984; Goulding 1994). After extensive data screening, the new BA model was fitted using data from 775 growth and stocking-trial plots, with SI ranging from 12 to 40 m and averaging 28 m. 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 ha^{-1}. Only 11% of the plots had measurements older than 30 years and only 3% older than 35 years. The model can therefore only be expected to perform well within these stocking and age limits.

The new BA model is generally referred to as the '300 Index Growth Model'. Strictly speaking, the BA model doesn't use the 300 Index directly, but rather uses an index based on BA. At the core of the model is a mathematical function that expresses BA in terms of age, stocking, SI, and this BA index. The BA index is similar to the 300 Index, in that it is defined as BA at a specified stocking and age. However, the user never sees the BA index, as when used in conjunction with height and volume functions, the model converts from BA and MTH to volume MAI and vice versa when required.

The index-based structure of the model appears to be unique for radiata pine BA models, although it is standard for most height models. The BA model EARLY, which predicts growth of a stand during the intensive pruning and thinning phase, requires the user to specify a site productivity class (West *et al.* 1982). However the new model is somewhat different in that the index is a numeric measure of growth. For the reference regime, the predicted volume MAI always equals the specified 300 Index, in the same way as in a height model, the predicted MTH always equals SI at the reference age.

Examples of predictions from the model are given in Fig. 4, which shows actual and predicted BA at three stockings for a fertile site with a 300 Index of 32 m^3 ha^{-1} yr^{-1}, and a very poor site with an index of only 12 m^3 ha^{-1} yr^{-1}. For each site, the predictions were obtained using a single 300 Index estimated from the initial BA measurement for the 200 stems ha^{-1} stocking, and this single index provided good predictions across the range of stockings and ages at both sites. This illustrates how the model can be used to predict BA for any stocking once a 300 Index and SI have been established for a site.

Fig. 4: Actual (solid lines) and predicted (dashed lines) BA for a high productivity ex-farm site at Tikitere, and a low productivity site in Balmoral Forest. At each site, stockings of 100, 200, and 400 stems ha^{-1} are given by the lower, middle and upper lines respectively.



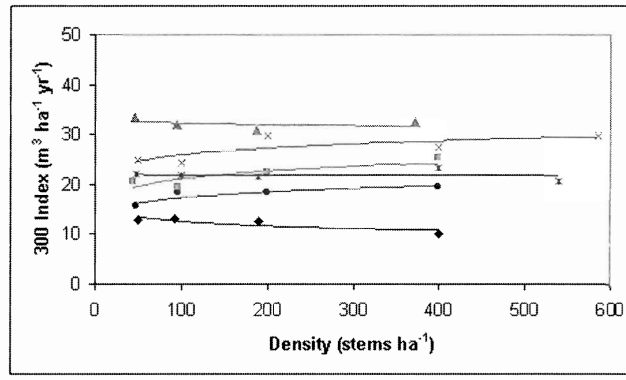
Site Index is required by the model, to allow it convert from the BA Index to the 300 Index, but also has a direct influence on predicted BA. The BA function is expressed in terms of age from breast height rather than age from planting, a concept suggested by Husch (1956) and used for modelling early radiata pine BA growth by Mason & Whyte (1997), and SI is used to predict the age at which breast height is achieved. Also, SI influences the slope and shape of the BA growth function. The new model accommodates the effects of pruning and thinning on growth using an age-shift technique. For example, during pruning, a function driven by crown length and pruned height is used to reduce the age increment supplied to the BA model at each growth step, causing a temporary slowing in BA growth.

In addition to predicting growth, the model can be used to predict the 300 Index using a measurement of BA, MTH, and age, along with stocking and pruning history, obtained either from permanent sample plot (PSP) data or from inventory data combined with stand history information. To do this, an iterative procedure is used to determine the 300 Index value that will predict the specified level of growth. The '300 Model' can therefore be viewed as both a growth model, and as an algorithm for establishing a site productivity index.

Performance of the model

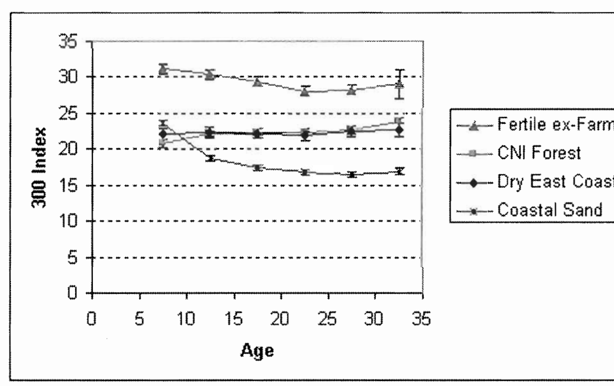
The model has been tested on data from a wide range of sites nationally, and generally performs well. One way of testing the model is to use it to estimate the 300 Index for different sites over a range of stockings and ages. If the model is performing well, estimates of the 300 Index should remain constant over time for measurements taken from the same plot, and should not vary with stocking in plots from the same site. In Fig. 5, the 300 Index is plotted against stocking for the same trial data shown in Fig. 3, and it can be seen that it remains stable across stockings, and that the model therefore accounts well for the effect of stocking on volume. Other validations using large numbers of PSPs have also found little trend in the 300 Index with stocking.

