Reprint 2874

ESTIMATING ROTATION AGE FOR PRODUCING CLEARWOOD AT SPECIFIC LEVELS*

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(Received for publication 1 November 2005; revision 26 July 2006)

ABSTRACT

Clearwood conversions were linked to stand growth using a multiple regression approach. Stand growth of *Pinus radiata* D. Don was modelled for a range of treatments that spanned extremes in site productivity, stocking levels, pruning practices, resin pocket incidence, and genetic seed sources. At 20 years and thereafter annually until 30 years of age, a pruned butt log was theoretically cut from the mean stem and sawn, and clearwood timber grades were calculated and expressed as a percentage of sawn timber volume. A multiple regression model that linked rotation age to clearwood conversions, site productivity, and treatments was developed for GF22 seedlot.

Application of the model to a site of moderate productivity, planted at 800 stems/ha, thinned to 400 stems/ha, and pruned when diameter over stubs measured 180 mm, indicated that a rotation of at least 33 years would be needed to achieve a clearwood production level of 40%. On extremely low or high productivity sites, rotations of 40 and 25 years respectively were predicted. At a final stocking of 200 stems/ha and under the same practices, rotations of 32, 25, and 17 years were predicted for the low, moderate, and high productivity sites respectively.

Preliminary validation of the model, through comparison of predicted age with that of real logs ranked as “stars” and “super-stars”, according to processing efficiency and profitability, produced close correspondence in

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* Based on a paper presented at IUFRO WP S5.01.04 Fifth Workshop on Wood Quality Modelling, 20–27 November 2005, Waiheke Island, New Zealand

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rotation age. The regression model predicted rotation ages for stars and super-stars to be 27.5 and 33.0 years respectively while actual ages were 28.1 and 32.0 years respectively.

Keywords: growth modelling; stocking; pruning.

INTRODUCTION

Tree growth and product quality are influenced by forest management practices such as pruning, thinning, crop stockings, and rotation age. Although there is no standard forest management practice, prescriptions of broad regimes have been provided by Maclaren (1993). One such regime, the "direct sawlog regime", is characterised by thinning to waste and pruning to 6 m with initial stocking levels on a fertile site ranging from 400 to 1000 trees/ha and final stocking levels from 200 to 400 trees/ha. Thinning operations remove malformed trees and encourage further growth in the remaining crop. However, if stocking levels are too low they can cause inferior quality in trees through greater sweep (Maclaren 2003) and increased incidence of resin pockets (Cown 1973; Somerville 1980). In contrast, pruning encourages growth of knot-free clearwood through the removal of branches. As clearwood is of greater value than knotty wood, the pruned butt log of a tree, although representing only 24% by volume, contains about 60% of the total tree value (New Zealand Forest Owners' Association 2003).

In addition to forest management practices, gains in tree growth rate can be achieved by planting on fertile ex-farm sites (West *et al.* 1982) or through genetic control (Burdon 1992). Unfortunately, trees with faster diameter growth rates also tend to grow larger branches (West *et al.* 1982), thus compromising product quality. Fortunately branch habit, growth, straightness, and other properties can be controlled genetically (Burdon 1992). Traits for growth and form, rated through the GF ratings system (Vincent 1987), have been linked to absolute changes in quality (Turner *et al.* 1997). In a genetic-gain trial that compared a control-pollinated seedlot (GF rating of 22) with a climbing select seedlot (GF7) increases of about 25% in volume, 20% in basal area, 12% in breast height diameter, and 4% in mean top height (Carson *et al.* 1999) were demonstrated in the GF22 seedlot.

The mean top height at age 20 of the 100 largest diameter trees per hectare is used to quantify site productivity or growth potential, and is commonly referred to as site index. In general the higher the site index the greater the trees' height, all other factors being equal. In New Zealand site index tends to decrease from north to south, with the median being 28 m, the lowest in a major forest 17 m, and the highest 42 m in a Bay of Plenty woodlot. Predictions of site index through knowledge of rainfall, temperature, soil fertility, acidity, and other environmental variables can be made through application of a multiple regression model (Hunter & Gibson 1984).

Basal area provides another measure of growth potential. Basal area is the area of stumps per hectare if each tree were felled at 1.4 m above the ground (breast height). The basal area of a stand of trees varies greatly with stocking and other management practices. In New Zealand, basal area growth tends to increase from north to south. A basal area model has been incorporated in the newly developed measure of productivity for *P. radiata*, the 300 Index (Kimberley *et al*. 2005). The index assumes a reference regime of 300 stems/ha.

