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Modelling the Influence of Silviculture on Wood Quality and Log-grade Outturn using FFR Forecaster

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

The aim of this paper was to determine how the latest wood quality models contained within FFR Forecaster v1.12 performed under standard regimes and regime variations, and to assess the implications of using those latest models on wood property distributions. Economic analysis was outside the scope of the project. A generic log grade, 5.2 m long, was used in place of conventional log grades to standardise this variable across all Forecaster runs.

The wood quality models used in this project were as follows:

- **Acoustic Velocity:** WQIAcousticVelocity model as a f(green density measure, elevation, latitude (or northing), age (to model AV with age), stem height (to model AV up stem), stem slenderness (stem diameter, stem height – to model between-tree variation)
- **Wood Density**: FFRDensity2011 model as a f(Site Index, 300 Index, density index, ring widths, age (to model density by age), stem height (to model density variation up then stem), stochastic element (to model between-tree variation))
- **Heartwood**: FFRWQI2009 model as a f(age, stem height (to model heartwood variation up the stem), stem diameter, longitude (or northing), stochastic element (to model between-tree variation))
- **Juvenile Corewood**: hard-wired as a f(ring width$_{1\text{-}10}$, ring width$_{1\text{-}n}$)
- **Branching**: BLOSSIM v3.0 model as a f(modelling region, stem height, stem diameter, stand MTH, stand BA, stand stocking, thinning timing, thinning severity, stochastic element (to model distributions of branch parameters))
- **PLI**: Pruned Log Index (hard-wired) as a f(Diameter Over Stubs-DOS, log diameter, sweep).

The entities for running Forecaster included: three sites (Northland, Bay of Plenty and Southland), three rotation ages (25, 30 and 35 years), and two base regimes with regime variations that represent current practice.

The Clearwood base regime was set in the Bay of Plenty, initial stocking 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha, and harvest at age 30 years. Clearwood regime variations included initial stocking (800, 1000 and 1200 stems/ha), initial pruned stocking (400, 525 and 650 stems/ha) and final thinned stocking (250, 300 and 350 stems/ha).

The Framing base regime was also set in the Bay of Plenty, initial stocking 1000 stems/ha, final thinned stocking 450 stems/ha, thinning when MTH > 14 m, and clearfell at age 30 years. Variations to the Framing regime included initial stocking (833, 1000, 1200 and 1500 stems/ha), final thinned stocking (250, 400, 450, 500 and 650 stems/ha) and timing of thinning (at MTH 6, 10, 14, 18 and 22 m).

NOTE: the entities used in this project, as inputs to Forecaster, will be made available to users via the FFR website.

Results showed that site, rotation age and final thinned stocking consistently had the greatest influence on the predictions from the wood quality models used in FFR Forecaster (Table 1). Log position number (i.e., butt, 2nd, 3rd, etc.) within the stem also had a large impact on the results from many of the models. Other silvicultural variations to the regimes (e.g., initial stocking, timing of thinning, pruned stocking) had a negligible impact on the wood property outputs produced by the models. In order to produce more significant improvements in wood quality, silviculture regimes further outside the range of current practice would need to be considered. The models also produced some unexpected and counter-intuitive results, and additional analysis is being undertaken to establish the reasons behind these results.

Table 1: Summary of the effects of the wood quality models on Framing and Clearwood regimes.

Regime Variables	Acoustic Velocity (AV)	Wood Density	Heartwood	Juvenile Corewood	Branching (BIX)	Pruned Log Index (PLI)
Site	↑ in AV with ↑ in Latitude.	↑ in Wood Density with ↑ in Latitude.	↑ in Heartwood with ↑ in Latitude.	BoP - least Juv. Corewood; Southland - most Juv. Corewood	BoP - smallest BIX; Southland - largest BIX	Southland - highest PLI; BoP - lowest PLI
Rotation Age	↑ in AV with ↑ in rotation length.	↑ in Wood Density with ↑ in rotation length.	↑ in Heartwood with ↑ in rotation length.	↓ in Juv. Corewood % with ↑ in rotation length.	Negligible Impact	↑ in PLI with ↑ in rotation length.
Initial Stocking			Negligible impact			
Initial Pruned Stocking			Negligible impact			
Timing of Thinning	Negligible impact	Negligible impact	Negligible impact	Negligible Impact	Butt logs - ↓in BIX with ↑ in MTH. Upper logs - reverse	Not examined
Final Thinned Stocking	Negligible impact	Negligible impact	Negligible impact	Negligible Impact	↓ in BIX with ↑ in FTS	↓ in PLI with ↑ in FTS

INTRODUCTION

Building on the foundations of the first two FFR tech transfer papers[1, 2], this third paper examines the effects of silviculture upon modelled acoustic velocity, wood density and heartwood. Traditionally, logs have primarily been assessed for size (length and diameter) and shape (roundness, taper, straightness), with branch size and distribution also affecting grading[3]. The introduction of the Pruned Log Index (PLI) in the mid-1980's was the first step at trying to create log grades that considered more than these aspects[4]. More recently, wood quality models have become more widely available to forest growers allowing them to consider wood quality characteristics, such as acoustic velocity, wood density, and heartwood content, when modelling their forests.

Site has been identified as having the largest impact upon wood quality, particularly wood density[5, 6]. In the previous FFR tech transfer papers, only sites in the Bay of Plenty (BoP) and Southland regions were modelled. This paper continues to use these sites, but restricts the BoP site to medium quality, and adds a site from Northland. This modelling exercise now covers the northern and southern extremes, and the BoP, one of New Zealand's most predominant forestry growing areas.

Management regime variations in stocking and rotation age are known to impact wood quality characteristics, such as wood density, heartwood formation, and branch size[6]. The initial and the final modelled crop stocking were varied for the clearwood and framing regimes. Regimes were run through a variety of clearfell ages, from ages 25 to 35 years at 5 year intervals. Silvicultural treatments have a lesser influence upon wood density[6], so timing of thinning and pruning events were not explored in great depth.

The latest models for acoustic velocity (WQIAcousticVelocity), wood density (FFRDensity2011), heartwood (FFRWQI2009) and branching (BLOSSIM version 3.0) that are available in Forecaster version 1.12 were used in this project. Analyses were run to produce log and stem distributions for these and other wood quality characteristics on a generic log grade, 5.2 m in length. Further analysis was undertaken to determine percentages of logs or stems that pass certain thresholds, as well as, the average values and standard deviations for each characteristic.

Acoustic Velocity

The WQIAcousticVelocity model in Forecaster uses stand average measurements of standing tree velocity and / or density to produce minimum, mean, maximum, and standard deviation of acoustic velocity values[7]. In the literature, acoustic velocity is linked to the microfibril angle of wood, and hence, the woods' stiffness[6, 8] or green density[9], and useful in log segregation[10].

Density

There are a number of definitions of wood density and it is important to understand the difference between them. Wood basic density is a measure of the mass of dry wood substance per unit volume of green timber[11]. In radiata pine[12], basic density is highest closest to the bark and at its lowest near the pith[5]. Outer wood density at breast height (OWDBH) should not be confused with the average density value of a log. OWDBH is typically much higher than the average log value, because density values are at their highest closest to the bark. Density also decreases with increasing height up the stem due to the increasing proportion of lower density corewood higher up the stem[6].

Site location (especially mean annual temperature) is one of the major influencing factors on wood density[5, 6]. The further north a site is, the higher the wood density. Conversely, southern or higher [redacted] average measurement of basic density, and the stand age at the time at which the measurement was taken. These values are entered for the OWDBH, typically at age 20 years. This OWDBH value is then used to calculate a mean basic density value for each log.

Heartwood

Heartwood is formed in the centre of the stem when there is an increase in the resin content of the wood. It typically begins to form in trees from age ~12 years onwards, and its development, or lack thereof, is closely related to tree age[6, 11, 13]. It has also been found to develop more quickly in northern sites than southern ones[6]. The amount of heartwood present is greatest at the stump level and at breast height, and decreases with height up the stem[13]. Variation in heartwood levels has been found between trees and stands, implying that its formation is affected by both genetic and environmental factors. Wilkes[13] found that sites with an absence of drying winds and an abundant and consistent supply of water aid the formation of heartwood in radiata pine.

The heartwood models in Forecaster do not require any inputs to be entered by the user. Instead they use a stem's site location and its age to predict the heartwood content as a percentage of volume for the stem / logs[7].

Juvenile Wood / Corewood

These terms are often used interchangeably to refer to the region of wood surrounding the pith. Burdon et. al.[12] argue that the term corewood should be used, and in radiata pine in New Zealand it is defined as the innermost 10 rings – a definition[5, 6] currently used by Forecaster v1.12. Corewood[14] is normally regarded as being of inferior quality as it typically has lower density, shorter fibres and increased spiral grain, microfibril angle (MFA) and longitudinal shrinkage compared to outer wood[5, 15]; although the quality improves the closer the rings get to the bark[5]. The amount of corewood present in a stem increases with stem height, but there is great variation in the amount of corewood present in a stem due to the impacts of site and seed source. Cown[15] suggests that the best approach to reduce the amount of corewood present in a stem would be to consider the specific site and initial stocking to use, increase the rotation length, and select improved genetic stock.

Branch Index (BIX)

Branches, particularly their size, condition and the distance between clusters, have a large impact upon log grade outturn[3]. BIX[16] is an index of maximum branch size defined as the mean diameter of the four branches representing the largest branch in each of the four quadrants of a log. BIX is affected by site, initial and final stocking, age of the stand, tree growth and height at the time of the final thinning[3]. Both timing and intensity of thinning and pruning will greatly impact upon the BIX value.

The branch model BLOSSIM v3.0[17] predicts the location of all branch clusters, and the position and size of all branches within a cluster for every tree in a stand[18], and in Forecaster[7], the model uses 5.5 m height classes to model BIX at time of clearfell. To do this, Forecaster first calculates an average BIX value for each height class for the entire crop. Then at the time of clearfell, each stem piece is calibrated by the average crop BIX. Finally, when the stem piece is assessed by the bucker, the average BIX for the log is calculated from the height class BIX values. The crop's average BIX is calculated for each 5.5 m height class from the crop stocking, mean DBH at age 20 years, thinning ages, MTH, residual stocking at each thinning, and mean SED (small end diameter) by 5.5 m height class.

Pruned Log Index (PLI)

The Pruned Log Index (PLI)[4, 19] was introduced to New Zealand in the mid-1980's, as a measure of basic pruned sawlog quality and clearwood potential[4, 20]. It is calculated from measures of log size and shape, and from the size of the knotty defect core. The PLI value for a group of trees is determined by a PLI survey in which a sample of trees are felled, split open and examined for defects[20]. Such sampling also provides the opportunity to gather data around incidence of other defects, such as, resin pockets and inter-ring checking[4, 20]. Stands with a higher PLI value are proven to produce better clearwood, and can attract higher prices in the market place[4, 20].

Forecaster allows users to set a minimum PLI value when they are setting up their log product definitions[7]. A PLI value is then assigned to every log; logs that are unpruned receive a PLI value of zero, while those logs with high sweep and / or a low SED receive a low PLI value.

Study Objectives

The objectives are to:

- Provide explicit guidance and specific examples of how to undertake regime analyses using the latest wood quality models within Forecaster.
- Assess the implications of using the latest wood quality models in Forecaster simulations on wood property distributions.

METHODOLOGY

Two broad silvicultural regimes (clearwood and framing) were modelled for sites in Northland, Bay of Plenty (BoP) and Southland. Each regime consisted of a base simulation with variations in final stocking, intensity of thinning, and rotation age.

Site and Crop Data

Standard, representative sites within 3 forest regions were obtained from the national lookup tables for the 300 Index and site index[21] (Table 2). These lookup tables were derived in 2006 from 4,608 PSPs established from 1975 onwards. These standard sites contained information on the average height and volume productivity indices (i.e. site index and 300 Index), elevation and latitude for each of the sixteen growth modelling regions. However, we felt that the national lookup tables did not accurately reflect the Northland region (originally site index = 26.5; 300 Index = 18.1; elevation = 400 m). Instead industry experts were asked to give average site and 300 Index values for their Northland forests. The average of those values were then used instead of the national values for the region.

Table 2: Characteristics of standard, representative sites for 3 forest regions: Northland, BOP and Southland.

Site	Latitude (deg. S)	Longitude (deg. E)	Elevation (m)	300 Index (m^3/ha/yr	SI (m)
Northland	35.5	173.6	200	24.6	29.8
BoP Forest Med	38.2	176.6	260	27.2	32.5
Southland	46.3	169.1	650	26.5	25.6

While Forecaster allows a crop to be created from two different levels of information, i.e. stemlist and whole stand summary, the analyses focus on the use of a stemlist-based crop. This crop was created using the Generate Start Age Crop functionality in Forecaster, based on the relevant site entity information and different initial stockings. Prior to running any of the simulations, the distributions of stem diameters and heights for these generated stem lists were checked to ensure that they were sensible and valid.

Regimes

Base regimes for clearwood and framing were set up with variations to the thinning intensity, final crop stocking and rotation ages. Timings of pruning and thinning operations were based on recommended best practice, such as scheduling pruning on DOS and thinning on MTH. Pruning regimes were initially based on “Largest DBH x Height”, with subsequent pruning operations based on “Most Pruning Lifts”. For the Clearwood regime, thinning events were based on “Fewest Pruning Lifts”, while the Framing regimes used “Smallest DBH x Height”. All thinning and pruning activities used a randomness factor of 2.0.

- The ***clearwood regime*** consisted of an initial stocking of 1000 stems/ha, followed by three pruning lifts to 6 m and a final thinning to 300 stems/ha.

- The ***framing regime*** consisted of an initial stocking of 1000 stems/ha, and waste thinned to 450 stems/ha at mean top height (MTH) of 14 m (Table 3).

Table 3: Descriptions of the base regimes and their variations

Clearwood base regime	Variations
Plant 1000 stems/ha	Plant 800 and 1200 stems/ha
Prune 525 stems/ha to 2.4m at DOS 16 cm with minimum green crown remaining 3.5 m.	Prune 400 and 650 stems/ha
Thin to waste to 525 stems/ha	N/A
Prune 300 stems/ha to 4.3 m at DOS 17 cm with minimum green crown remaining 3.5 m.	Prune 250 and 350 stems/ha
Prune 300 stems/ha to 6.0m at DOS 17 cm with minimum green crown remaining 3.5 m	Prune 200 and 350 stems/ha
Thin to waste to 300 stems/ha	Thin to waste to 250 and 350 stems/ha
Clearfell at age 30 years	Clearfell at ages 25 and 35 years

Framing base regime	Variations
Plant 1000 stems/ha	Plant 833, 1200 and 1500 stems/ha
Thin to waste to 450 stems/ha at MTH 14 m	Thin to 250, 400, 500 and 650 stems/ha MTH 6 m, 10 m, 18 m and 22 m
Clearfell at age 30 years	Clearfell at ages 25 and 35 years

Log Product Definitions and Cutting Strategies

With the focus of this paper on wood quality characteristics, market-based log grades (currently not based on wood quality attributes, but rather, based on various log lengths and diameters) would be less appropriate due to confounding factors. To overcome this, a single, generic log grade was used, which enabled differences in acoustic velocity, heartwood and wood density characteristics to be examined. This generic log grade had the following specifications:

- Minimum SED – 100 mm
- Maximum SED – 999 mm
- Log Length – 5.2 m.

Analyses were also conducted using existing Ministry for Primary Industries (MPI) log grades and prices from MPI's generic domestic log grade specifications[22, 23] (Appendices 1 and 2). This was done to allow users to better understand the implications of the wood quality models on existing log grades.

Models

Details on the specific models used in Forecaster are in Appendix 3. Additional inputs required by the models are described below.

Model inputs for the:

1. 300 Index growth model:
   - Mortality addition
     - Input is used to account for extra mortality not included in the model, for example windthrow (default value of 0).
   - Mortality multiplier
     - Input is used to adjust the predicted mortality to account for regions with above or below average mortality (default value of 0).

- Regional drift setting
    - The drift setting allows a 300 Index drift correction function to be applied to adjust growth and account for subtle regional differences in growth trajectories.

2. BLOSSIM v3.0 Branch model
    - Region as indicated (Northland = Clays; BoP = CNI; Southland = South)

3. WQIAcousticVelocity model
    - Seeded using the density index value, as indicated
        i. Northland = 440; BoP = 420; Southland = 380

4. FFR Density2011 model
    - Seeded using the density index value, as indicated
        i. Northland = 440; BoP = 420; Southland = 380

Values for mortality addition and mortality multiplier were kept at the default values of 0. The regional drift setting was set at the recommended settings, 0 for BoP and Canterbury, 0.05 for Northland and 0.35 for Southland[21].

Data Analysis

The log trace tables that are produced from Forecaster were exported to Excel and the data analysed via distribution graphs to determine what percentage of logs/stems pass a given threshold for each wood quality trait. Average values for each scenario will also be calculated. Traits examined (and their thresholds) will include:

- Acoustic Velocity (AV): What percentage of logs produce
    - AV < 3.0 km / sec
    - AV > 3.0 km/sec
- Wood Density (D): What percentage of logs have a
    - D < 400 kg
    - D > 400kg
- Heartwood: What percentage of log volume is heartwood
- Juvenile Corewood: what percentage of log volume is juvenile corewood
- Branch Size: What percentage of logs have braches
    - < 4 cm
    - < 5 cm
    - < 6 cm
    - < 7 cm
    - < 8 cm
    - > 8 cm
- Pruned Log Index (PLI): Percentage of logs are
    - < PLI 4
    - PLI 4,
    - PLI 5
    - PLI 6
    - PLI 7
    - PLI 8
    - PLI9
    - > PLI 10

RESULTS

The analysis involved examining how the differences in one of the regime variables (i.e., site, stocking, timing of thinning, rotation length, etc.) affected the predictions from the models. Once a better understanding had been achieved about the influence of these individual factors, all of the factors were combined to see how they interacted.

Note: Clearwood base regime = Bay of Plenty site, plant 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha, harvest at clearfell age 30 years.

Framing base regime = Bay of Plenty site, plant 1000 stems/ha, thin when MTH 14 m, final thinned stocking 450 stems/ha.