Fig. 5: The 300 Index calculated at age 25 years for a range of stockings at six sites.



To determine whether the index remains stable over time, an extensive validation was carried out using PSP data from the following four geo-climatic zones: Central North Island (CNI) forest sites; New Zealand-wide fertile ex-farm sites; dry east coast sites from both North and South Islands; and coastal sand sites from the west coast of the North Island. The results are summarised in Table 2 and Fig. 6, and show that the index remained very stable over time for the dry sites, showed a slight increasing trend for the CNI forest sites, and a slight decreasing trend for the ex-farm sites.

Fig. 6: Mean 300 Index calculated from PSP measurements taken over time for four contrasting site types. Error bars show 95% confidence intervals.



Overall it was concluded that the model accounts adequately for the development of volume over time on these three site types. However, there was a pronounced downward drift in the index for coastal sand forests, with the index averaging 24 m^3 ha^{-1} yr^{-1} for age 5-10 year growth data, reducing to 17 m^3 ha^{-1} yr^{-1} for age 25 data. The drift was particularly pronounced for coastal forests north of Auckland, and is probably caused by a deterioration in the nitrogen status of these forests following suppression of previously established nitrogen-fixing lupins by the growing pine trees.

In all cases however, predicting the 300 Index from stand age 15 years or older was reliable. A similar downward drift was noticed for several of the driest sites such as Eyrewell Forest in Canterbury, although on most dry sites the index was stable. Care must be taken when using the model on sites showing a downward drift in the index, as projecting growth forward from early measurements on these sites will result in over-estimation of yield.

Table 2: Mean 300 Index and mean drift in the index over time in four site types.

Site type	Number of plots	Number of measurements	Mean 300 Index	Mean Drift (%/yr)
East Coast Dry	439	4005	22.8	0.04
Fertile ex-Farm	337	4712	31.7	-0.60
Coastal Sand	733	6543	18.6	-1.59
C.N.I. Forest	756	8155	22.4	0.29

Discussion

This study has shown that dominant height growth expressed as SI is insufficient on its own to predict site quality in terms of volume. Although it is widely believed that diameter and height growth are strongly related, this study shows that for radiata pine in New Zealand, this is not so, especially after competition becomes more intense at older ages and higher stockings. The lack of a relationship is not entirely unexpected. It is well known, for example, that there is a strong trend of decreasing height growth with increasing altitude in the Central North Island (Hock *et al.* 1994), but no such clear trend has been established for diameter growth. There is also a perception that trees growing on fertile ex-farm sites show better diameter growth but little difference in height growth compared to adjacent but less fertile forest sites (West *et al.* 1982). These observations suggest that somewhat different environmental drivers influence diameter and height growth.

Height has a direct effect on stem volume, because volume is approximately proportional to the product of BA and height. Across New Zealand, there is almost a three-fold range in SI for radiata pine, from below 15 m to as high as 40 m. The range for BA at a fixed age and stocking appears to be of a similar order (Fig. 2). Therefore, the direct effects of height and BA on stem volume should be of about equal importance, and SI will explain little more than half the site variation in volume in mature stands. With the development of the volume-based 300 Index, the continued use of SI as a sole measure of site quality is therefore no longer justified.

Predictions of the 300 Index provided by the model will have various uses. They can be used to produce site quality maps, more closely representing actual productivity than current SI maps. They can also be used to identify environmental factors that influence site quality. Studies of this type have been performed using SI in New Zealand (Hunter & Gibson, 1984), Australia (Truman *et al.* 1983), and South Africa (Louw 1991; Grey 1989), but the use of a better productivity index should give more useful results.

Use of the index to identify changes in productivity can also be envisaged. For example, preliminary analysis of the 300 Index from historical PSP data suggests that there has been a substantial gain in productivity over time from stands established in the 1920s and 1930s compared with those established on the same sites since 1980. When using the index to assess improvements in productivity as a result of, for example, site preparation, fertilising, or tree breeding, it will be important to determine whether changes are long-term or only temporary. This can be done by plotting the 300 Index for a series of measurements against age. The trend in the index for coastal sand forests provides an example of declining site productivity (Fig. 6).

Because volume is approximately proportional to the product of BA and MTH, an index of diameter or BA growth can be provided by the ratio of the 300 Index to SI. For example, we have found that dividing the 300 Index by SI and multiplying by 60, closely approximates BA at age 30 for the reference regime. Analyses of this ratio and of SI in relation to environmental variables, will lead to a better understanding of the factors that most influence dominant height and BA growth.