Stand growth and log and timber quality can be predicted, and silvicultural operations scheduled, using a computer modelling system such as STANDPAK (Whiteside 1990). STANDPAK applies a regression approach within the Sawlog Evaluation Module (Whiteside & McGregor 1987) to predict timber grades from log variables such as defect core size, resin pocket incidence, sweep, and diameter at breast height.

Given that many regime variables can be controlled, there is an opportunity to develop forest management practices with specific seedlots chosen to suit particular site conditions or target products. This is the concept of "designer trees" (Carson 1996). Ideally the trees would provide benefits to log buyers and processors alike in terms of quality and processing requirements. Todoroki & Carson (2003) proposed a method, based on data envelopment analysis (Charnes *et al*. 1978), for identifying "designer logs", i.e., those logs with increased potential to produce clearwood. A sample of pruned logs with mean small-end diameter of 400 mm and standard deviation 60 mm, defect core of 270 ±40 mm, and sweep 7 ±3 mm/m was used within the optimisation model. The best logs in terms of profitability and efficiency in processing, the "super-stars", had an average small-end diameter of 500 mm, a 220-mm clearwood sheath, minimal sweep averaging 5 mm/m, and moderate taper of about 15 mm/m. In terms of lumber quality, the "super-stars" produced on average 0.49 m^3 clearwood volume, equivalent to 56% of sawn yield or 39% by log volume. To achieve "super-star" status, simulations with STANDPAK indicated that a rotation of 31 years would be required with an unimproved *P. radiata* seedlot (GF7) and 27 years with improved stock (GF22) for a regime initially stocked at 750 stems/ha, pruned to a target DOS of 200 mm, and on a moderately fertile site (Todoroki & Carson 2003).

The aim of this study was to broaden the scope beyond that developed for seeking "stars" and "super-stars" and apply stand growth modelling to elucidate relationships that connect forest resources to wood quality. While the influences of site, silviculture, and other factors on wood quality have been much researched (e.g., Carson 1990; Tombleson *et al*. 1990; West 1997) and numerous growth, yield, and log processing models have been developed, many questions remain unanswered. The impetus for this research stemmed from wanting to produce New Zealand's most valuable forest products, clearwood from pruned logs, to specified levels and wanting to know the length of rotation needed to grow them.

METHODS

Stand growth was modelled using STANDPAK over a range of site, genetic, and silvicultural conditions to create a diverse matrix of forest conditions and management practices (Fig. 1). Extremes in site productivity (SI42 and SI17) were modelled, along with medium site productivity (SI28) and average stocking levels (Maclaren 1993). Initial crop stocking was established at 800 stems/ha on the SI42 site, at 1000 stems/ha on the SI17 site, and at both 800 and 1000 stems/ha on the SI28 sites. The combination of site productivity and initial stocking is referred to hereafter as "site".

Site Index × **initial stocking** (m × stems/ha)		**Diameter over stubs** (mm)		**Final stocking** (stems/ha)		**Seedlot** (GF rating)
42 × 800		160		400		7
28 × 800	×	180	×	200	×	22
28 × 1000		200		100		
17 × 1000						

FIG. 1–Matrix of forest management practices.

Three pruning trials were simulated for each site with a three-lift pruning regime scheduled according to diameter over stubs sizes of 160, 180, and 200 mm. A thinning to waste operation was scheduled with each pruning operation. Three final-crop stockings were evaluated: 400, 200, and 100 stems/ha. All simulated trials were replicated for GF7 and GF22 seedlots and grown using a direct sawlog regime through to age 30 years. In all, 72 combinations (4 sites × 3 pruning trials × 3 final stocking levels × 2 seedlots) were evaluated. From age 20 to age 30 years stand variables including mean height, diameter at breast height, and basal area were recorded annually.

The following models within STANDPAK were used:

- Growth model: 23 (EARLY) and 22 (PPM88)
- Monthly growth adjustment function: 3 (EARLY, Jackson *et al*. 1976)
- Height/age function: 34 (KGM3 Interim Pumice Plateau 1987)
- Basal area increment adjustment level: Medium

- Crown function (Beekhuis 1965)
- Taper functions (Gordon 1983a).