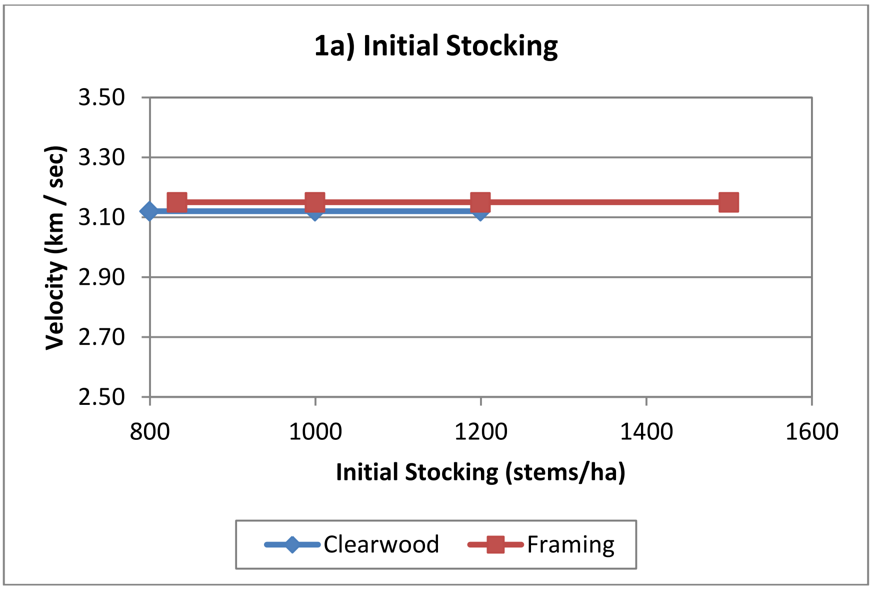
Note: scales on the charts often do not start at zero, in order to show in better detail the minimal impact of the some of the regime variations on the wood quality attribute of interest.

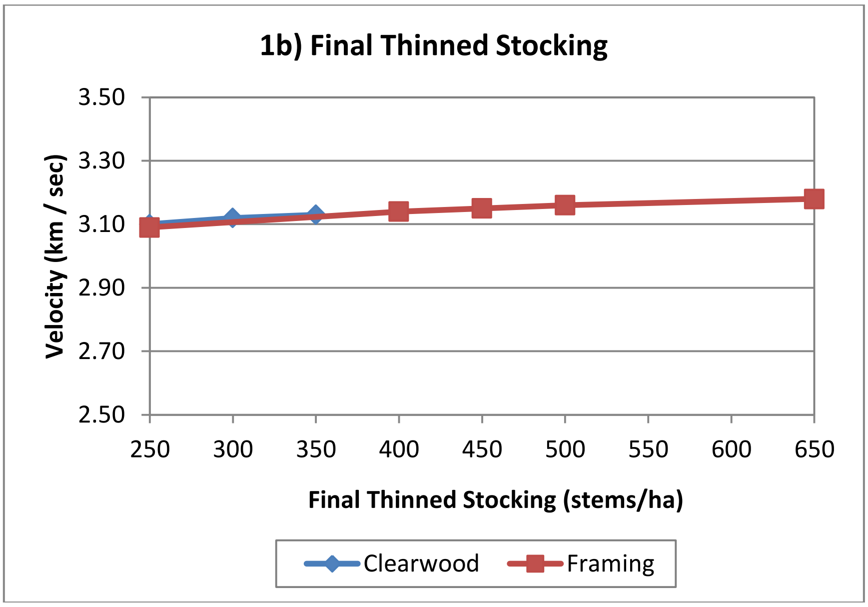
Acoustic Velocity

The WQIAcousticVelocity model is a function of green density measure, elevation, latitude, age (to model acoustic velocity with age), stem height (to model acoustic velocity up a stem) and stem slenderness (stem diameter and stem height).

For the Clearwood and Framing regimes initial stocking had a negligible impact upon the average velocity of logs (Chart 1a). Final thinned stocking has a small effect, with higher velocity values predicted for higher final thinned stocking values (Chart 1b). This is clearer in the Framing regimes where the final thinned stocking values extend out to 650 stems/ha.

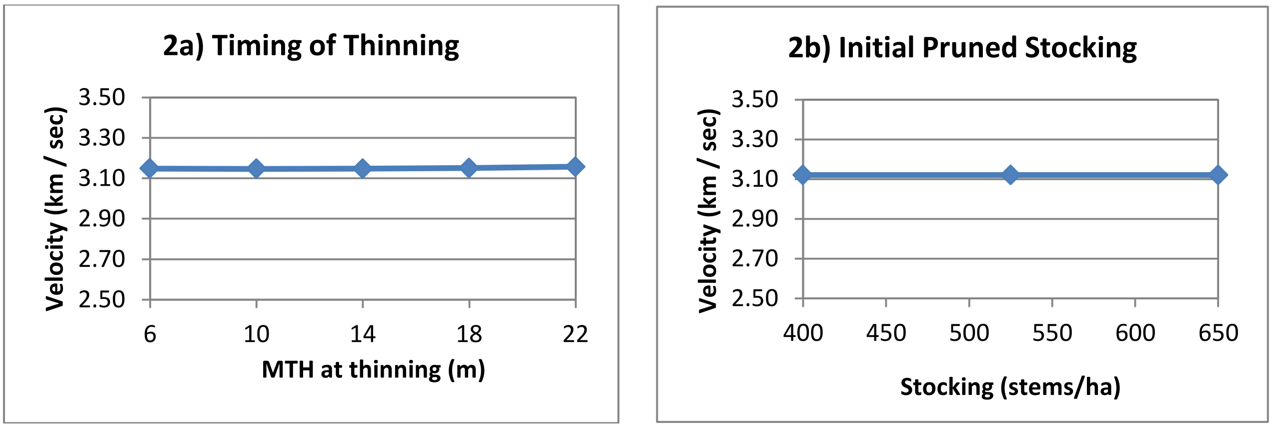
Charts 1a and 1b: Impact of initial stocking and final thinned stocking on Average Velocity in Log 1 (butt log) for the Clearwood and Framing regimes.





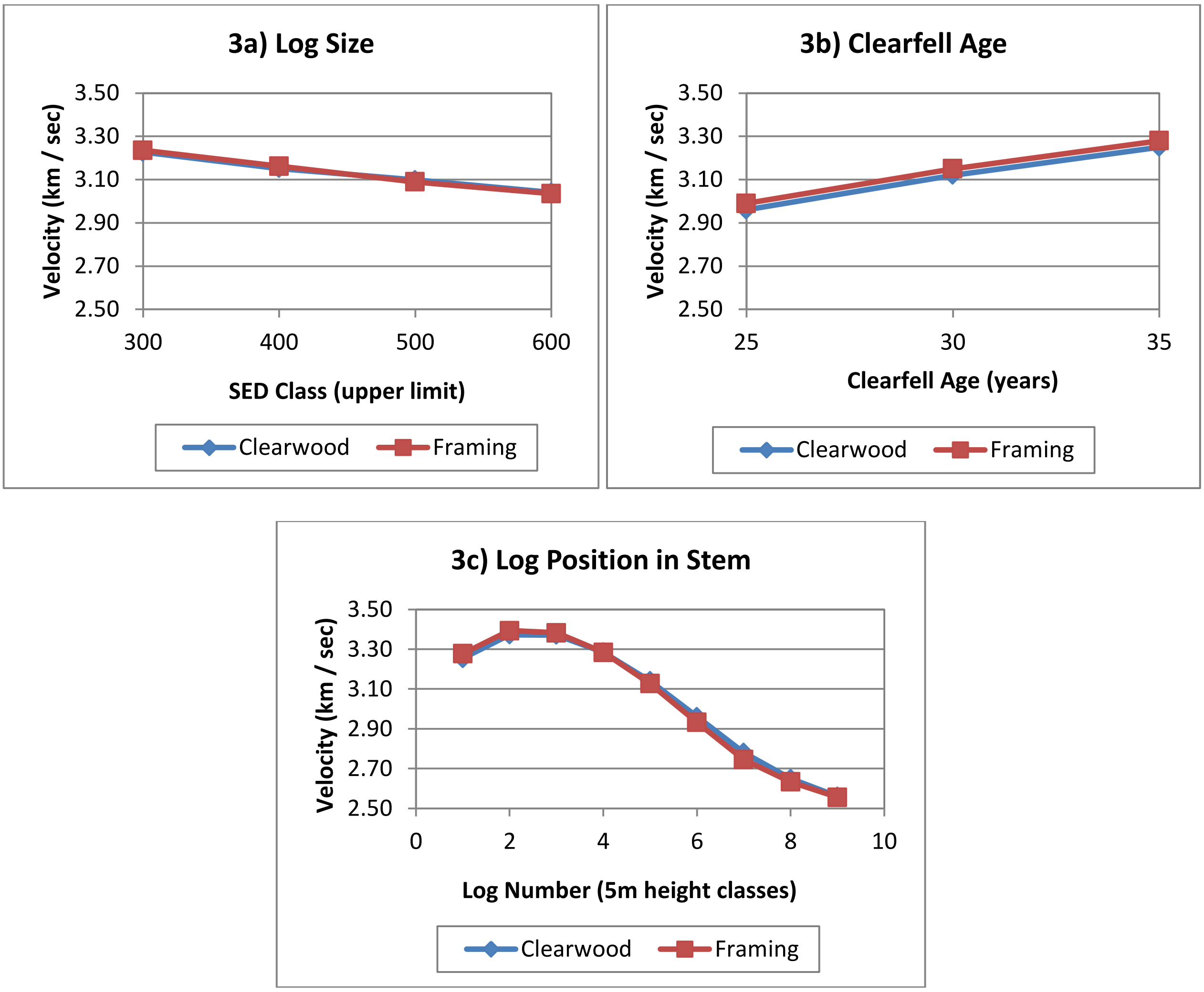
Timing of thinning variations (at differenct MTH) for the Framing regimes and the initial pruned stocking variations for the Clearwood regimes also had a negligible impact upon the average acoustic velocity values for the logs (Charts 2a and 2b).

Charts 2a and 2b: Impact of Timing of Thinning and Initial Pruned Stocking on average acoustic velocity in Log 1 for the Framing regimes and Clearwood regimes, respectively.



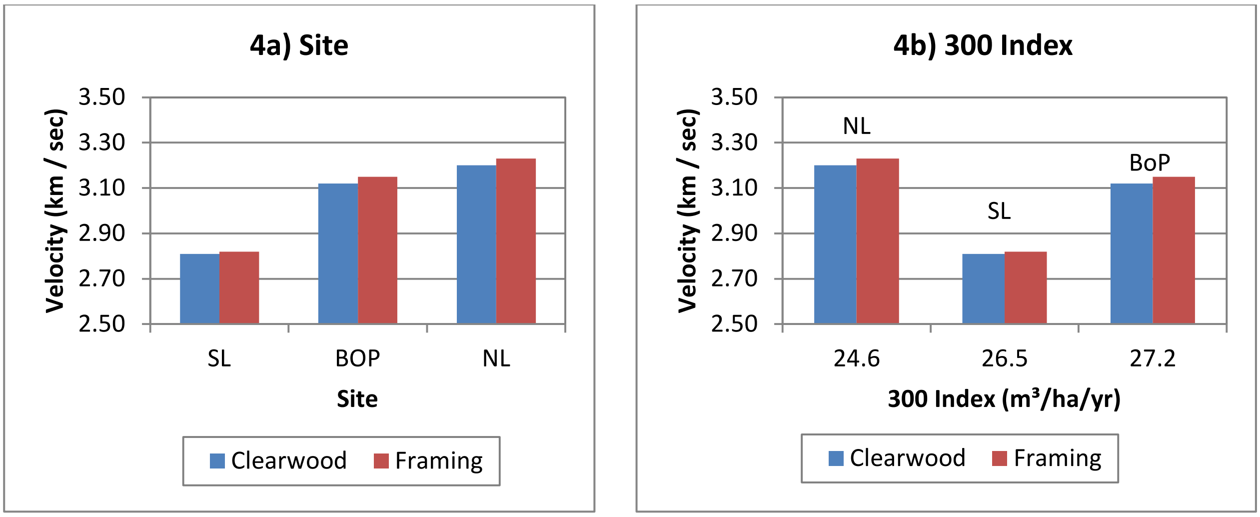
For both the Clearwood and Framing regimes, log size and clearfell age have a bigger effect on velocity, with increased rotation lengths and smaller logs having higher velocity values (Charts 3a and 3b). However, it is the log's position along the stem that has the greatest impact upon a log's average velocity value (Chart 3c). The second and third logs produce the highest velocity values, a trend that holds true across all regime variations. After peaking at the third (occasionally fourth) logs, the velocity value decreases at a sharp gradient until the last log in the stem. This trend agrees with Waghorn et. al.[24] who found that acoustic velocity initially increased with height up the stem before decreasing.

Charts 3a, 3b and 3c: Impact of Log Size, Clearfell Age and Log Position in Stem on average acoustic velocity in Log 1 for the Clearwood and Framing regimes.



At a site level, the lowest acoustic velocity values for both regimes occurred in Southland, while the highest occurred in Northland (Chart 4a). In this analysis, acoustic velocity did not seem to correspond with 300 Index values (Chart 4b), as the Bay of Plenty site had the highest 300 index value, but its velocity values were lower than those produced by the Northland site.

Charts 4a and 4b: Impact of Site and 300 Index values on Velocity in Log 1 for the Clearwood and Framing regimes.



A clearfell age of 35 years produces the highest percentage of logs which pass the acoustic velocity threshold of 3.0 km/s, across all three sites (Table 4) for the Clearwood and Framing regimes. However, in the case of the Northland and Bay of Plenty sites, the percentage gains are minimal, so that delaying to clearfell at an age past 30 years provides negligible benefits. At the Southland site, none of the logs exceeded this threshold for rotation lengths of 25 and 30 years; only when clearfell age reached 35 years did 58% of the logs to pass the threshold.

Table 4: Clearwood and Framing regime results, showing the percentage of logs that meet the velocity threshold of > 3 km/s, over time for the three sites.

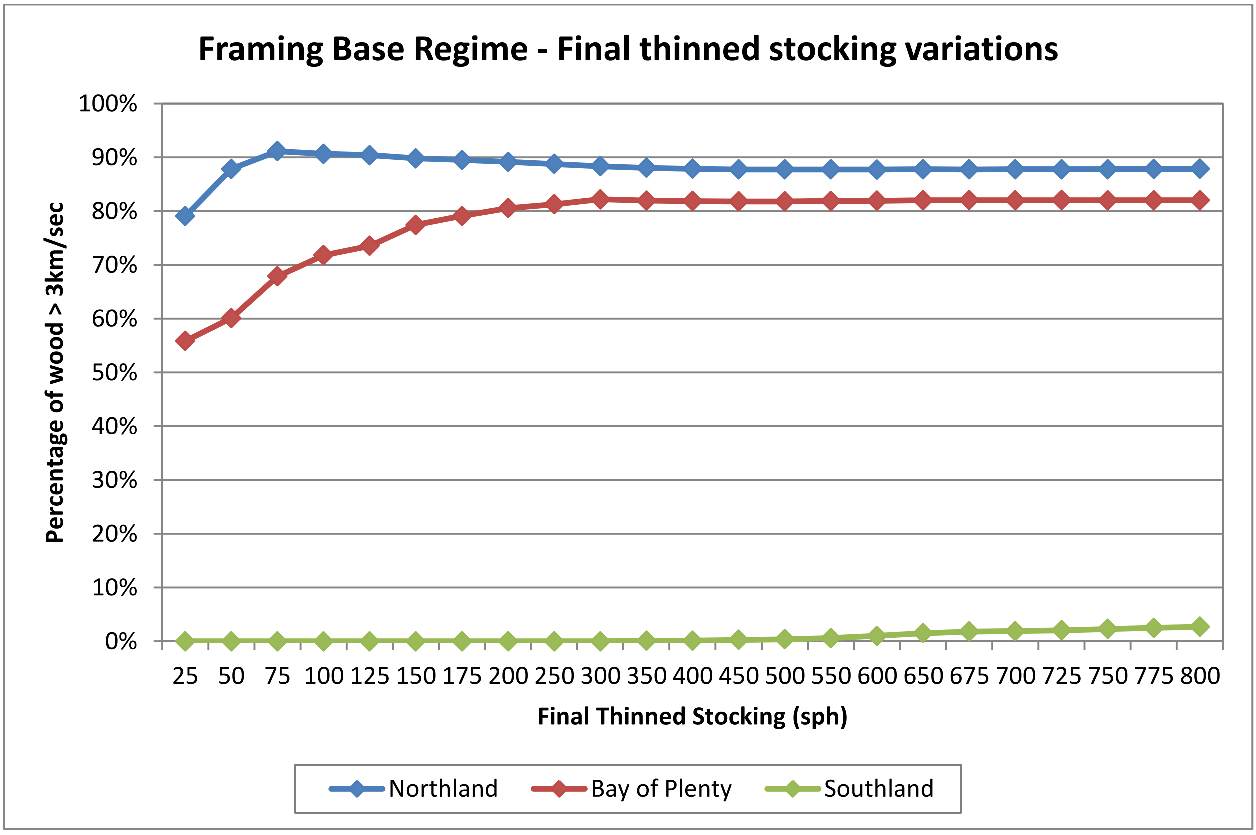
Site	Clearfell Age	Clearwood	Framing
Northland	25 years	72%	77%
	30	90	90
	35	95	95
Bay of Plenty	25	39	49
	30	84	84
	35	90	90
Southland	25	0	0
	30	0	0
	35	58	58

Clearwood and Framing regime variations produced no difference to the percentage of logs that met or exceeded the acoustic velocity threshold of 3 km/s (Table 5). For the Clearwood regime, 84% of the logs passed the threshold in every regime variation. The lack of differences between the different final thinned stocking values could be due to the relatively small range in stocking levels that were examined in this study. Interestingly, it is only when the final thinned stocking value drops below 250 stems/ha that a difference is shown in the percentage of logs passing the acoustic velocity threshold (Chart 6). For final thinned stocking to have any real impact upon the percentage of logs passing the threshold, a forest manager would have to thin down to extremely low levels that are beyond what is considered practically reasonable. Once the final thinned stocking exceeds 250 stems/ha, the percentage of logs passing the threshold is constant at 84%.

Table 5: Framing regime results showing the percentage of logs that meet the velocity threshold of > 3 km/s for the variations to base regimes at age 30 for the Bay of Plenty site.

Framing Regime Variation	> 3 km/s
Initial Stocking 833 stems/ha	84%
Initial Stocking 1000 stems/ha	84
Initial Stocking 1200 stems/ha	84
Initial Stocking 1500 stems/ha	84
Timing of Thinning MTH > 6 m	82%
Timing of Thinning MTH > 10 m	82
Timing of Thinning MTH > 14 m	82
Timing of Thinning MTH > 18 m	82
Timing of Thinning MTH > 22 m	82
Final Thinned Stocking 250 stems/ha	82%
Final Thinned Stocking 400 stems/ha	84
Final Thinned Stocking 450 stems/ha	84
Final Thinned Stocking 500 stems/ha	84
Final Thinned Stocking 650 stems/ha	84

Chart 6: Effect of final thinned stocking variations on the percentage of stems passing the 3 km/s threshold for the Framing base regime.