As a growth model, the 300 Index Model can be used in similar ways to existing growth models. These include regime evaluation, scheduling, and projecting yields from inventory data. The model is particularly suited to regime evaluation because, once the SI and 300 Index have been established for a forest or growth region, the model can be used to predict yields for any stocking, and to assess the effects of intensity and timing of thinning and pruning. Because of the care taken when developing the model to predict early growth and the responses to pruning and thinning operations accurately, we believe it should also be useful for scheduling silvicultural operations. Implementation of model in systems such as FORECASTER, and the Radiata Pine Calculator, where it is complemented by other models predicting, e.g., defect core and branch size, simulating log making operations, and performing financial analysis, enables most of these functions to be readily performed.

Development of the model will continue with emphasis on the following areas:

- Continued validation across a wide range of sites and regimes.
- Adapting the model to perform better on sites showing a pronounced drift in the 300 Index (e.g., coastal sand).
- Simulating fertilising by varying the 300 Index within a run.
- Incorporating genetic gain in terms of GF into the models.
- Developing a means of using the model to project growth of individual tree measurements, particularly for mid-rotation/pre-harvest inventory.
- Prediction of the 300 Index from easily measured site variables.

Acknowledgements

We wish to acknowledge the contribution of Piers

Maclaren, who played a key role in developing the concept of the 300 Index. The Plantation Management Cooperative and the Foundation for Research Science and Technology jointly provided funding for the model, and for trials used in its development. The Sustainable Farming Fund provided funding and numerous forestry companies provided data for validating the model. Also, thanks to Dr. Chris Goulding for many helpful comments on the manuscript.

References

Assman, E. 1970: "The principles of forest yield study". Pergamon Press, Oxford. 506p.

Belyea, H.C. 1931: "Forest Measurement". John Wiley and Sons, New York. 319p.

Bruce, D.; Schumacher, F.X. 1950: "Forest Mensuration", 3rd edition. McGraw-Hill Book Co., New York. 483p.

Cajander, A.K. 1909: Über Waldtypen. *Acta Forestalia Fennica* 1: 1-175

Garcia, O. 1984: New class of growth models for even-aged stands: Pinus radiata in Golden Downs Forest. *N.Z. Journal of Forestry Science* 14(1): 65-85.

Goulding, C.J. 1994: Development of growth models for Pinus radiata in New Zealand - experience with management and process models. *Forest Ecology and Management* 69: 331-343.

Goulding, C.J. 2005: "Measurement of Trees"; Section 6.5 of the NZIF Forestry Handbook, 4th Edition, Mike Colley (ed.), NZIF. 318p.

Grey, D.C. 1989: A site-growth study of Pinus radiata in the Southern Cape. *South African Forestry Journal* 150: 32-39.

Hock, B.K.; Payn, T.W.; Shirley, J.W. 1994: Using a geographic information system and geostatistics to estimate site index of Pinus radiata for Kaingaroa Forest, New Zealand. *N.Z. Journal of Forestry Science* 23(3): 264-277.

Hunter, I.R.; Gibson, A.R. 1984: Predicting Pinus radiata site index from environmental variables. *N.Z. Journal of Forestry Science* 14(1): 53-64.

Husch, B. 1956: Use of age at d.b.h. as a variable in the site index concept. *Journal of Forestry* 54(5): 340.

Husch, B.; Beers, T.W.; Kershaw, J.A.; 2003: "Forest Mensuration ", 4th Edition, John Wiley & Sons, New York. 442p.

Johnson, D.R.; Grayson, A.J.; Bradley, R.T. 1967: "Forest Planning". Faber & Faber Ltd., London. 541p.

Louw, J.H. 1991: The relationship between site characteristics and Pinus radiata growth on the Tsitsikamma plateau, South Africa. *South African Forestry Journal* 158: 37-45.

Maclaren, J.P.; Grace, J.C.; Kimberley, M.O.; Knowles, R.L.; West, G.G. 1995: Height growth of Pinus radiata as affected by stocking. *N.Z. Journal of Forestry Science* 25(1): 73-90.

Mason, E.G.; Whyte, A.G.D. 1997: Modelling initial survival and growth of radiata pine in New Zealand. Acta Forestalia Fennica No. 255, 38p.

Truman, R.; Humphreys, F.R.; Lambert, M.J. 1983: Prediction of site index for Pinus radiata at Mullions Range State Forest, New South Wales. *Australian Forest Research* 13: 207-215.

Ure, J. 1950: The natural vegetation of the Kaingaroa plains as an indicator of site quality for exotic conifers. *N.Z. Journal of Forestry* 6(2): 112-123.

West, G.G.; Knowles, R.L.; Koehler, A.R. 1982: Model to predict the effects of pruning and early thinning on the growth of radiata pine. *FRI Bulletin* No. 5.