"EARLY" growth model (West *et al*. 1987), compatible with the "Diameter Over Stubs" model (Knowles *et al*. 1987), was used to simulate early growth and silviculture, especially the effects of pruning and early thinning on tree growth. Set at the "Medium" adjustment level of basal area increment, the "EARLY" model predicts tree growth on typical unimproved forestland. For specific stands or paddocks this may be varied using local knowledge but in general terms this adjustment is appropriate for forest level analysis. The "EARLY" monthly growth adjustment function, constructed in 1976 by Jackson *et al*., describes the monthly proportions of annual growth for a given site, stand, or tree parameter.

Once mean crop height reached 18 m, the PPM88 growth model was used. The PPM88 Pumice Plateau growth model was constructed in 1988 following an interim growth model (KGM3) developed by the Stand Growth Modelling Cooperative in 1987 (A.G.Dunningham & M.E.Lawrence unpubl. data). PPM88 describes *P. radiata* growth in the central North Island Pumice Plateau over a wide range of ages and treatments. It is capable of predicting growth losses from low site occupancy after heavy thinning and pruning. The height growth, thinned basal area, and stand volume from KGM3 are used without change in PPM88. PPM88 modified the growth model by reduction factors that are functions of relative crown closure, to allow for changes in growth rates after thinning.

A 5.4-m-long butt log was theoretically cut from the mean stem at each age for each simulation (72 × 11 = 792 observations). Log conversion, defined as the percentage of sawn timber divided by log volume, and clearwood conversion, defined as the percentage of clearwood divided by timber volume, were calculated using the Quickgrades module of STANDPAK.

Calculations were based on several assumptions. Stump height was assumed to be 0.23 m (Fraser *et al*. 1997). Sweep in the butt log was assumed to be 7 mm/m, based on the mean sweep of a 440-log sample (Todoroki & Carson 2003) and a more recent sample of 2258 pruned logs that had mean sweep of 7.5 mm/m. Resin pocket incidence was set to moderate when stocking was at 100 stems/ha, low at 200 stems/ha, and none at 400 stems/ha. Butt log taper was calculated as:

$$(\text{DBH} \times 0.951 - \text{SED})/(\text{Length} - 1.17)$$

where DBH represents the under-bark diameter at breast height (mm), SED small-end diameter (mm), log length is measured in metres, and 1.17 represents the difference between breast height (1.4 m) and stump height (0.23 m). Under-bark diameter at breast height was calculated as the product of 0.951 and diameter at breast height (Gordon 1983b). The minimum small-end diameter for clearwood calculations was 300 mm. Clearwood calculations were based on defect core size

(DC) that in turn was calculated from diameter over stubs (DOS) measurements using:

DC = 62.976 + 0.995 × DOS mm (Park 1982).

Statistical analysis was performed using SAS (SAS Institute Inc. 1999). Mean basal area for GF22 seedlot was compared with that of GF7 seedlot across 396 combinations (4 sites × 3 pruning trials × 3 final stockings × 11 age classes) using pairwise comparisons with SAS's TTEST procedure. Breast height diameter for each seedlot was similarly compared. Linear regression models linking the two seedlots were developed for basal area and diameter at breast height. Individual regression models for each of the sites were developed and a general multiple regression model that linked age to site index, initial and final crop stockings, diameter over stubs, and clearwood conversion, with cross-effects of those variables, was developed for GF22 seedlot.

RESULTS

The extremes in site index occasionally caused models within STANDPAK to operate beyond the limits of their normal operating range. Warnings of "crown/hectare too high in EARLY" were issued with GF22 for site SI42 × 800 when pruning to 180 and 200 mm over-stub diameters and a "severe pruning" warning was issued for site SI17 × 1000 when diameter over stubs measured 160 mm Warnings were noted as they occurred.

Basal Area

Basal area (BA) was significantly greater for the GF22 seedlot, being on average about 9% greater than that for GF7 (Eqn 1). As expected, the goodness-of-fit statistic R^2 was high and standard error of the basal area coefficient SE_{BA} low:

$$BA(GF22) = 1.087 \times BA(GF7) \ (m^2/ha) \quad R^2 = 0.999 \quad SE_{BA} = 0.002 \qquad \text{Eqn 1}$$

Basal area increased with site index, stocking, and GF rating (Table 1). Basal area was greatest (nearly 73 m^2/ha at 25 years with GF22 seedlot, and 67 m^2/ha with GF7) for the regime with highest productivity and stockings (SI42 × 800 at 400

TABLE 1–Basal area (m^2/ha) at age 25 years with diameter over stubs measuring 160 mm.