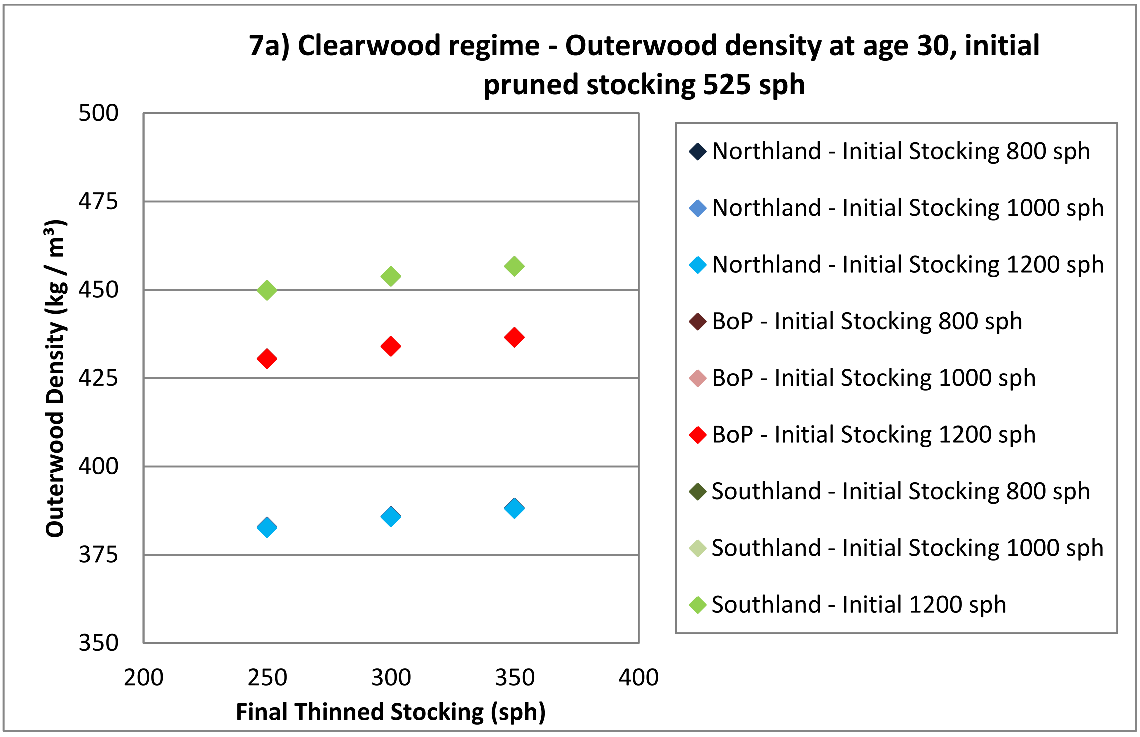
Density

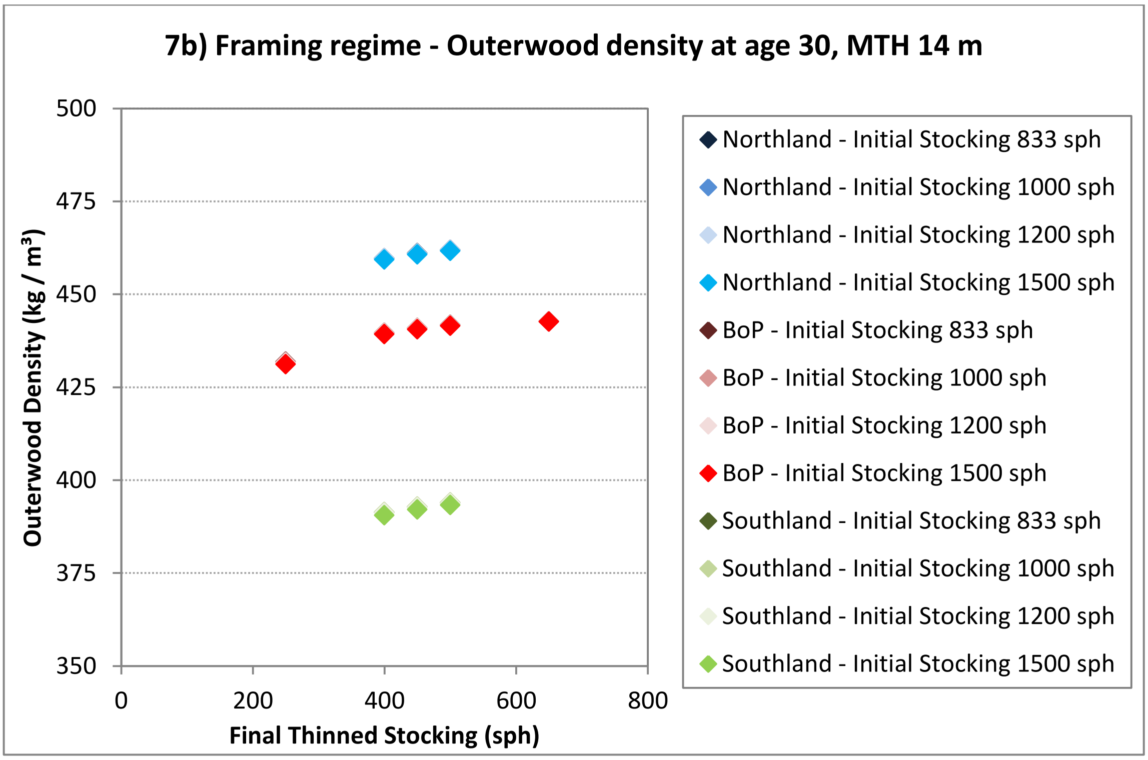
The FFRDensity2011 model is a function of Site Index, 300 Index, and a stand-average value of density at a given age, ring widths, age (to model density by age), stem height (to model density up a stem) and a stochastic element (to model between tree variation). Users can either enter breast height measurement of outerwood density, at a known age, into Forecaster, or they can select a value of the density index from the recently developed national surface. The density index is defined as breast height outerwood density of a stand growing at 200 stems/ha at age 20 years. The density model then uses these outerwood density values to calculate an average density value for the logs, which can be 40 kg/m^3 lower but follow the same trend with stocking.

Charts 7a and 7b clearly shows that different initial stocking values have no impact upon outerwood density, something which holds true across all of the three sites, both the Clearwood and Framing regimes, and for all of the final thinned stocking values.

Charts 7a and 7b: Outerwood density values over the range of different initial and final thinned crop stockings, at age 30 for the Clearwood and Framing regimes respectively, for all three sites.

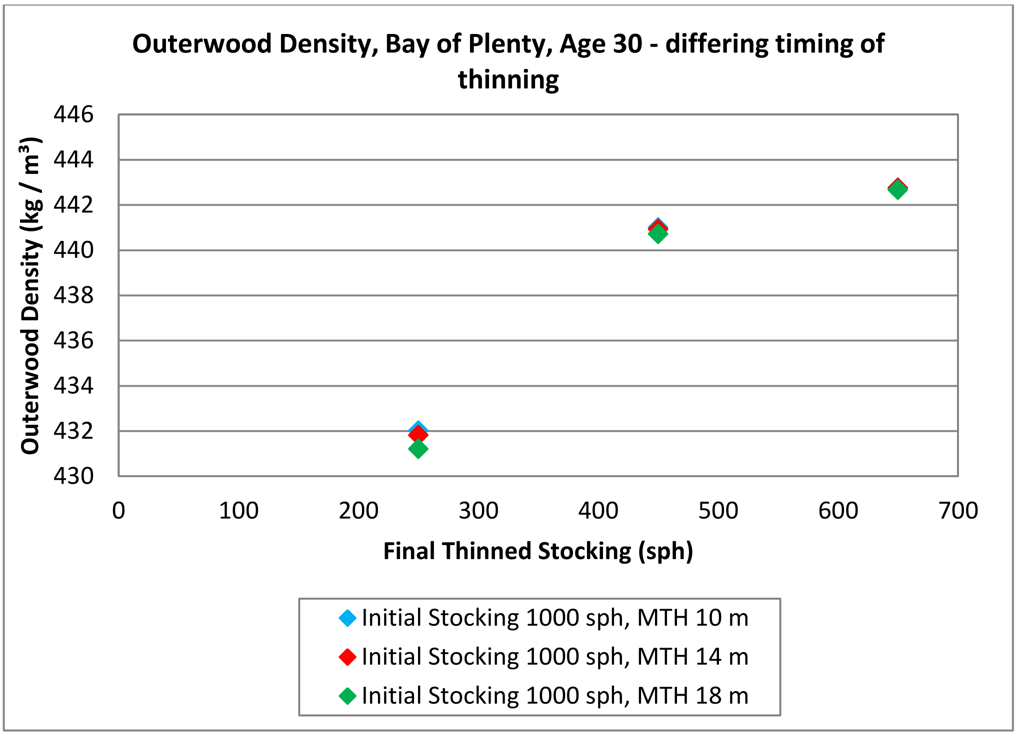
> **NOTE:** All points are present on the charts, however only the highest initial stocking for each site is visible as the other initial stocking points are directly underneath them. These points have been retained to demonstrate that initial stocking variations have no impact on outerwood density for a given final thinned stocking.





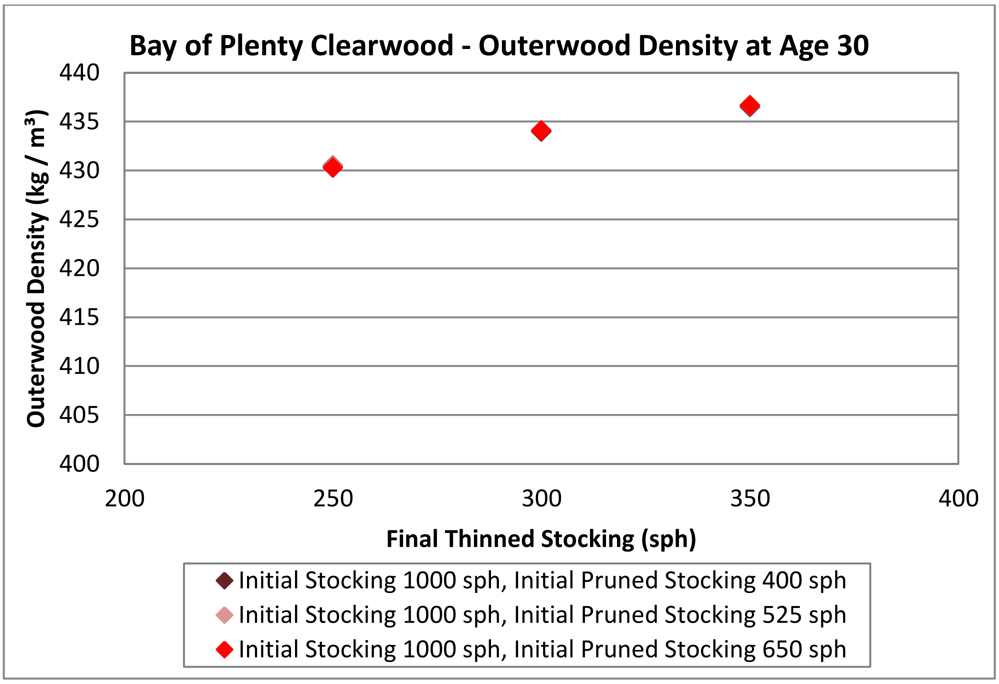
Timing of thinning also had a negligible impact upon outerwood density values (Chart 8). It did however interact with final thinned stocking values, in that the lower the final thinned stocking value, the greater the effect for the different thinning timings had on density.

Chart 8: The impact that timing of thinning has on outerwood density values for the Bay of Plenty's Framing regimes, age 30 years, for different and final thinned stockings.



For the Clearwood regime initial pruned stocking had no effect at all on density (Chart 9).

Chart 9: Showing the impact that initial pruned stocking variations have on outerwood density values for the Bay of Plenty site's Clearwood regimes, age 30 years, for different final thinned stockings.



With increasing rotation length, a greater percentage of logs meet or exceed the density threshold of 400 kg/m³ (Table 6). The Northland region produces the best density results for a clearwood regime, with over half of the logs meeting the threshold at age 25 years. Southland is the poorest region for producing logs which meet this criterion, with Southland clearwood regimes producing a maximum of 13% logs with density values greater than 400 kg/m³. This is probably due to an effect by the 300 Index value, as the Bay of Plenty site had the highest 300 Index value of the three sites used in this report; while Southland had the lowest 300 Index value. Also, density is largely driven by temperature, a factor that also affects 300 Index, so any association between 300I and density are likely to be due to their mutual associations with temperature.

Densities are lower across the board for the Clearwood regime, due to the lower final thinned stockings used in the base regime.

Table 6: Clearwood base regime, showing the percentage of log volume made up of logs that meet or exceed the average density threshold of 400 kg/m³ for the three sites.

Site	Clearfell Age	> 400 kg/m³
Northland	25 years	53%
	30	61
	35	67
Bay of Plenty	25	28
	30	36
	35	42
Southland	25	9
	30	10
	35	13

The proportion of logs meeting or exceeding the density threshold also increased with rotation length for the Framing regimes (Table 7). This held true across all three sites, with Northland again producing the most wood capable of meeting the threshold (47% for a rotation length of 25 years increasing to 60% for a rotation length of 35 years). Interestingly, a greater proportion of logs in the clearwood regimes exceeded the 400 kg/m^3 density threshold. This result was unexpected and appears counter-intuitive given the higher stocking levels in the Framing regimes. Further analysis, including analysis of data from regime trials, is needed to further understand this result.

Table 7: Framing base regime, showing the percentage of log volume that meets or exceeds the density threshold of 400 kg/m³ for the three sites.

Site	Clearfell Age	> 400 kg/m³
Northland	25 years	47%
	30	54
	35	60
Bay of Plenty	25 years	20%
	30	26
	35	30
Southland	25 years	6%
	30	8
	35	9

Different initial stockings do not greatly affect density values for logs and neither do different initial pruned stockings (Table 8). Both these variations to the Clearwood base regime only resulted in minor changes (3-4%) to the proportion of logs meeting or exceeding the density threshold. Final thinned stocking variations had a slightly greater impact upon the percentage of logs that meet the threshold, but the difference is still very small (Table 8).

Table 8: Clearwood regime variations that show the percentage of logs that meet or exceed the density threshold of 400 kg/m³ for the Bay of Plenty site at age 30 years.

Clearwood Regime Variation	> 400 kg/m³
Initial Stocking 800 stems/ha	33%
Initial Stocking 1000 stems/ha	36
Initial Stocking 1200 stems/ha	32
Initial Pruned Stocking 400 stems/ha	32%
Initial Pruned Stocking 525 stems/ha	36
Initial Pruned Stocking 650 stems/ha	35
Final Thinned Stocking 250 stems/ha	35%
Final Thinned Stocking 300 stems/ha	36
Final Thinned Stocking 350 stems/ha	31

Similarly for the Framing regimes, the proportion of logs meeting or exceeding the density threshold is not greatly influenced by different initial stocking values (Table 9). However, timing of thinning and the final thinned stocking values produced a much bigger variation in the proportion of logs exceeding this threshold, especially at the extreme ranges. The later a thinning occurred, and the lower the final thinned stocking value, the greater the proportion of wood that passed the density threshold. We assume that this is due to the higher stocking levels restricting the development of higher density outerwood, so that the corewood content is higher and the overall average density is lower. Again, this result requires additional investigation. Although there was a change of 15% over the final thinned stocking range of 250 stems/ha to 650 stems/ha, over the range of values that represent standard practice (i.e. 400-500 stems/ha), the proportion of logs that met or exceeded the threshold, was relatively constant at approximately 25%.

Table 9: Framing regime variations that show the percentage of logs that meet or exceed the density threshold of 400 kg/m³ for the Bay of Plenty site at age 30 years.

Framing Regime Variation	> 400 kg/m³
Initial Stocking 833 stems/ha	24%
Initial Stocking 1000 stems/ha	26
Initial Stocking 1200 stems/ha	25
Initial Stocking 1500 stems/ha	24
Timing of Thinning MTH > 6 m	22%
Timing of Thinning MTH > 10 m	22
Timing of Thinning MTH > 14 m	25
Timing of Thinning MTH > 18 m	26
Timing of Thinning MTH > 22 m	28
Final Thinned Stocking 250 stems/ha	34%
Final Thinned Stocking 400 stems/ha	26
Final Thinned Stocking 450 stems/ha	26
Final Thinned Stocking 500 stems/ha	24
Final Thinned Stocking 650 stems/ha	19

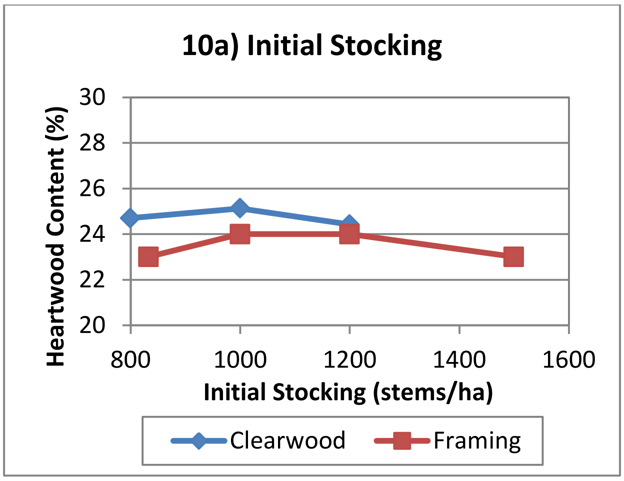
Forest managers wanting to improve wood density in Clearwood regimesshould lengthen the rotation age and grow their wood in the Northland region. Similarly if, the highest density values for a Framing regime were from wood at age 30 in Northland. In all cases Southland produced the lowest amount of wood to meet or exceed the density threshold of 400 kg/m³. However, it is important to note that wood density is not necessarily, if at all, a key trait for appearance products. Here wood colour (pale is preferred) and low resin content are much more important attributes. Southland is well-known for the favourable appearance of its clearwood. Density is more important for the upper logs which are likely to be sawn or pulped.

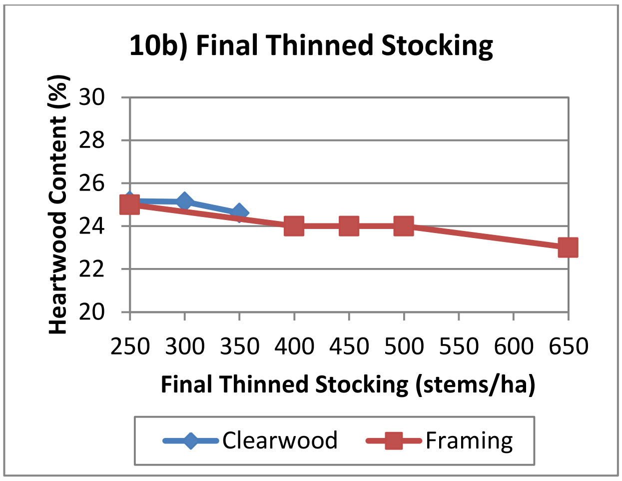
Heartwood

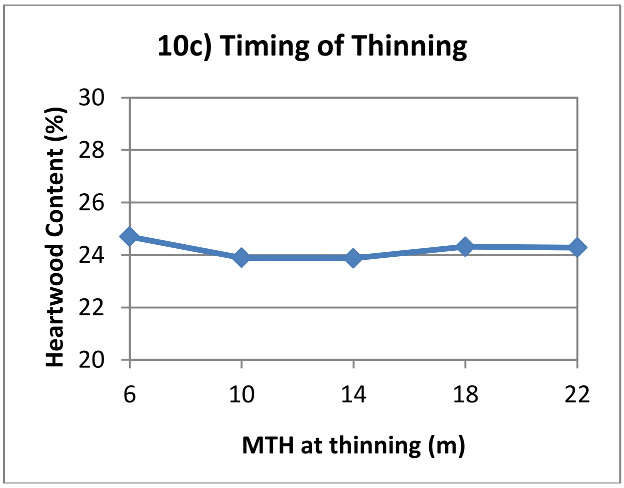
The FFRWQI2009 heartwood model is a function of age, stem height (to model heartwood up a stem), stem diameter, latitude and a stochastic element (to model between-tree variation).