Site index (m) × initial stocking (trees/ha)	Final stocking					
	100 stems/ha		200 stems/ha		400 stems/ha	
	GF22	GF7	GF22	GF7	GF22	GF7
42 × 800	45.6	41.5	61.0	55.5	72.7	66.7
28 × 800	31.9	29.0	44.1	40.4	55.6	51.5
28 × 1000	32.2	29.4	44.1	40.4	55.6	51.5
17 × 1000	20.0	18.3	29.6	27.3	38.3	35.7

stems/ha) and lowest (38 and 36 m^2/ha at 25 years for GF22 and GF7 respectively) for the regime with lowest productivity and stockings (SI17 × 1000 at 100 stems/ha). Differences in basal area between the SI28 × 800 and SI28 × 1000 sites were small.

Diameter at Breast Height

Mean diameter at breast height was significantly higher with the higher GF rating. With the 396 DBH pairs from the forest matrix a strong linear relationship was demonstrated between the two seedlots (Eqn 2).

$$\text{DBH (GF22)} = 1.064 \times \text{DBH (GF7)} - 9.506 \text{ (mm)} \qquad R^2 = 0.999$$
$$SE_{DBH} = 0.001 \quad SE_{const} = 0.633 \qquad \text{Eqn 2}$$

Mean breast height diameter increased with increasing site index and lower final stockings (Fig. 2). At 100 stems/ha it was about 20% greater than at 200 stems/ha and 50% greater than at 400 stems/ha on the SI28 and SI42 sites. On the SI17 site mean breast height diameter at 100 stems/ha final stocking was about 15% greater than at 200 stems/ha, and about 40% greater than at 400 stems/ha.

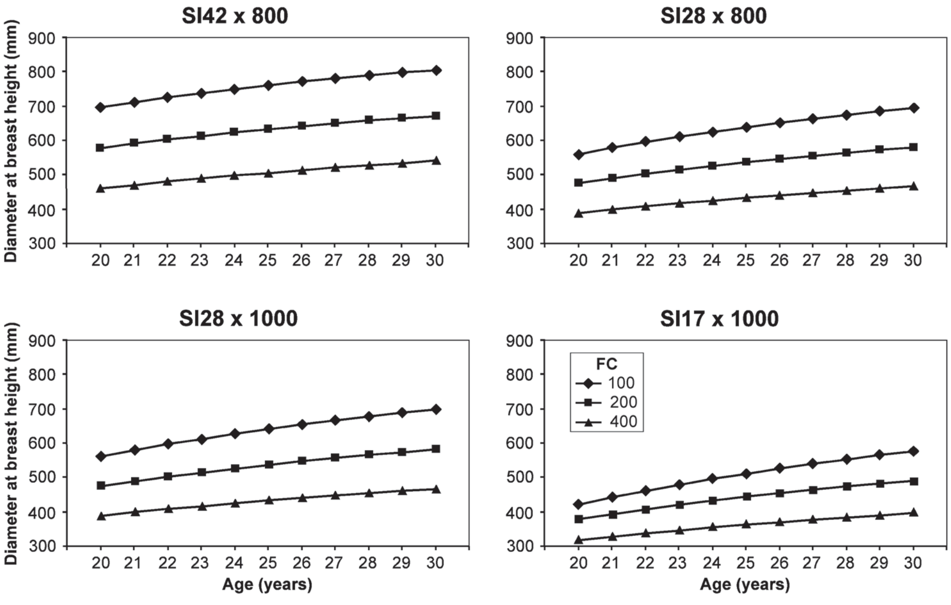

FIG. 2–Mean diameter growth at 100, 200, and 400 stems/ha final crop stocking (FC) with a target DOS of 180 mm and GF22 seedlot.

The two SI28 sites, one planted at 800 stems/ha and the other at 1000 stems/ha, recorded identical mean breast height diameter for both GF22 and GF7 seedlots when diameter over stubs was 160 mm and final stocking was at 400 stems/ha. The TTEST statistic also indicated that differences were not significant for two other combinations — one with final stocking levels of 400 stems/ha and DOS at 180 mm

($p = 0.34$), the other with final stockings of 200 stems/ha and DOS at 160 mm ($p = 0.31$). All other diameter comparisons between the SI28 × 800 and SI28 × 1000 combinations with identical management practices were significantly different ($p < 0.05$); however, the difference in breast height diameter was no more than 3 mm.

Within most sites the effect of pruning (DOS) on breast height diameter was statistically significant ($p < 0.05$) but of no practical importance. There were, however, a few exceptions and these were noted for the SI17 × 1000 site. With final-crop stocking at 100 stems/ha, mean breast height diameter was approximately 14 mm greater with a 200 mm DOS than with a 160 mm DOS; at 200 stems/ha the difference was 15 mm, and at 400 stems/ha nearly 23 mm.

Butt Log Volume

The mean volume of a 5.4-m butt log increased with site index and lower final stockings (Table 2). At age 25 years, with GF22 seedlot, and pruned to a 180 mm diameter measured over stubs, log volume for site SI42 × 800 was 1.62 m^3 at 100 stems/ha, 1.17 m^3 at 200 stems/ha, and 0.79 m^3 at 400 stems/ha. For sites SI28 × 800 and SI28 × 1000 the corresponding volumes were 1.12, 0.82, and 0.56 m^3 respectively; and for site SI17 × 1000 0.69, 0.53, and 0.37 m^3 respectively. The effect of pruning on log volume was particularly noticeable for site SI17 × 1000, with a reduction of up to 0.02 m^3 with earlier pruning (160 mm DOS) and an increase in volume of up to 0.02 m^3 with later pruning (200 mm DOS).

TABLE 2–Mean volume (m^3) of a 5.4-m butt log at age 25 years, GF22 seedlot.

Site index (m) × initial stocking (trees/ha)	Final stocking								
	100 stems/ha			200 stems/ha			400 stems/ha		
	160*	180	200	160	180	200	160	180	200
SI42 × 800	1.62	1.62	1.61	1.17	1.17	1.16	0.79	0.79	0.78
SI28 × 800	1.11	1.12	1.13	0.81	0.82	0.83	0.55	0.56	0.57
SI28 × 1000	1.11	1.12	1.12	0.81	0.82	0.82	0.55	0.56	0.57
SI17 × 1000	0.67	0.69	0.70	0.52	0.53	0.55	0.35	0.37	0.39

* Diameter over stubs (mm)

Log and Clearwood Conversion

Log conversion increased with small-end diameter, ranging from 52% for a log with 300-mm small-end diameter to 58% for logs with diameters greater than 570 mm.

Site productivity had a large effect on clearwood conversion. The timing of pruning, as measured by diameter over stubs and final-crop stocking, also had a significant effect on clearwood conversion (Table 3, Fig. 3).

TABLE 3–Clearwood conversion (%) at age 25 years, GF22 seedlot.

Site index (m) × initial stocking (trees/ha)	Final stocking								
	100 stems/ha			200 stems/ha			400 stems/ha		
	160*	180	200	160	180	200	160	180	200
SI42 × 800	71	67	63	62	57	52	49	43	37
SI28 × 800	56	51	47	46	41	35	33	28	24
SI28 × 1000	56	51	46	46	40	35	33	28	23
SI17 × 1000	32	27	23	25	21	18	†	†	†

* Diameter over stubs (mm)
† Requirement for minimum small-end diameter of 300 mm not met