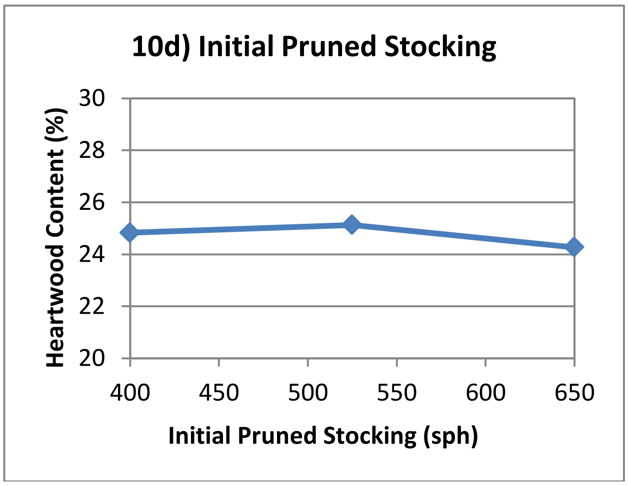
Initial stocking, final thinned stocking, timing of thinning and initial pruned stocking did not impact on heartwood content (Charts 10a-d). While these variations to the regimes produced minor changes in the heartwood percentage in the logs, these differences were minimal and we would not recommend forest managers varying stocking with the aim of manipulating heartwood content.

Chart 10a, 10b, 10c and 10d: Impact of Initial Stocking, Final Thinned Stocking, Timing of Thinning and Initial Pruned Stocking on the Heartwood Content in Log 1 for the Clearwood and Framing regimes.



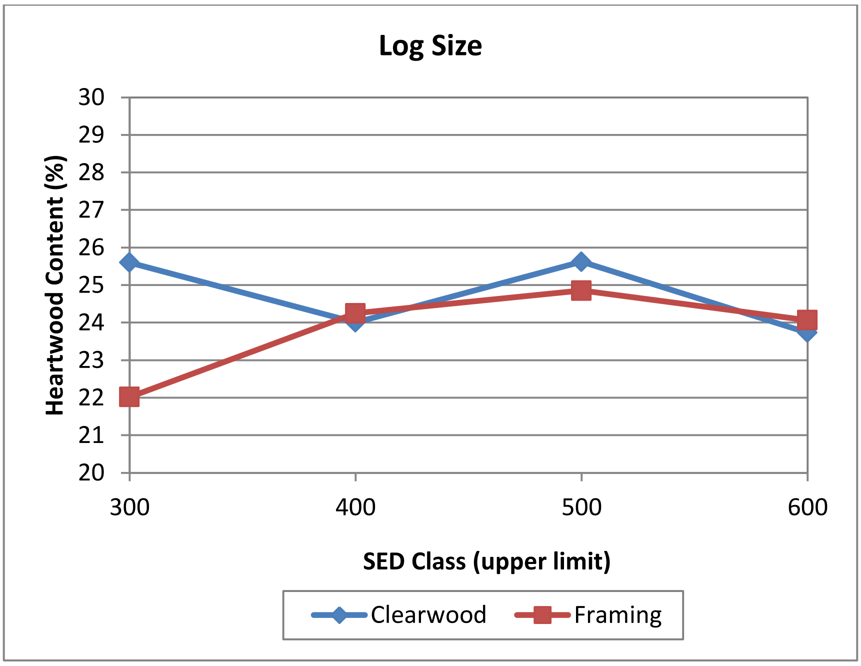






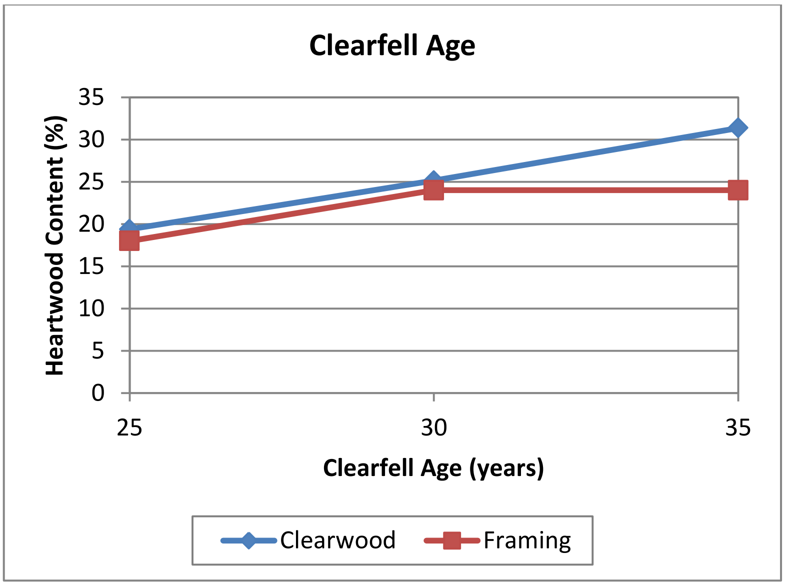
There was more variation in heartwood content with log size for both regimes (Chart 11). For the Framing regime, the model predicted a consistent increase in heartwood content up to an SED of 500 mm, followed by a slight decrease for SED>500 mm. However, there was no clear trend in heartwood content with log size for the Clearwood regime.

Chart 11: Impact of log size on the Heartwood Content in Log 1 for the Clearwood and Framing regimes.



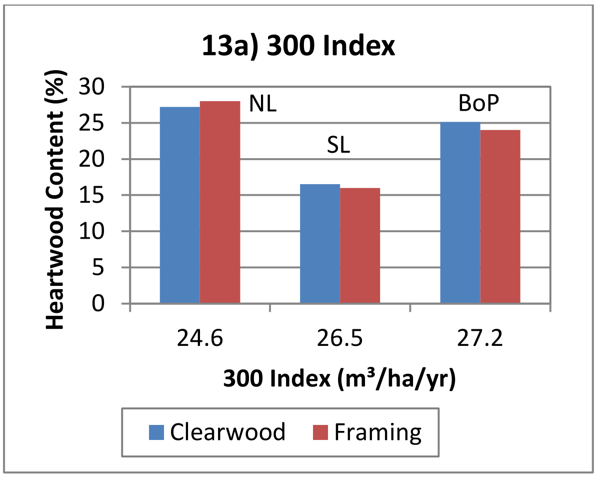
Rotation length and site have a bigger impact upon the percentage of heartwood present in a log than stocking. For the Clearwood regime, increasing the rotation length from 25 years to 35 years resulted in a predicted increase in heartwood content of 10% (Chart 12). For the Framing regimes, increasing the rotation age for 25 to 30 years increased the amount of heartwood in a log by around 6%. However, after age 30 years, predictions from the model showed that further increases in rotation length did not result in further increases in the heartwood content of log. It is believed that this is an artefact of the model, as empirical evidence indicates that heartwood formation continues beyond age 30. Further investigation is required in order to better understand this result.

Chart 12: Impact of clearfell age on the heartwood content in Log 1 for the Clearwood and Framing regimes.



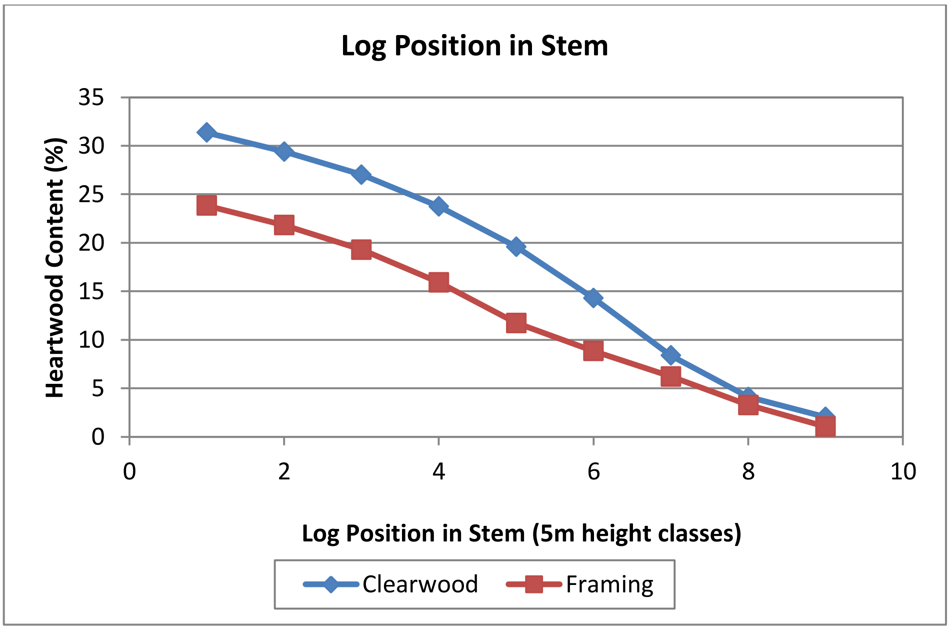
At a site level there is no association between 300 Index values and the percentage of heartwood present in a log (Charts 13a and 13b), but there is a positive association between latitude i.e. logs from more northerly sites contain a greater percentage of heartwood, which was to be expected given that this was an explicit term in the model. Both the Clearwood and Framing regimes showed the same patterns for 300 Index and site.

Charts 13a and 13b: Impact of 300 Index and site on the heartwood content in Log 1 for the Clearwood and Framing regimes.



Once again it was the log position within the stem that resulted in the largest variation in heartwood content (Chart 14). For both regimes, butt logs (Log 1) contained the highest percentages of heartwood, while those logs cut from the top of the stem (Logs 7, 8 or 9 depending upon rotation age) contained the least amount of heartwood. Chart 14 clearly shows that a clearwood regime produces larger amounts of heartwood content than a Framing regime for a given log height class, although by the time the upper logs are reached, the heartwood content for both regimes are similar, indicating a steeper rate of decline in the longitudinal direction under the Clearwood regime.

Chart 14: Impact of the log position in the stem on the heartwood content in Log 1 for the Clearwood and Framing regimes.



Heartwood content, (as a percentage of volume) increases over time (Table 10). All three sites for both base regimes showed an increase in the percentage of heartwood for the butt logs (Log 1). The heartwood model also produced almost identical results across the two base regimes, indicating that forest managers can carry out either a Clearwood or a Framing regime and get the same percentage of heartwood.

Table 10: The heartwood content (as a percentage of volume) of the butt logs (Log 1) for different clearfell ages and sites of the Clearwood and Framing base regimes.

Site	Clearfell Age	Clearwood	Framing
Northland	25 years	21%	21%
	30	27	28
	35	34	35
Bay of Plenty	25	19	18
	30	25	24
	35	31	30
Southland	25	12	11
	30	17	16
	35	21	21

None of the Clearwood regime variations resulted in any substantial differences in the heartwood content present in the butt logs. Increased initial stocking values and initial pruned stocking values produced a slight decrease in the heartwood content, but the magnitude of the decrease was very small. The final thinned stocking value had no effect on heartwood content.

The variations in initial stocking for the Framing base regime produced similar results to those for the Clearwood regime, in that there was no discernible trend (Table 11). The final thinned stocking variations resulted in a small decrease in heartwood content. However, even in this case the decrease is only 2% over a range in final thinned stocking from 250 to 650 stems/ha, which would suggest that such a regime variation has minimal impact upon heartwood content. Timing of thinning variations also had no impact on heartwood content.

Table 11: The heartwood content (as a percentage of volume) of the butt logs (Log 1) for the Framing regime variations on the base regime for the Bay of Plenty site at age 30 years.

Framing Regime Variation	Heartwood Content (% of volume)
Initial Stocking 833 stems/ha	23%
Initial Stocking 1000 stems/ha	24
Initial Stocking 1200 stems/ha	24
Initial Stocking 1500 stems/ha	23
Timing of Thinning MTH > 6 m	25%
Timing of Thinning MTH > 10 m	24
Timing of Thinning MTH > 14 m	24
Timing of Thinning MTH > 18 m	24
Timing of Thinning MTH > 22 m	24
Final Thinned Stocking 250 stems/ha	25%
Final Thinned Stocking 400 stems/ha	24
Final Thinned Stocking 450 stems/ha	24
Final Thinned Stocking 500 stems/ha	24
Final Thinned Stocking 650 stems/ha	23

Juvenile Wood/Corewood

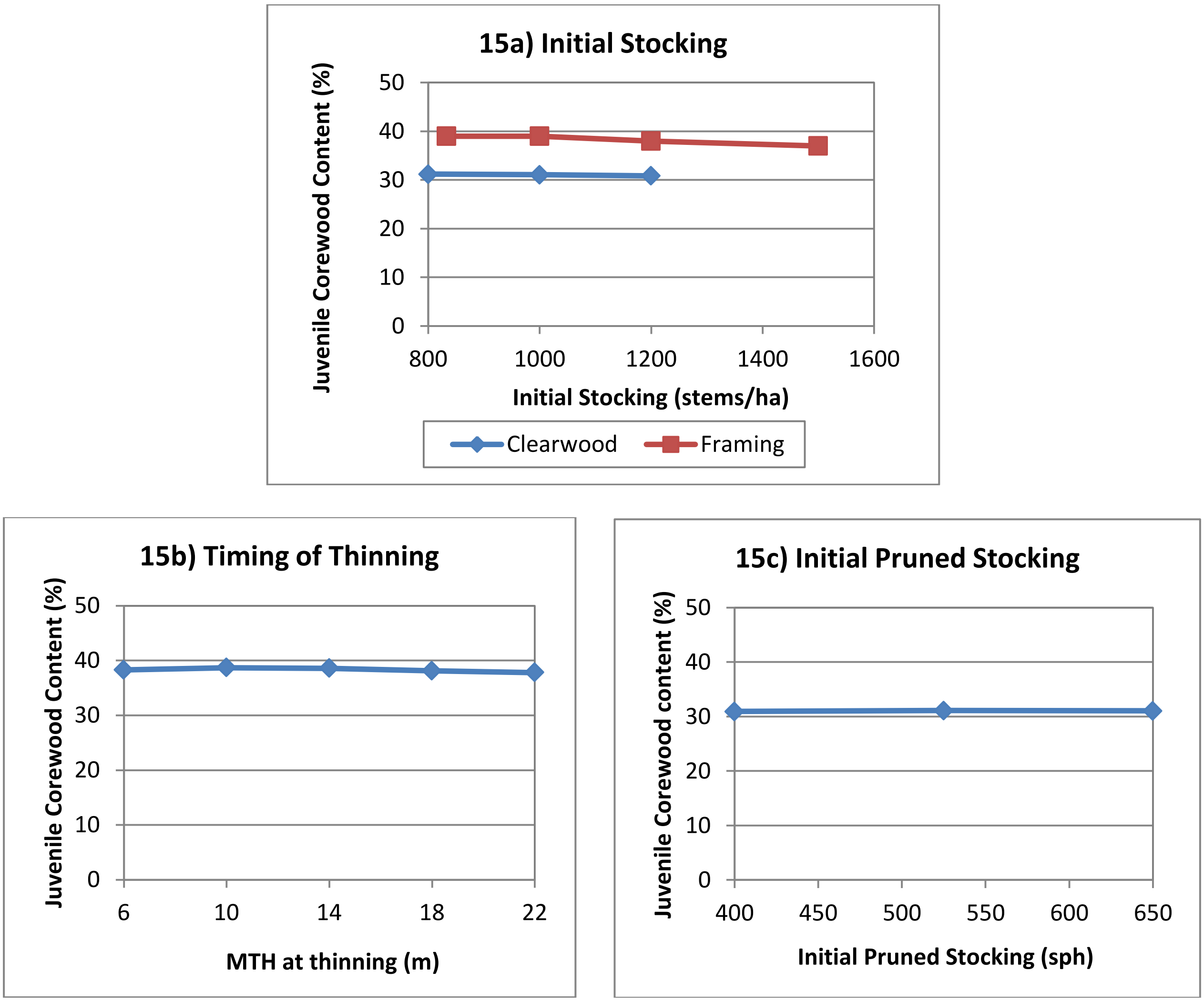
Corewood is defined as the inner ten rings at all heights in the stem of a tree in version 1.12 of Forecaster. The corewood model is hardwired into Forecaster and calculates the proportion of corewood at any height in the tree as a function of the area of corewood and the total cross sectional at that height.