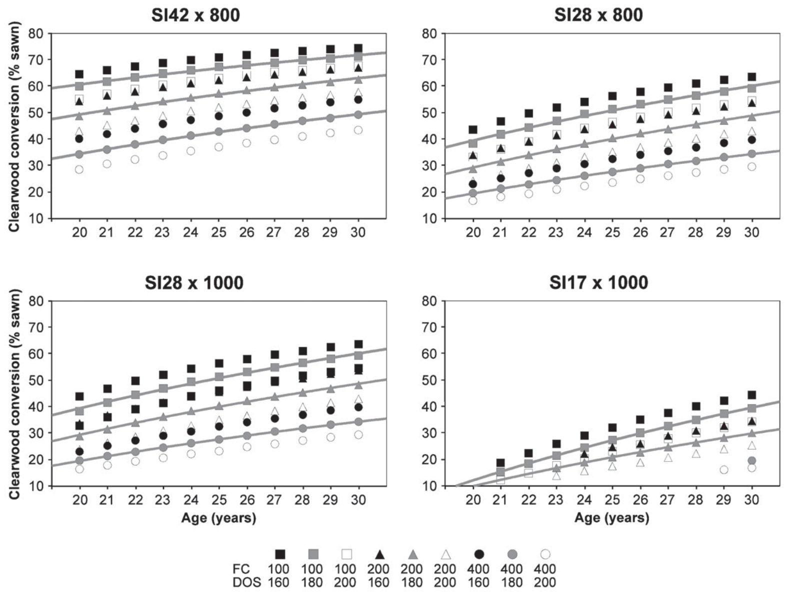

FIG. 3–Clearwood conversion at 100, 200, and 400 stems/ha final crop stocking with GF22 seedlot.

Given the same levels of final stocking, clearwood conversion increased with site index. With the same site index, clearwood conversion increased with reduced levels of final stocking. However, the 28 × 1000 × 100 combination gave greater conversions than the 42 × 800 × 400 combination, and the 28 × 1000 × 400 greater than 17 × 1000 × 100 only until about 25 years; thereafter the converse was true.

There was no significant difference ($p < 0.05$) in clearwood conversions between the final crop stocked at 100 stems/ha and pruned to 200 mm and the final crop stocked at 200 stems/ha and pruned to 160 mm for either the SI28 × 800 ($p = 0.059$) or SI28 × 1000 ($p = 0.330$) sites (shown by the boxed area within Table 3).

Relationships between Site, Silviculture, Clearwood Conversion, and Age

Both non-linear and linear relationships were evaluated with age as the dependent variable. On sites SI42 × 800, SI28 × 800, and SI28 × 1000 the best fits were obtained with a multiple regression consisting of the variables clearwood conversion (%Clr), diameter over stubs (DOS), and final-crop stocking (FC), and an interaction between those three variables %Clr·DOS·FC. On site SI17 × 1000, final-crop stocking by itself was not significant, but the interaction with the two other variables %Clr and DOS in the combination %Clr·DOS·FC was highly significant.

A general formula was developed to predict the rotation age required to produce a specified level of clearwood conversion for all sites with GF22 seedlot (Eqn 3):

$$\text{Age} = a_1 + a_2\cdot\text{SI} + a_3\cdot\%\text{Clr} + a_4\cdot\text{DOS} + a_5\cdot\text{FC} + a_6\cdot\%\text{Clr}\cdot\text{DOS}\cdot\text{FC} + a_7\cdot\text{IC} + a_8\cdot\text{IC}\cdot\text{SI} \qquad \text{Eqn 3}$$

where IC and FC are the initial and final crop stockings respectively (stems/ha)
SI the site index (m)
DOS (mm) the diameter over stubs.

Parameter estimates and standard errors are given in Table 4 along with goodness-of-fit values.

Comparison with "Stars" and "Super-stars"

The regression formula was applied to each of the sites to predict the age required to produce "stars" and "super-stars", i.e., stands from which the mean butt log would produce 45.2% and 55.7% clearwood conversion (Todoroki & Carson 2003) respectively (Table 5). In general "super-star" status was achieved 5 years after "star" status at 100 stems/ha, 5–6 years later at 200 stems/ha, and 6–7 years later at 400 stems/ha.

The estimated time required to grow a "star" on a site SI28 × 800 with a final stocking of 200 stems/ha and pruned to a 180-mm target DOS was 27.5 years; and to grow a "super-star" under the same conditions, 33.0 years. This compares well to the logs used in the Data Envelopment Analysis (Todoroki & Carson 2003) which had actual ages of 28.1 and 32.0 years for the "stars" and "super-stars" respectively.

DISCUSSION

Estimated rotation age for producing a given level of clearwood conversion is based on a pruned butt log from the mean stem within a stand. As there is a distribution of trees within a stand, the estimated age represents a minimum threshold for

TABLE 4–Parameters of regression for each of the sites and goodness-of-fit statistics.