Ignoring the effects of productivity (in terms of diameter growth), then:

> Diameter of inner rings f (early between-tree competition – i.e. initial stocking, thin age)
> Diameter of outer rings f (late between-tree competition – i.e. final crop stocking, rotation length)

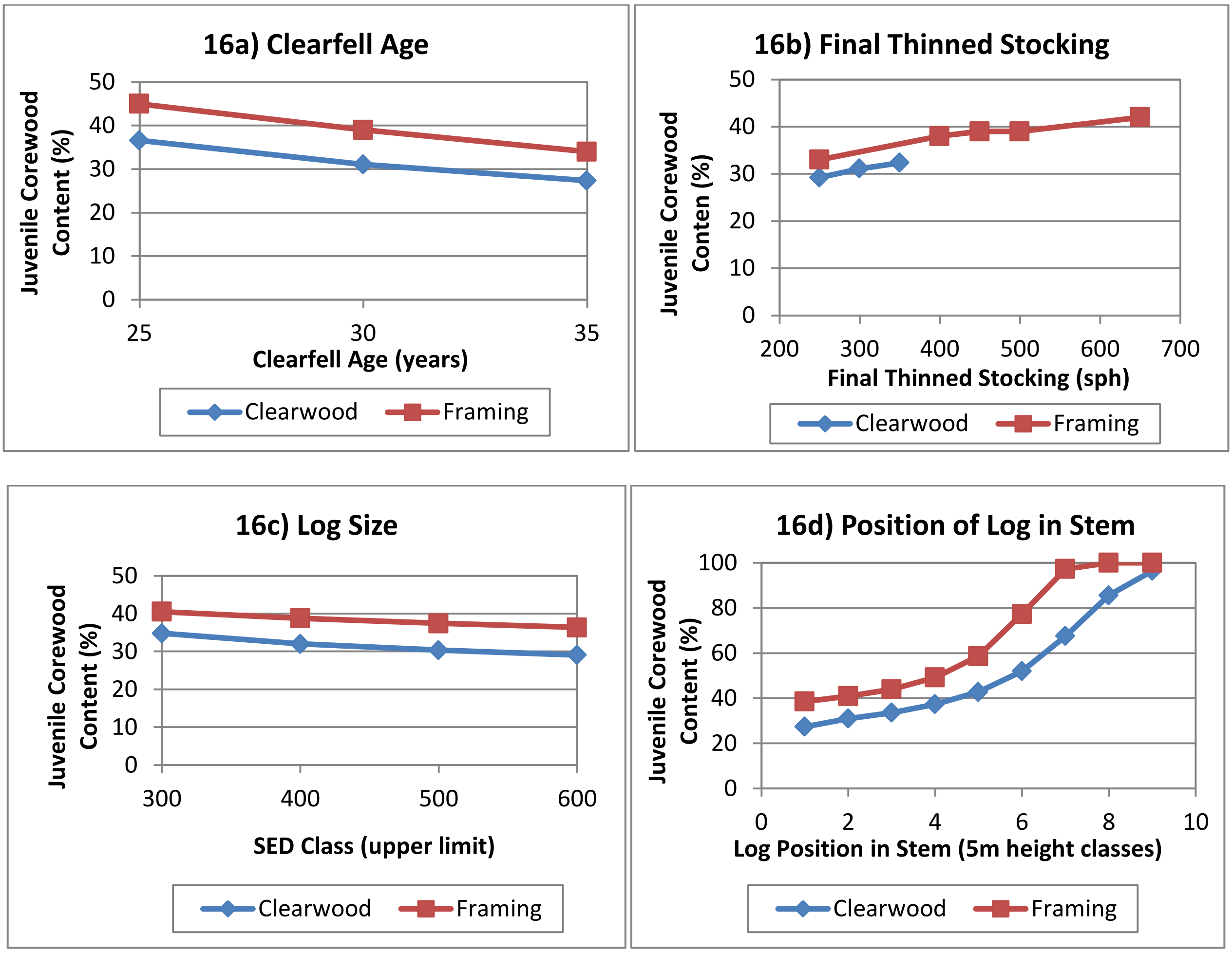
Initial stocking, the timing of the thinning events and initial pruned stocking have no impact upon the percentage of corewood present in a log (Charts 15a-c). However, the Framing regime does produce more corewood than the Clearwood regime for the same initial stocking values due to the higher final crop stocking which reduces the radial growth at the time when the tree is producing outerwood.

Charts 15a, 15b and 15c: Impact of the Initial Stocking, Timing of Thinning and Initial Pruned Stocking on Juvenile Corewood Content in Log 1 for the Clearwood and Framing regimes.



Increasing the clearfell age and decreasing the final thinned stocking value both act to decrease the percentage of corewood present in a log under both Clearwood and Framing regimes (Charts 16a and 16b, respectively). Larger logs have lower corewood content compared to smaller logs (but this effect is also minimal), and logs cut from further up the stem have more corewood compared to butt logs (Charts 16c and 16d, respectively). Logs at the top of the stem are almost entirely made up of corewood, especially in the case of the Framing regimes. In all instances the Framing regimes produced greater amounts of corewood than the Clearwood regimes.

Charts 16a, 16b, 16c and 16d: Impact of clearfell age, final thinned stocking, log size and position of log in the stem on corewood content for the Clearwood and Framing regimes. Results are shown for the butt logs, except for 18d, where all logs are shown.



In terms of site, Bay of Plenty produces the highest proportion of corewood in logs, followed by Northland and then Southland (Chart 17a). Chart 17b shows that 300 Index values alone have no relationship with corewood percentages.

Charts 17a and 17b: Impact of the site and 300 Index on corewood content in Log 1 for the Framing regimes.

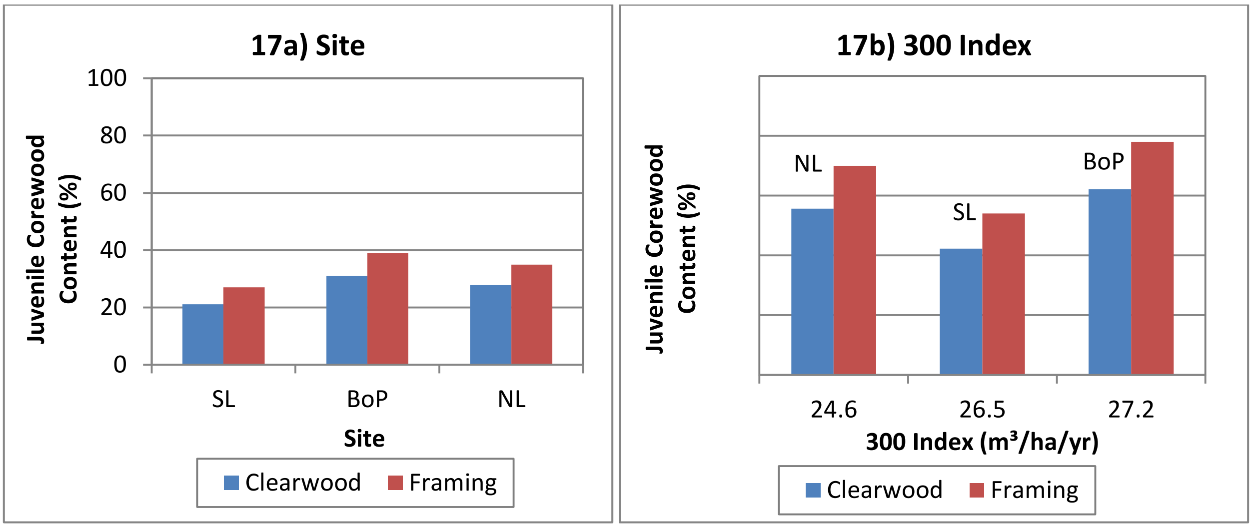


Table 12 shows the combined effect of initial stocking, timing of thinning and final thinned stocking on the Framing regime. It clearly shows that the final thinned stocking value has the biggest impact upon the percentage of corewood present in a log, while initial stocking and timing of thinning have less impact.

Table 12: Percentage of volume made up by corewood in the butt log for a Bay of Plenty example (green = lower proportion of juvenile core, red = higher).

Final Thinned Stocking (stems/ha)	MTH at time of thinning (m)	% Juvenile Core			
		Initial Stocking (stems/ha)			
		833	1000	1200	1500
250	6	32%	33	32	32
250	10	33	33	33	32
250	14	33	33	32	31
250	18	32	32	31	29
250	22	32	31	29	27
450	6	38	38	38	38
450	10	39	39	39	38
450	14	39	39	38	37
450	18	38	38	37	35
450	22	38	38	37	34
650	6	42	41	41	41
650	10	42	42	41	41
650	14	42	42	41	40
650	18	42	41	41	39
650	22	42	41	40	38

The corewood model produced the opposite results to the heartwood model, i.e. as rotation age increased the percentage of log volume that was corewood decreased across all three sites (Table 13). Unlike the heartwood results, where the Clearwood and Framing base regimes produced nearly identical results, the corewood model predicted greater volumes of corewood for the Framing regime. Due to higher final thinned stockings, once again Southland produced the least amount of corewood, while the Bay of Plenty region produced the most.

Table 13: The corewood content (as a percentage of volume) of the butt logs (Log 1) for different clearfell ages and sites of the Clearwood and Framing base regimes.

Site	Clearfell Age	Clearwood	Framing
Northland	25 years	33%	41%
	30	28	35
	35	24	30
Bay of Plenty	25	37	45
	30	31	39
	35	27	34
Southland	25	27	33
	30	21	27
	35	18	24

For the Clearwood regime variations, neither initial stocking variations nor initial pruned stocking variations produced any difference in the juvenile corewood content (Table 14). The final thinned stocking variations showed a slight increase in corewood content as the final thinned stocking increased from 250 stems/ha to 350 stems/ha.

Table 14: The corewood content (as a percentage of volume) of the butt logs (Log 1) for the Clearwood regime variations on the base regime for the Bay of Plenty site at age 30 years.

Clearwood Regime Variation	Corewood Content (% of volume)
Initial Stocking 800 stems/ha	31%
Initial Stocking 1000 stems/ha	31
Initial Stocking 1200 stems/ha	31
Initial Pruned Stocking 400 stems/ha	31%
Initial Pruned Stocking 525 stems/ha	31
Initial Pruned Stocking 650 stems/ha	31
Final Thinned Stocking 250 stems/ha	29%
Final Thinned Stocking 300 stems/ha	31
Final Thinned Stocking 350 stems/ha	32

For the Framing regime, decreasing the initial stocking resulted in a decrease in corewood content (Table 15). Similar to the Clearwood regime, increasing the final thinned stocking resulted in an predicted increase in corewood content. Timing of thinning had a negligible impact on the corewood content of a log.

Table 15: The corewood content (as a percentage of volume) of the butt logs (Log 1) for the Framing regime variations on the base regime for the Bay of Plenty site at age 30 years.

Framing Regime Variation	Corewood Content (% of volume)
Initial Stocking 833 stems/ha	39%
Initial Stocking 1000 stems/ha	39
Initial Stocking 1200 stems/ha	38
Initial Stocking 1500 stems/ha	37
Timing of Thinning MTH > 6 m	38%
Timing of Thinning MTH > 10 m	39
Timing of Thinning MTH > 14 m	39
Timing of Thinning MTH > 18 m	38
Timing of Thinning MTH > 22 m	38
Final Thinned Stocking 250 stems/ha	33%
Final Thinned Stocking 400 stems/ha	38
Final Thinned Stocking 450 stems/ha	39
Final Thinned Stocking 500 stems/ha	39
Final Thinned Stocking 650 stems/ha	42

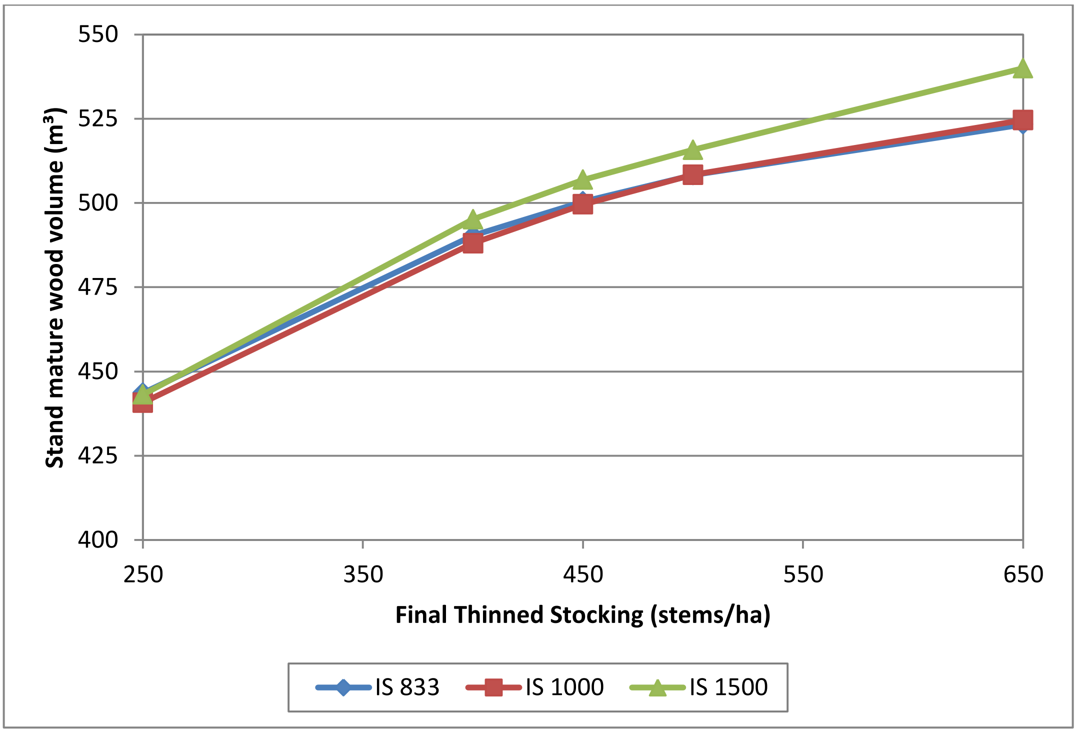
Foresters can achieve the greatest control over corewood size by increasing initial planting stocking, delaying thinning, ensuring that trees have the necessary space to grow following thinning, and increasing rotation length. However, this approach may be counter-productive when considering other factors e.g. economic profitability, management of wind risk and other wood properties, etc. (Table 16). For the Clearwood regime, initial stocking and initial pruned stocking had no impact upon the percentage of corewood. The other treatment variables followed the same patterns as the Framing regime.

Table 16: Summary of framing treatment options, and subsequent effect on corewood content.

Silvicultural treatment	Intermediate effect(s)	Corewood % effect	Quantum of effect
Final crop stocking ↑	Outer radius ↓	↑	Medium
Final crop stocking ↓	Outer radius ↑	↓	Medium
Initial stocking ↑	Inner radius ↓	↓	Small
Initial stocking↓	Inner radius ↑	↑	Small
Age at thinning ↑	Inner radius ↓	↓	Small
Age at thinning ↓	Inner radius ↑	↑	Small
Rotation length ↑	Outer radius ↑	↓	Large
Rotation length ↓	Outer radius ↓	↑	Large

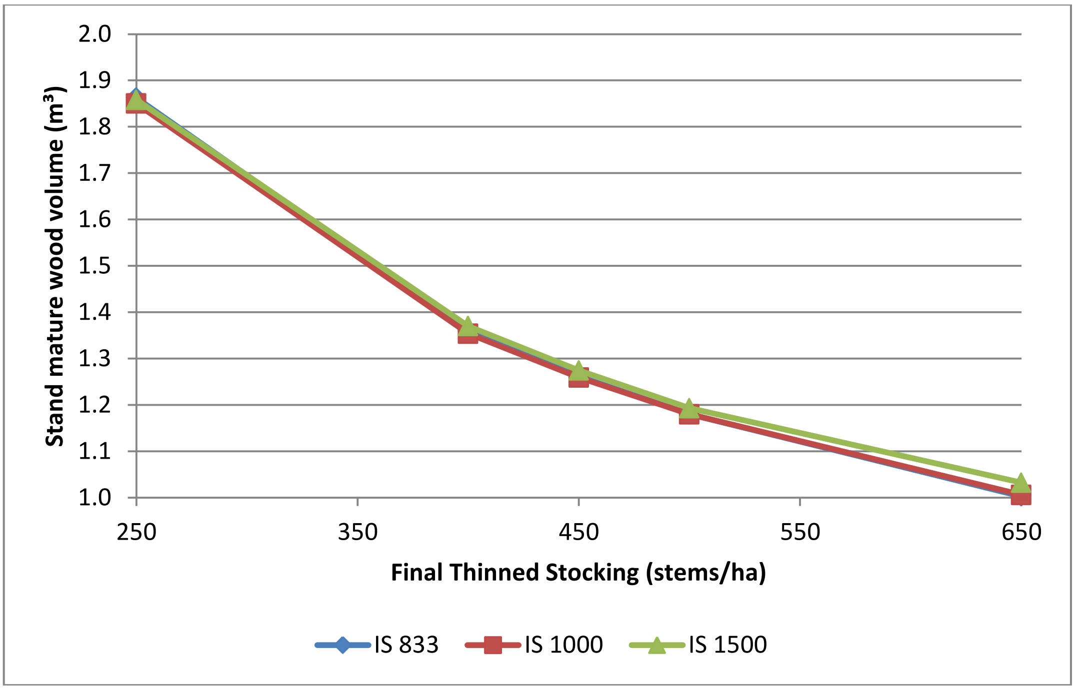
Because the grower's goal is to maximise the volume of mature wood, rather than just minimise the proportion of juvenile wood, the per ha volume of mature wood was also analysed across a range of regimes. Timing of thinning and initial stocking were again found to have a negligible effect on the mature wood volume (Chart 18). As final thinned stocking was increased, the volume of mature wood increased across the whole range of stockings analysed.

Chart 18: Effect of initial stocking (IS) and final thinned stocking on total mature wood volume for the Framing regime, Bay of Plenty site at age 30 years.



Clearly this effect is countered by the decreasing size of individual stems with higher stockings, a trend evident when comparing the average mature wood volume per stem. What this means is that while increasing stand stocking will increase total volume of mature wood, the additional mature wood comes in smaller and less efficiently-handled logs, and is likely to yield lower recovery of high quality sawn lumber (Chart 19). A future study extended to also cover primary processing may identify a "sweet spot" to optimise the trade-off between this recovery and operational costs.

Chart 19: Average mature wood volume per stem for the Framing regime, Bay of Plenty site at age 30 years.



BIX

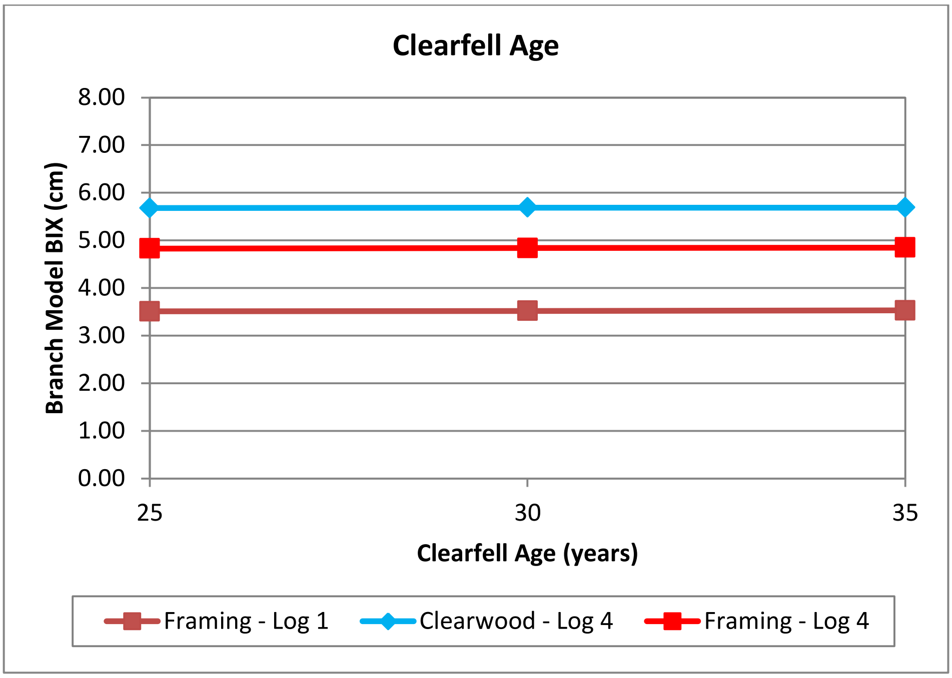
Values of branch index (BIX) were estimated by the BLOSSIM branch model (version 3.0). The BLOSSIM model uses a combination geographic (growth modelling) region, stem height, stem diameter, stand MTH, stand BA, stand stocking, timing of thinning, thinning severity and a stochastic element to model distributions of branch parameters (e.g., branch cluster frequency, number of branch per cluster, diameter of the largest branch per cluster).

Results from the analysis showed that rotation length had no impact upon branch size in either the Clearwood or Framing regimes (Chart 20). The absence of any trend with increasing clearfell age is due to the empirical basis of the BLOSSIM v3.0 model[18]. The destructive sampling dataset used in model development indicated that branches grow to a maximum diameter, and then, remain that size or decrease slightly as the stem grows out over the branch. Since there was very limited evidence of decreasing branch size, BLOSSIM assumes that there is no decrease in branch size, and the maximum branch size will be the same regardless of rotation length.

The pruned butt logs from the Clearwood regimes were predicted to have very low BIX values (around 0.4). However, upon closer examination, not all of the pruned logs were actually pruned to the full height of 6.0 m, resulting in some logs that were partially pruned, which when combined with those logs that were pruned to the full 6.0 m gave a very low mean BIX value.

The Clearwood regime produced higher BIX values for the upper logs compared with the Framing regime, because the former has lower final thinned stockings. Likewise the lower logs in both regimes have lower BIX values compared to the upper logs. This is because the lower logs did most of their growing prior to the stand being thinned, thus the branches developed under a higher stocking where there was greater control over branch size, while the upper branches were produced often post-thinning, under a lower stocking leading to larger branches (Jenny Grace *pers. comm.*).

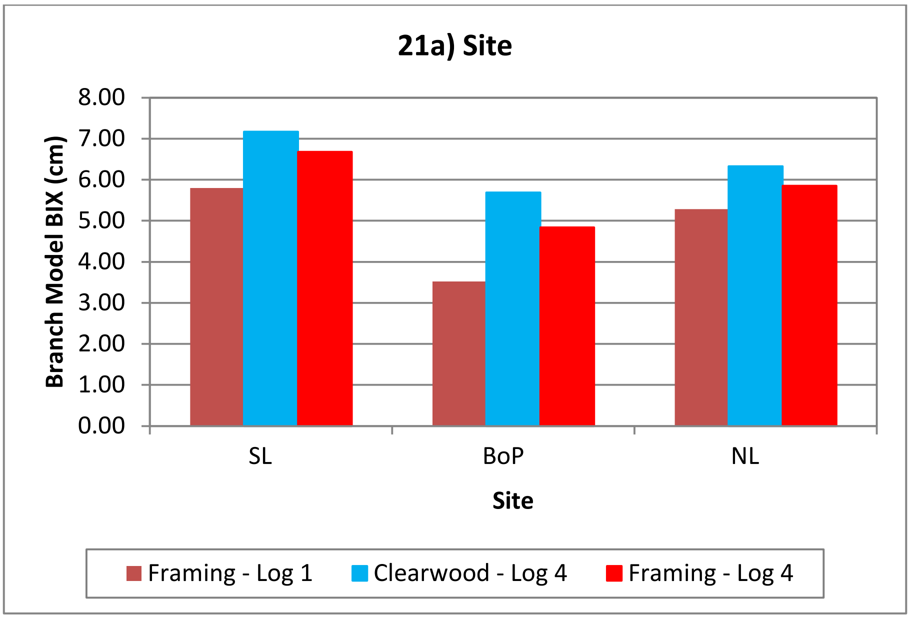
Chart 20: Impact of Clearfell Age on BIX for the Bay of Plenty site in Logs 1 (butt log) and 4 (4th log) for the Clearwood and Framing regimes.

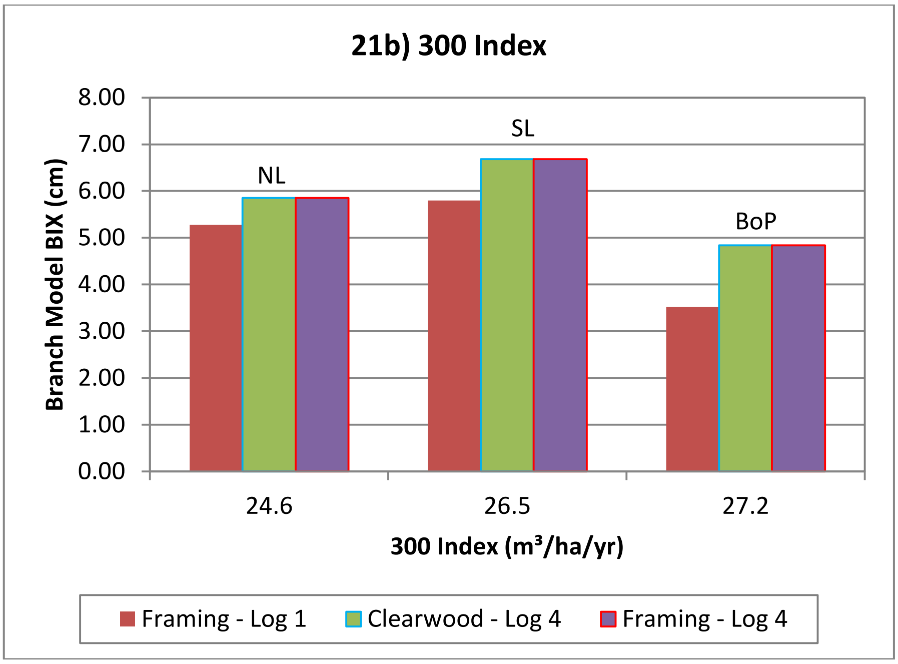


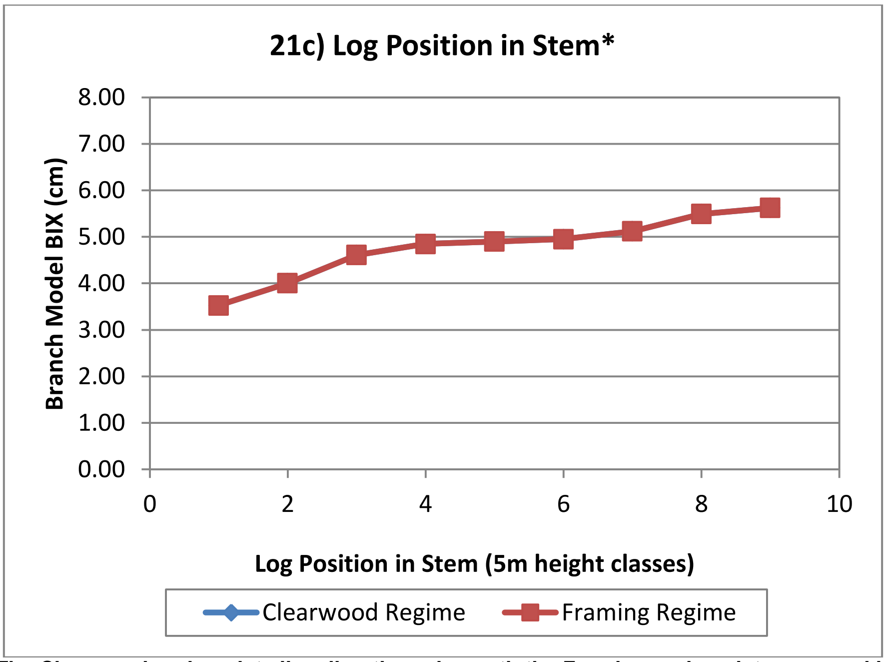
In terms of site, there seems to be no real association between BIX and either latitude or 300 Index. This makes sense as the equations within the BLOSSIM model are for each of the growth modelling regions and do not use 300 Index values (Jenny Grace, *pers. comm.*). Southland produced the largest BIX values on average, followed by Northland, with the Bay of Plenty region producing the smallest BIX values. For all regions, logs further up the stem produce larger branches (Chart 21c). However, the simulations never seem to produce BIX values greater than 8 cm. This compares with anecdotal evidence from Forecaster users.

Note that because BIX represents the average of the largest branches in each of the four quadrants of the log, the max branch size will be larger than the BIX value produced for each log (see Chart 28, ahead).

Chart 21a, b, c. Impact of site, 300 index and log position in stem on BIX for Logs 1 and 4 for the Clearwood and Framing regimes.





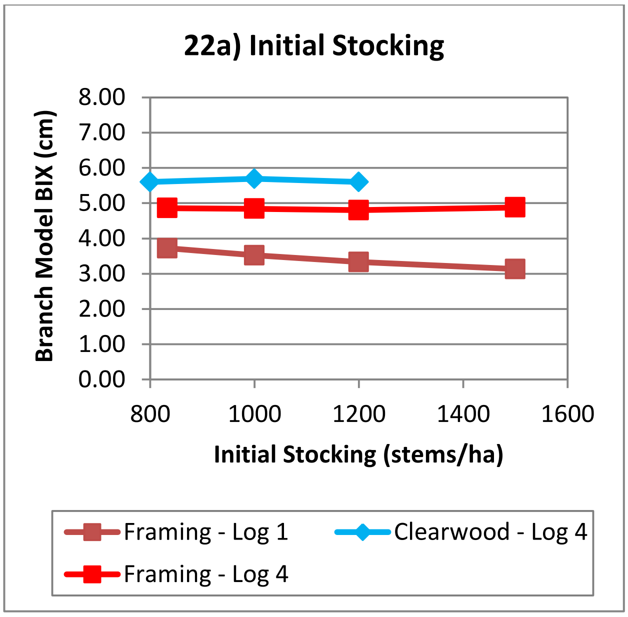


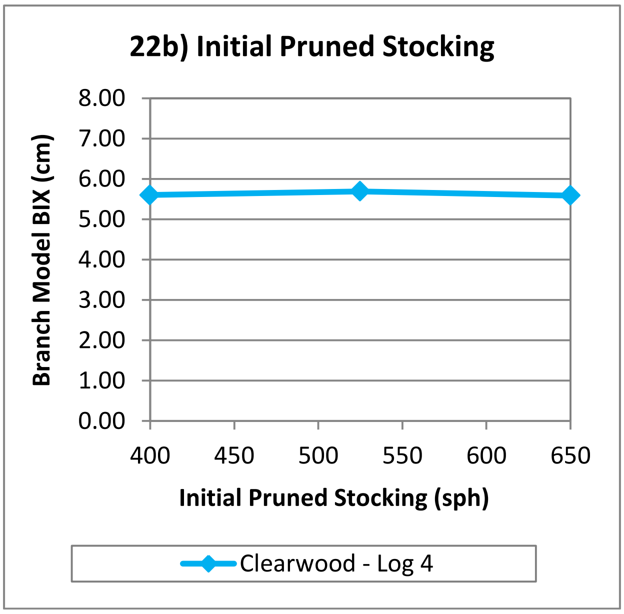
*** Please note: The Clearwood regime data lies directly underneath the Framing regime data – caused by the differences between the two base regimes.**

Initial stocking variations for both regimes and initial pruned stocking variations for the Clearwood regimes all resulted in no difference in the estimate of BIX produced by the BLOSSIM v3.0 branching model, with the exception of Log 1 for the Framing regime where BIX was 0.59 cm lower for an initial stocking of 1500 stems/ha compared with 833 stems/ha (Chart 22). Such a decrease may not be seen as meaningful by forest managers, unless it results in a reduction in BIX below the threshold of 7 cm, which is also the cut-off between domestic and export log grades.

Again the upper logs will most likely have been formed after thinning has occurred and will not have been subjected to the effect caused by initial stocking values. By comparison, the butt log for the framing regime will have been affected by the initial stocking, which will have produced smaller branches, and thus a lower BIX value (Grace, *pers. comm.*).

Chart 22: Impact of initial stocking and initial pruned stocking on BIX for Logs 1 and 4 for both Framing and Clearwood regimes, respectively.

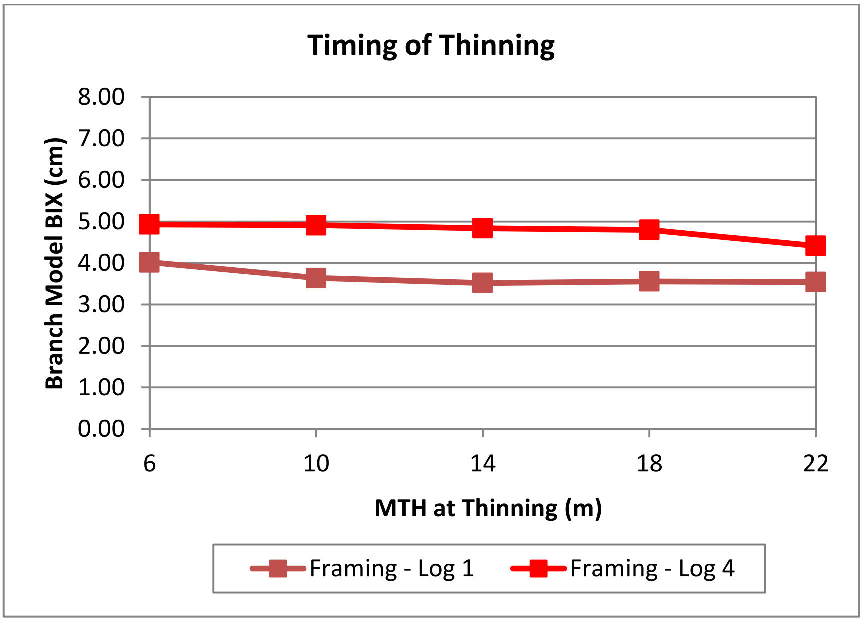




Overall, the timing of the thinning event had a minimal impact upon the BIX values being estimated by the BLOSSIM v3.0 branch model (Chart 23). However, for the butt logs, lower values of BIX occurred when thinning was scheduled at a MTH of ≥ 10 m, after which BIX was invariant with MTH at time of thinning. The branches on the butt log are likely to still be actively growing when the thinning occurs at MTH 6 m, so an increase in BIX under such an early thinning is to be expected. BIX values for upper logs only decreased when the thinning was scheduled at MTH > 22 m. This is because the height of the tree at time of thinning plays a role in the BIX value for a log (Grace *pers. comm*.). The upper logs (Log 4 and above) are not formed until the tree is at least 20 m tall, so only delayed thinning (i.e. when MTH is at least 22 m) has any effect on the BIX value.

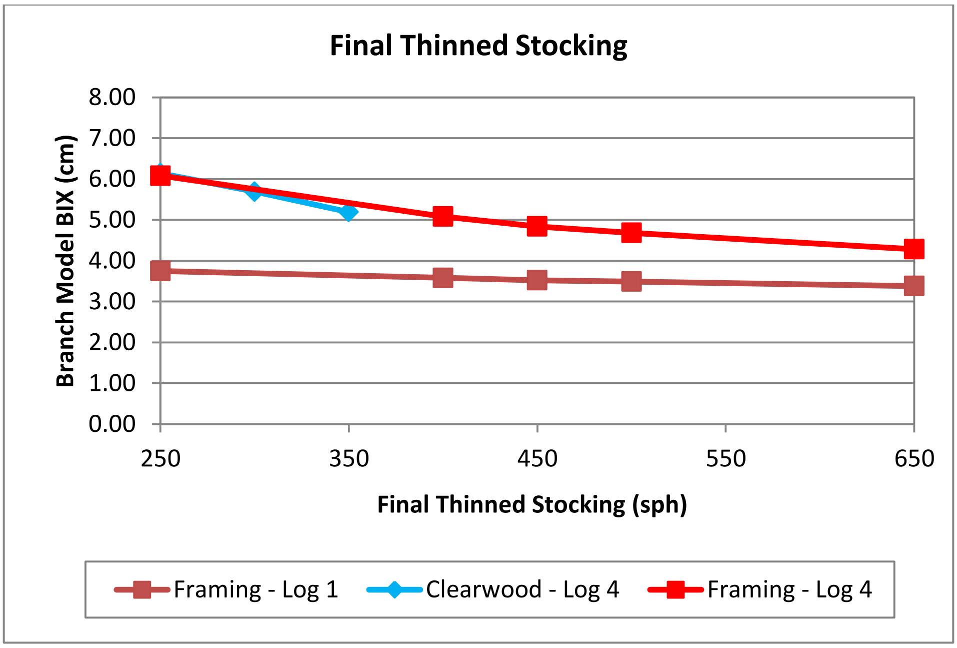
Users need to remember that the BLOSSIM branching model predicts the location and size of each branch in each cluster, and then derives BIX from first principles. BLOSSIM predicts branch diameter from a range of variables including MTH at time of thinning, then calculates BIX. This is why there are differences in BIX value between two logs for the different timings of thinning.

Chart 23: Impact of timing of thinning on BIX for Logs 1 and 4 the Framing regimes.



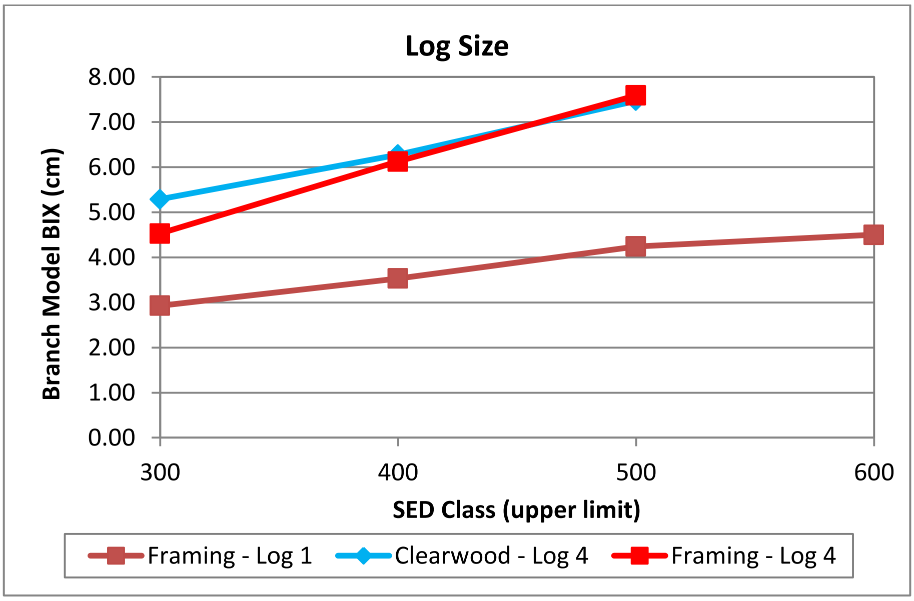
Overall, final thinned stocking and log size had the greatest impact on BIX for both the Clearwood and Framing regimes (Chart 24). In both regimes, the butt logs were less affected by final thinned stocking, because they had already been formed before thinning occurred. For the upper logs, BIX decreased by 1.80 cm and 0.95 cm for the Framing and Clearwood regimes, respectively, across the range of final thinned stockings investigated. Branch size does increase as stocking decreases, particularly below about 300 stems/ha, as there are fewer stems to help control the size of branches.