Site	Parameter†	Estimate	Standard error	R^2	Root MSE
SI42 × 800	Intercept	–49.643	3.579	0.917	0.935
	%Clr	0.621	0.031		
	DOS	0.154	0.010		
	FC	0.039	0.005		
	%Clr·DOS·FC	1.73E-06	5.4E-07		
SI28 × 800	Intercept	–14.781	1.049	0.981	0.445
	%Clr	0.355	0.011		
	DOS	0.093	0.004		
	FC	0.010	0.002		
	%Clr·DOS·FC	4.72E-06	2.6E-07		
SI28 × 1000	Intercept	–15.290	1.055	0.981	0.448
	%Clr	0.353	0.011		
	DOS	0.097	0.004		
	FC	0.010	0.002		
	%Clr·DOS·FC	4.76E-06	2.6E-07	0.992	0.250
SI17 × 1000	Intercept	2.782	0.512		
	%Clr	0.259	0.005		
	DOS	0.066	0.002		
	%Clr·DOS·FC	6.94E-06	1.3E-07		
All sites	Intercept	–37.559	2.480	0.930	0.840
	SI	0.653	0.071		
	%Clr	0.422	0.009		
	DOS	0.104	0.003		
	FC	0.019	0.001		
	%Clr·DOS·FC	2.95E-06	1.9E-07		
	IC	0.045	0.002		
	SI·IC	–1.59E-03	8.4E-05		

† SI = site index (m), IC = initial crop stocking (stems/ha), DOS = diameter over stubs (mm), FC = final-crop stocking (stems/ha)

rotation age. Furthermore, as the model is based on other assumptions (e.g., sweep, resin incidence), any inclement conditions such as excessive wind exposure will tend to cause loss in clearwood and so the rotation age will need to be extended to allow further growth.

Timing of pruning was not critical on high-productivity sites, particularly at low stockings. On medium-productivity sites a trade-off between timing of pruning and final-crop stocking was demonstrated. There was no significant difference in clearwood conversions between crops with a final stocking of 100 stems/ha and pruned when diameter over stubs was 200 mm, and crops stocked at 200 stems/ha and pruned to a 160 mm diameter over stubs (Table 3). However, pruned logs obtained at a stocking of 100 stems/ha were smaller in volume (Table 4). With fewer logs and reduced log volumes, economic returns will differ between the two final-

TABLE 5–Number of years required to attain "star" and "super-star" status, i.e., 45.2% and 55.7% clearwood conversion from a pruned butt log grown from GF22 seedlot.

Site index × initial stocking (trees/ha)	Final stocking								
	100 stems/ha			200 stems/ha			400 stems/ha		
	160*	180	200	160	180	200	160	180	200
"Stars"									
SI42 × 800	12.2	14.5	16.9	16.2	18.8	21.4	24.3	27.4	30.6
SI28 × 800	20.8	23.2	25.5	24.9	27.5	30.1	32.9	36.1	39.2
SI28 × 1000	20.9	23.3	25.6	25.0	27.6	30.2	33.0	36.2	39.3
SI17 × 1000	31.2	33.6	35.9	35.3	37.9	40.5	43.3	46.5	49.6
"Super-stars"									
SI42 × 800	17.1	19.5	21.9	21.6	24.4	27.1	30.7	34.1	37.5
SI28 × 800	25.8	28.2	30.6	30.3	33.0	35.8	39.4	42.8	46.1
SI28 × 1000	25.9	28.3	30.7	30.4	33.1	35.9	39.5	42.8	46.2
SI17 × 1000	36.2	38.6	41.0	40.7	43.4	46.2	49.8	53.2	56.6

* Diameter over stubs (mm)

stocking levels. Economic returns will also differ with initial crop stocking levels; however, it appears that there is no benefit to be gained from planting 1000 stems/ha on SI28 when 800 stems/ha produces similar results and comes without the expense of planting an additional 200 stems/ha.

While the pruned butt log accounts for 60% of the value of the tree, there remains a further 40% contribution from upper logs. These should be considered in a more detailed study that accounts for variation in height and diameter around the mean stem to examine the effects of the mix of log sizes on clearwood conversion. Economic analysis should also be considered across the range of treatments.

The model in its current form provides an estimate for minimum rotation age, given forest management practices. Because the model has a simple structure it can also be rearranged to estimate, for example, the final-crop stocking, given harvest age, timing of pruning, site productivity, and initial crop stocking levels.

ACKNOWLEDGMENTS

Piers Maclaren is thanked for his contribution to discussions on silvicultural regimes and site conditions. Financial support from the New Zealand Foundation of Research, Science and Technology is also gratefully acknowledged.

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