Chart 24: Impact of final thinned stocking on BIX for Logs 1 and 4 the Clearwood and Framing regimes.



Larger logs had larger BIX values (Chart 25), with the exception of the butt logs from the Clearwood regime which were generally pruned to 6.0 m and, therefore, did not generally have any branches. It is logical that larger trees should have larger BIX values, due to the known relationship between stem diameter and branch size.

Chart 25: Impact of log size on BIX for Logs 1 and 4 the Clearwood and Framing regimes.

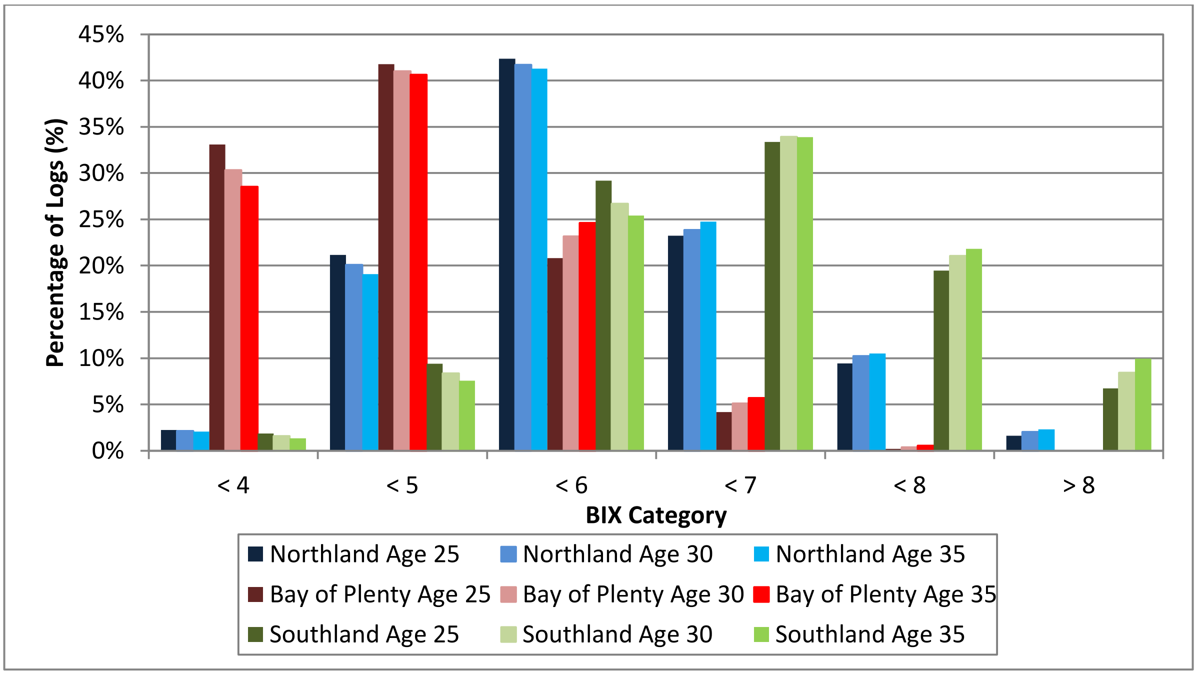


As can be seen by Table 17 and Chart 26 below, with increasing rotation length the percentage of logs moves from the smaller BIX classes towards the upper classes. At least 70% of the logs from the Bay of Plenty region were in the smallest BIX categories (specifically <5 cm), while Southland produces the greatest proportion of logs with larger branches, the majority of which were > 5cm but < 7 cm. Approximately 40% of the logs from the Northland site were in the < 6 cm category, with a further 20-25% in each of the <5 cm and <7 cm categories for all rotation lengths.

Table 17: Percentage of logs (weighted by volume) for each BIX category for different clearfell ages and sites. Framing regime - initial stocking 1000 stems/ha, final thinned stocking 450 stems/ha, thin when MTH > 14 m.

Site	Clearfell Age	BIX category					
		< 4	< 5	< 6	< 7	< 8	≥ 8
Northland	25 years	2%	21	42	23	9	2
	30	2	20	42	24	10	2
	35	2	19	41	25	11	2
Bay of Plenty	25 years	33	42	21	4	0	0
	30	30	41	23	5	0	0
	35	29	41	25	6	1	0
Southland	25 years	2	9	29	33	19	7
	30	2	8	27	34	21	8
	35	1	8	25	34	22	10

Chart 26: Percentage of logs (weighted by volume) for each BIX category for different clearfell ages and sites for the Framing regime.



Increasing the initial stocking and final thinned stocking for the Framing regimes resulted in a shift towards smaller branches (Table 18). Timing of thinning had a large impact upon the proportion of logs in each of the BIX categories. The later a thinning occurred, the greater the proportion of logs in the smaller BIX categories.

Table 18: Variations to the base Framing regime, showing the percentage of logs for each BIX category for the Bay of Plenty site at age 30 years.

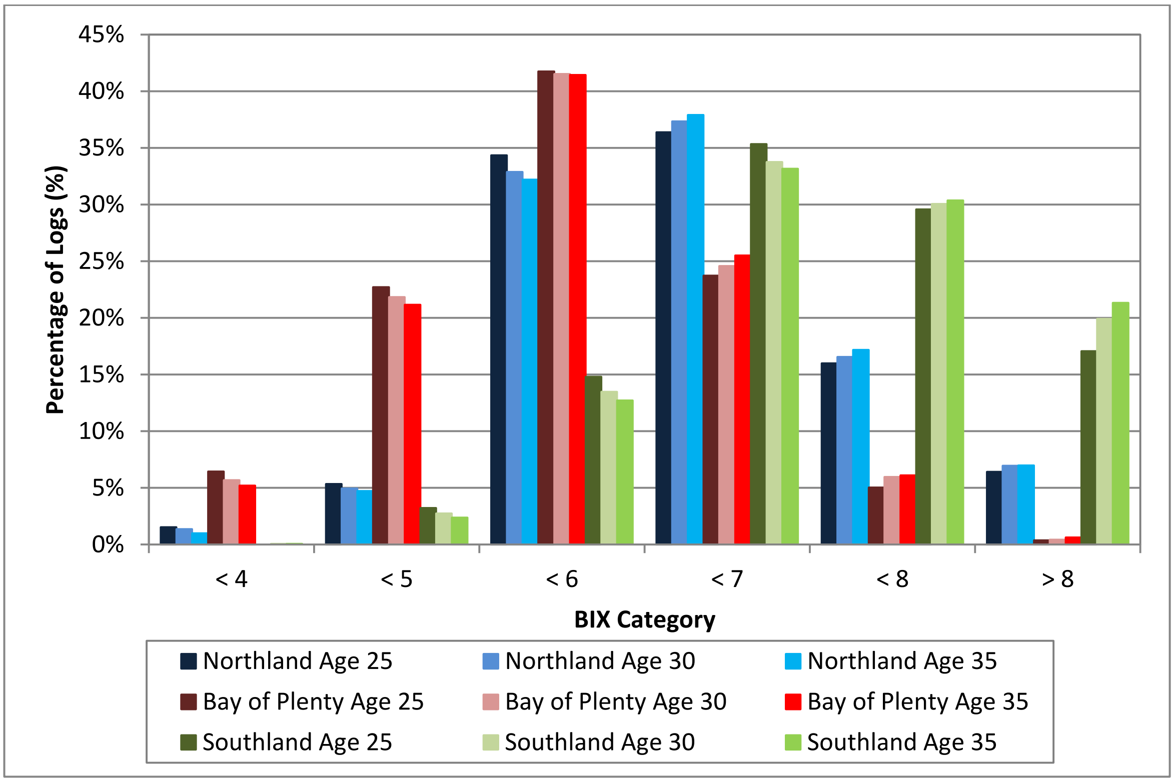
Framing Regime Variation	< 4	< 5	< 6	< 7	< 8	≥ 8
Initial Stocking 833 stems/ha	28%	42	24	5	1	0
Initial Stocking 1000 stems/ha	30	41	23	5	0	0
Initial Stocking 1200 stems/ha	35	39	21	5	0	0
Initial Stocking 1500 stems/ha	39	36	21	3	0	0
Timing of Thinning MTH > 6 m	19%	41	31	8	1	0
Timing of Thinning MTH > 10 m	26	40	27	6	0	0
Timing of Thinning MTH > 14 m	35	39	22	5	0	0
Timing of Thinning MTH > 18 m	40	38	17	4	1	0
Timing of Thinning MTH > 22 m	44	38	14	3	0	0
Final Thinned Stocking 250 stems/ha	19%	26	27	18	9	1
Final Thinned Stocking 400 stems/ha	26	41	25	7	1	0
Final Thinned Stocking 450 stems/ha	30	41	23	5	0	0
Final Thinned Stocking 500 stems/ha	35	42	19	4	0	0
Final Thinned Stocking 650 stems/ha	45	39	14	2	0	0

The Clearwood regimes showed the same trend as the Framing regimes for variations to clearfell age (Table 19 and Chart 27). The longer the trees were allowed to grow for, the greater the percentage of logs with larger branches. Bay of Plenty once again produced the highest proportion of logs with the smallest branches, while Southland produced much higher percentages of logs in the largest BIX categories. Because this was the Clearwood regime, the percentage of logs with a BIX value of < 4 cm remained relatively constant, with the percentage increases in the upper BIX categories coming from the remaining low categories.

Table 19: Percentage of logs (weighted by volume) for each BIX category for different clearfell ages and sites. Clearwood regime - initial stocking 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha.

Site	Clearfell Age	BIX Category					
		< 4	< 5	< 6	< 7	< 8	≥ 8
Northland	25	2%	5	34	36	16	6
	30	1	5	33	37	17	7
	35	1	5	32	38	17	7
Bay of Plenty	25	6%	23	42	24	5	0
	30	6	22	42	25	6	0
	35	5	21	41	25	6	1
Southland	25	0%	3	15	35	30	17
	30	0	3	13	34	30	20
	35	0	2	13	33	30	21

Chart 27: Percentage of logs (weighted by volume) for each BIX category for different clearfell ages and sites. Clearwood regime - initial stocking 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha.



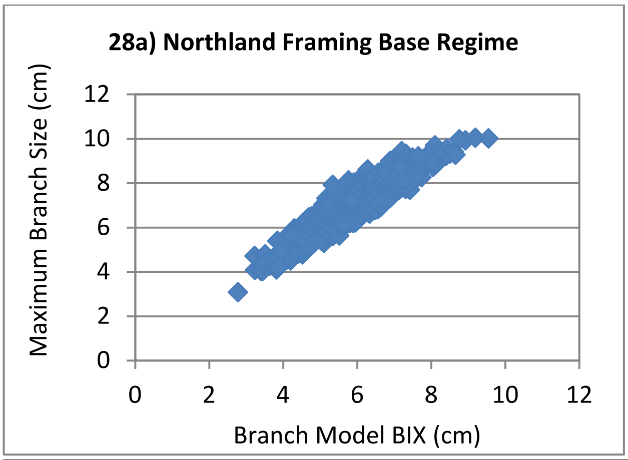
Varying either the initial stocking or initial pruned stocking for the Clearwood regime had very little impact upon the percentage of logs in each BIX category (Table 20 and Chart 28a, b, c, d). Final thinned stocking had the most impact, with higher stocked stands predicted to have a greater proportion of logs with smaller branches. Increasing the stocking following final thinning from 250 stems/ha to 350 stems/ha resulted in a reduction in the proportion of logs with BIX>7 cm from 13% down to 3%.

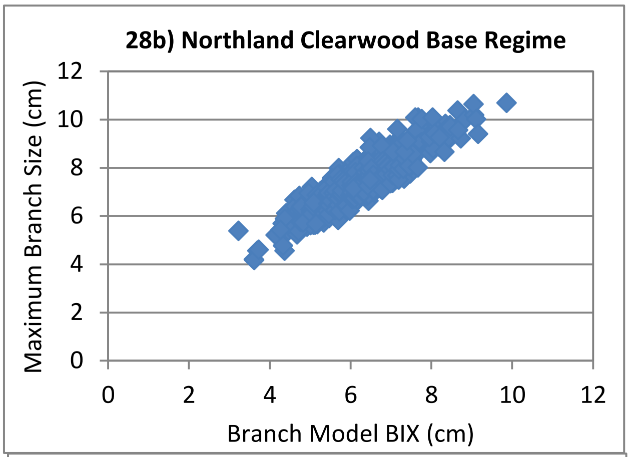
Table 20: Clearwood regime variations to the base regime, showing the percentage of logs in each BIX category for the Bay of Plenty site at age 30.

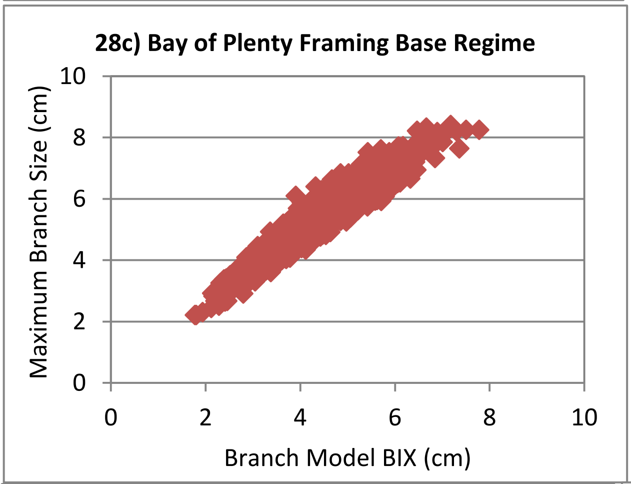
Clearwood Regime Variation	< 4	< 5	< 6	< 7	< 8	≥ 8
Initial Stocking 800 stems/ha	6%	25	42	21	5	1
Initial Stocking 1000 stems/ha	6	22	42	25	6	0
Initial Stocking 1200 stems/ha	5	26	37	25	5	1
Initial Pruned Stocking 400 stems/ha	5	25	40	23	6	1
Initial Pruned Stocking 525 stems/ha	6	22	42	25	6	0
Initial Pruned Stocking 650 stems/ha	7	25	38	24	5	1
Final Thinned Stocking 250 stems/ha	4	13	35	35	12	1
Final Thinned Stocking 300 stems/ha	6	22	42	25	6	0
Final Thinned Stocking 350 stems/ha	8	33	42	13	3	0

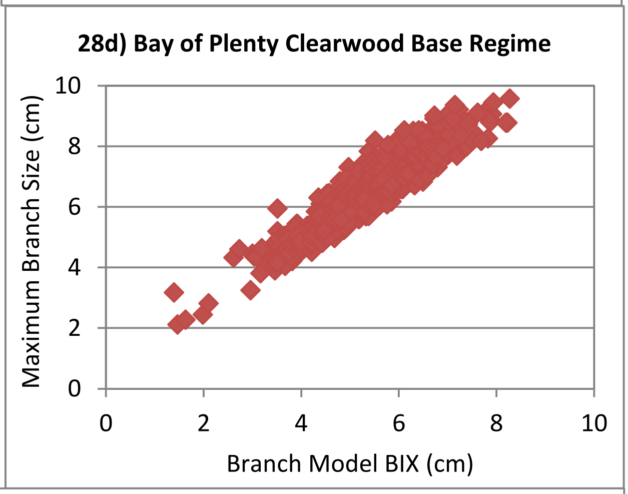
The results from the BLOSSIM branching model have caused some concern, as people have looked at the results and queried why there were few branches greater than 8 cm. What needs to be remembered by users is that in this instance Forecaster is actually producing a branching [redacted] in each of the four quadrants of a log. So, the values shown in the section above are not the maximum branches found in each log. However, because of this confusion, the branching results from Forecaster were further examined using the Log Trace File, which contains an output of the maximum branch for each log. These maximum branch sizes were then plotted against the branch model BIX values to see if there was a relationship and if the maximum branches were larger than the BIX values (Chart 28). It was found that logs with a larger BIX value tended to produce larger maximum branch sizes, and that there was a clear difference between sites. However, no maximum branches were produced that were greater than 12 cm for the Framing regime and 13 cm for the Clearwood regime.

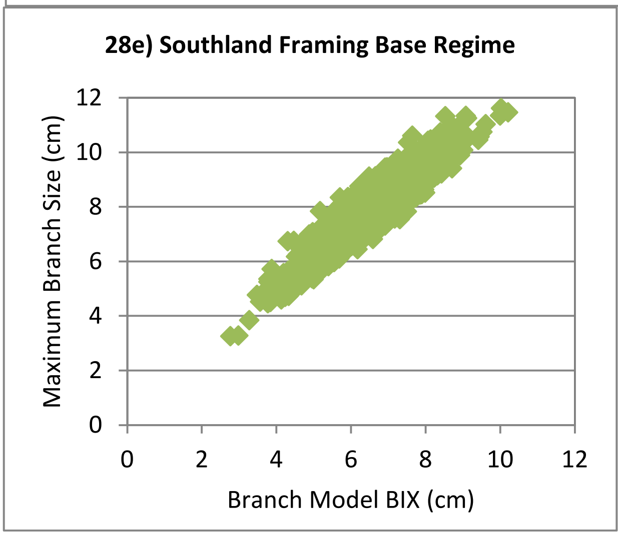
Charts 28a, b, c, d, e, and f: Comparison of the relationship between branch model BIX (cm) and maximum branch size (cm) for logs in the Clearwood and Framing base regimes for the three sites.

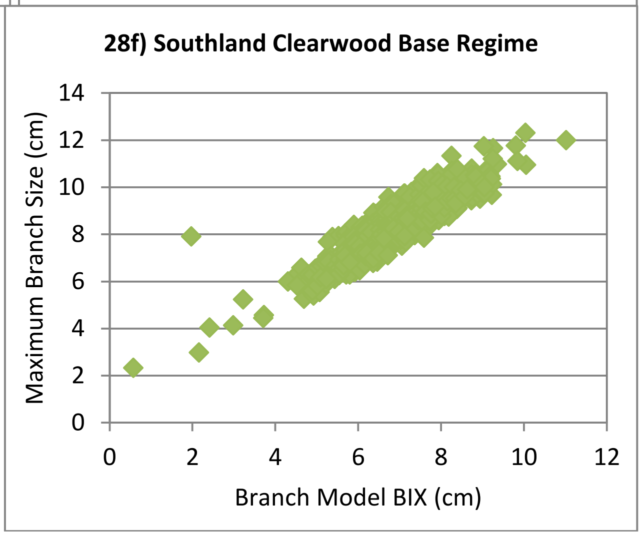










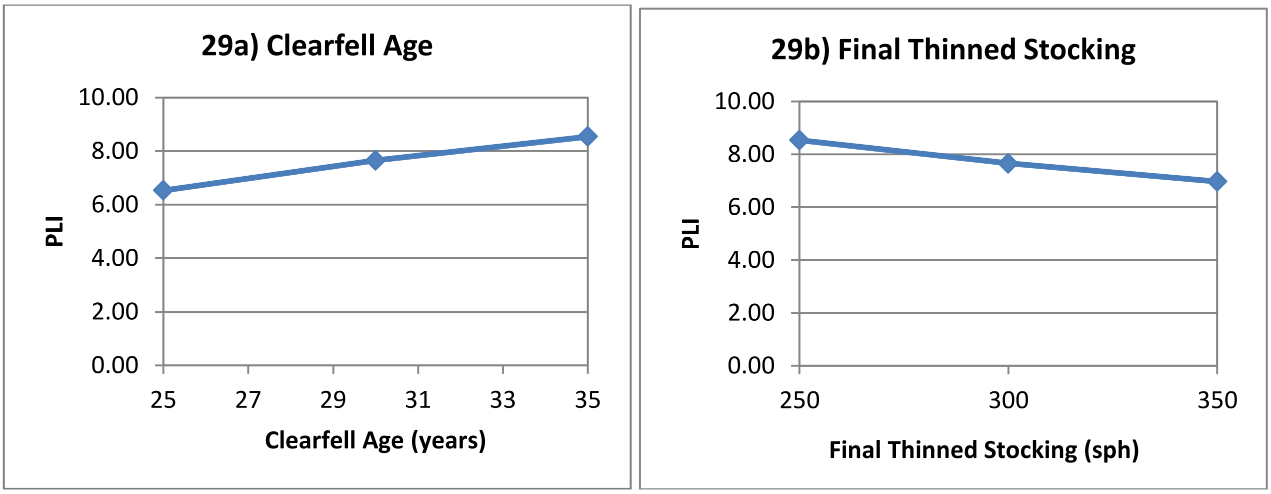


Pruned Log Index (PLI)

PLI is calculated using the model developed by Park[4, 19], which is hard wired into Forecaster. This model predicts PLI as a function of DOS, log diameter and sweep. PLI analysis was only conducted on the butt logs (Log 1) for each scenario, as it was assumed that these would be the only truly pruned logs produced. Any other logs with PLI values were ignored.

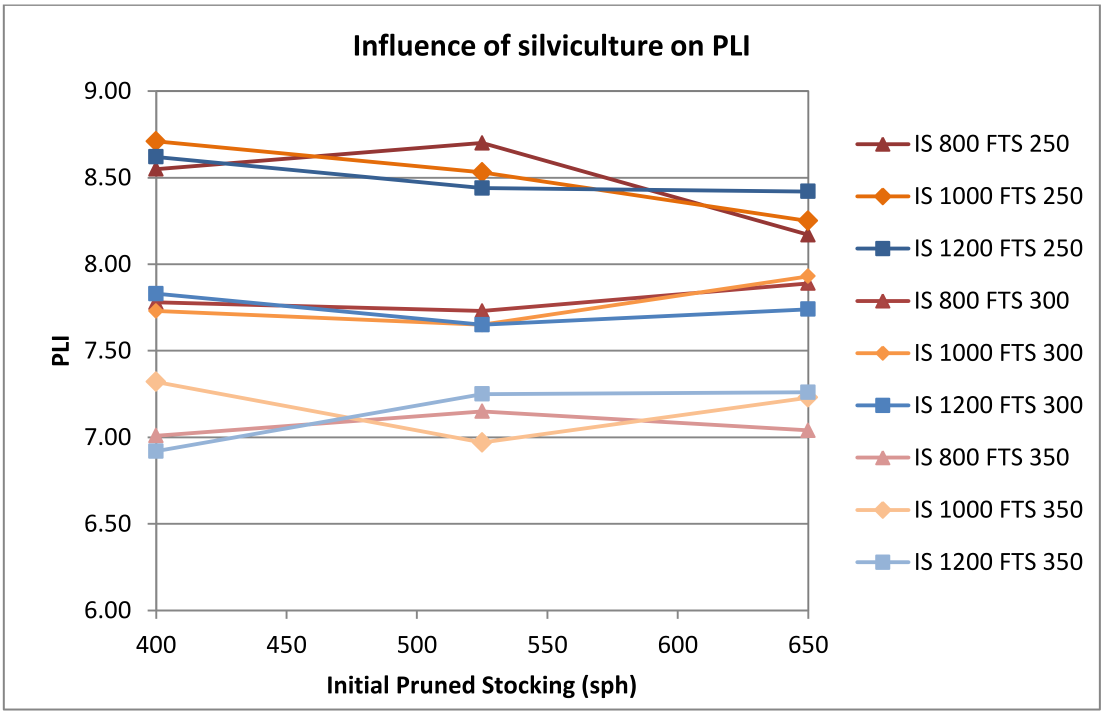
Rotation length and final thinned stocking were predicted to have the greatest impact upon the PLI value of butt logs (Chart 29). As rotation length increases the PLI also increases, while lower final thinned stocking rates produce higher PLI values. Both these factors increase the amount of radial growth of the tree and, therefore, increase the ratio of clearwood to defect core.

Chart 29: Impact of Clearfell Age and Final Thinned Stocking on PLI for the Bay of Plenty site in Log 1 for the Clearwood regime.



When final thinned stocking values were assessed in conjunction with initial stocking and initial pruned stocking values, there is a clear difference between the different final thinning stocking values, but no impact from changes in initial or initial pruned stocking values (Charts 30 and 32).

Chart 30: Impact of Initial Stocking and Final Thinned Stocking on PLI for the Bay of Plenty site in Log 1 for the Clearwood regime.



Across the three sites there appeared to be little real difference in PLI, with logs from Southland (SL) having the highest PLI value (8.12), followed by Northland, NL (7.79) and then the Bay of Plenty, BOP (7.65). There was no apparent association between PLI and 300 Index (Chart 31).

Chart 31: Impact of Site and 300 Index on PLI for the Bay of Plenty site in Log 1 for the Clearwood regime.

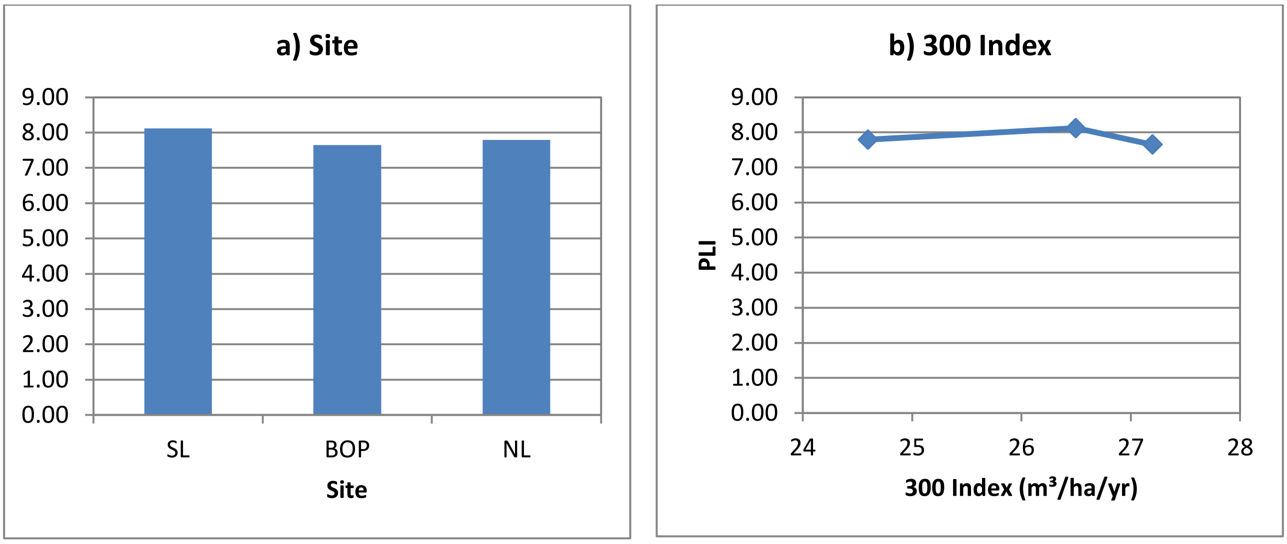
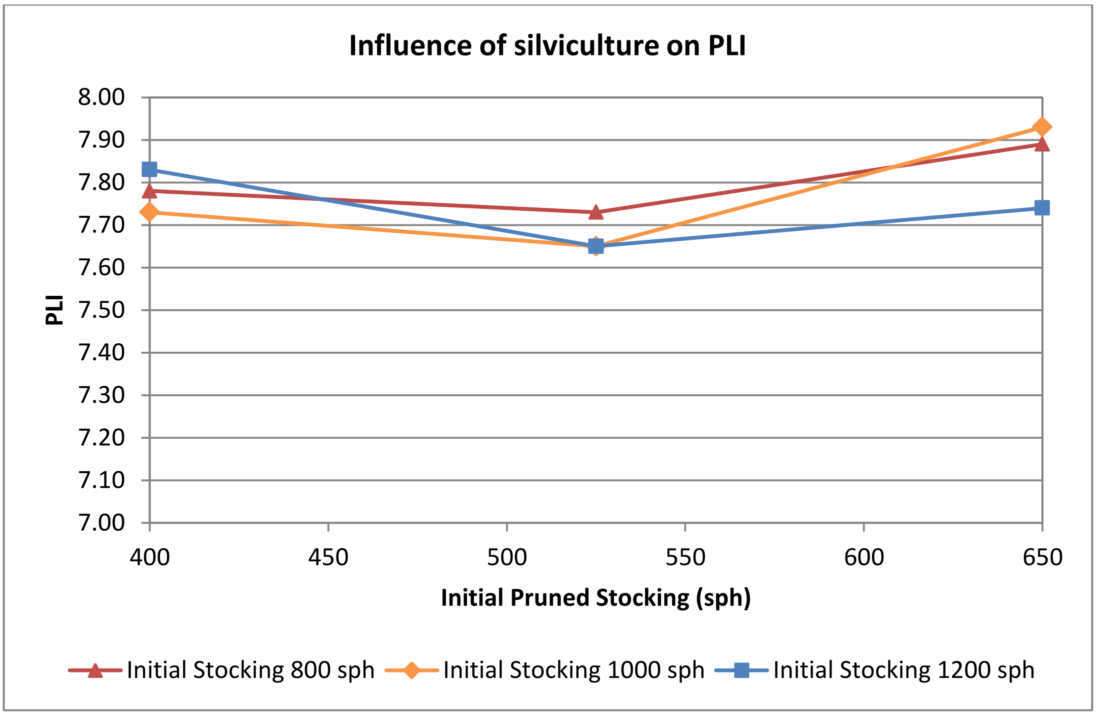


Chart 32: Impact of Initial Stocking on PLI for the Bay of Plenty site in Log 1 for the Clearwood regime.



Having determined the different influencing factors on PLI, the logs were assigned to a PLI category ranging from < 4 PLI to >10 PLI in intervals of one unit of PLI. Table 21 below shows that the proportion of logs assigned to each category showed trends consistent with the above findings across the three sites and three clearfell ages. As clearfell age increased the proportion of butt logs in the higher PLI classes (9 and above) also increased, while the proportion in the medium classes (6-8 inclusive) decreased. These trends were consistent across all three sites.

Table 21: Percentage of butt logs (Log 1, weighted by volume) that fall into each PLI category for each of the three sites and different clearfell ages for the base clearwood regime (initial stocking 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha).

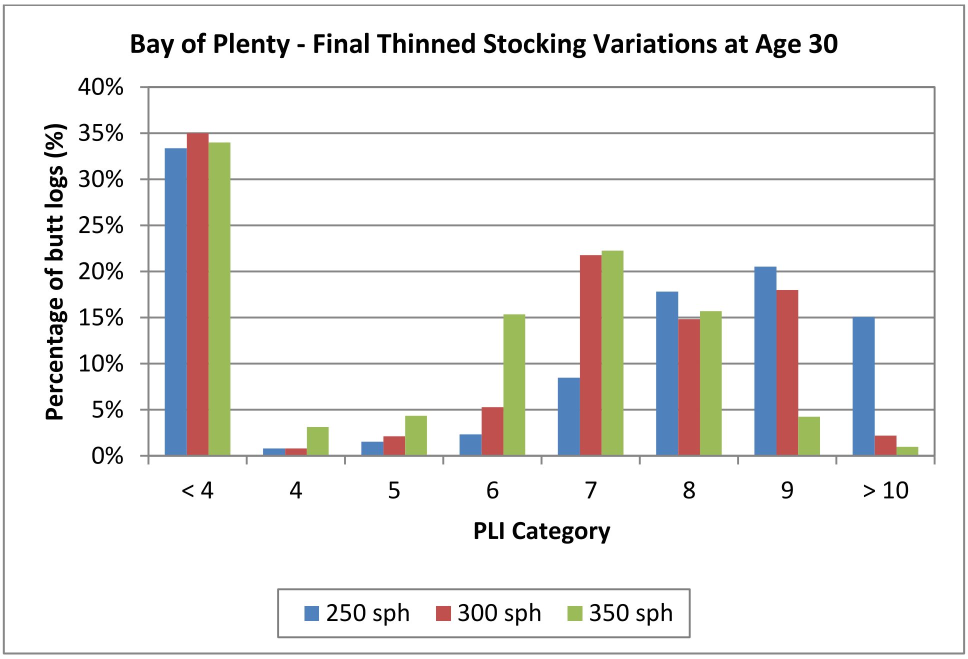
Site	Clearfell Age	Percentage of butt logs by PLI Category							
		< 4	4	5	6	7	8	9	> 10
Northland	25	31%	5	9	26	14	11	5	0
	30	33	2	2	5	18	18	12	10
	35	31	3	1	2	4	17	20	24
Bay of Plenty	25	38	3	4	23	21	7	2	1
	30	35	1	2	5	22	15	18	2
	35	34	3	2	2	4	19	15	21
Southland	25	38	4	8	21	23	6	1	0
	30	36	2	1	4	11	24	16	7
	35	33	1	0	0	2	9	19	36

Neither initial stocking, nor initial pruned stocking had any significant impact upon the proportion of logs in each PLI class (Table 22 and Chart 33). However, final thinned stocking had a big impact upon the percentage of logs in each PLI class. At lower values of final thinned stocking there was a much greater the proportion of butt logs in the higher PLI categories (8 and above). As the final thinned stocking value increased, the majority of the butt logs shifted into the lower and middle PLI classes (7 and below)

Table 22: Percentage of butt logs (Log 1, weighted by volume) that fall into each PLI category for the Bay of Plenty, age 30 years, base clearwood regime (initial stocking 1000 stems/ha, initial pruned stocking 525 stems/ha, final thinned stocking 300 stems/ha).

Framing Regime Variation	< 4	4	5	6	7	8	9	> 10
Initial Stocking 800 stems/ha	28%	4	1	6	22	18	15	6
Initial Stocking 1000 stems/ha	35	1	2	5	22	15	18	2
Initial Stocking 1200 stems/ha	33	1	4	6	18	17	15	5
Final Thinned Stocking 250 stems/ha	33	1	2	2	8	18	21	15
Final Thinned Stocking 300 stems/ha	35	1	2	5	22	15	18	2
Final Thinned Stocking 350 stems/ha	34	3	4	15	22	16	4	1

Chart 33: Percentage of butt logs (Log 1, weighted by volume) that fall into each PLI category for the different final thinned stocking values of 250, 300 and 350 stems/ha for the Bay of Plenty, age 30 years, base Clearwood regime.



In all scenarios the proportion of logs that was present in the lowest category (< 4 PLI) stayed relatively constant at around 33% (range of 28-38%). This was caused by a combination of logs that had not been pruned sufficiently to reach the minimum pruned height of 5 m that Forecaster requires before it will calculate a PLI value, followers, and logs with high sweep and / or low SED's which were given very low PLI values.

Results from the analyses reported here show that if a forest manager wishes to increase the PLI values that they are getting in their butt logs then increasing the rotation age and decreasing the final thinned stocking value would be the two most effective options.

SUMMARY AND CONCLUSIONS

Acoustic Velocity

Site, clearfell age and log position within the stem were the three factors that had the biggest influence on log acoustic velocity predicted by the WQIAcousticVelocity model. Log acoustic velocity decreased in more southerly latitudes. Increasing the clearfell age to 35 years increased the average acoustic velocity value per log for both Clearwood and Framing regimes. At this clearfell age, all the regimes produced the greatest proportion of logs that passed the threshold value of 3 km/s on all sites – in the case of Southland, no logs that passed this threshold were produced when the rotation age was 25 or 30 years.

Log position within the stem also influenced log acoustic velocity values. Second and third logs were predicted to have the highest values of acoustic velocity, regardless of regime type, site, and rotation length or regime variations. This is consistent with the results of Waghorn et. al.[24] who observed that the maximum acoustic velocity occurred at 5-6 metres up the stem in 17-year-old radiata pine and is assumed to be due to the increased amounts of heartwood in the middle of the stem.

Variations to the Clearwood and Framing regimes resulted in little change in the proportion of logs meeting the acoustic velocity threshold of 3.0 km/s. For the Clearwood regime, the proportion of logs meeting or exceeding the acoustic velocity threshold was consistently 84%, while it varied between 82% and 84% for the various Framing regimes.

Density

While users of the density model enter a value of outerwood density value at breast height into Forecaster when they are setting up their project, Forecaster does not output a comparable outerwood density values for logs, instead predicting average density values for each log (which are significantly lower than the outerwood values initially entered into the model). This may cause some confusion for model users by making them initially assume that the model is not working correctly. Because of this issue, we recommend that an enhancement be added into a future version of Forecaster that outputs the outerwood density value for each log, as part of the log trace table.

Predictions from the FFRDensity2011 model showed an increasing proportion of logs with a mean density value of at least 400 kg/m³ with increasing rotation length for both regimes. The Framing regime produced less wood that passed the threshold than the Clearwood regime for all rotation ages and all sites. Interestingly, the Southland site produced the same amount of wood that passed the density threshold for both regimes. These results appear counter-intuitive, although the simulations do show the higher corewood percentage for the framing regimes, so perhaps this is a silvicultural paradox.

Across all regime variations, Northland produced the highest average and outerwood density values, followed by the Bay of Plenty site, and then Southland. This is interesting as the FFRDensity2011 model did not include a latitude element, but it does include the 300 Index and Site Index elements. However, the density model is partially driven by density index, which in turn is a function of tree age and mean air temperature. Any apparent link between site productivity and density is due to the fact that they are both related to temperature.

Regime variations had a smaller impact upon the percentage of logs passing the 400 kg/m³ density threshold. Of the variations examined, final thinned stocking had the largest impact over the extreme ranges used in the Framing regime. Here, the model results ran counter to what may be expected and showed that the proportion of logs meeting or exceeding the density threshold actually decreased from 34% to 19%, as the stocking after final thinning increased from 250 stems/ha up to 650 stems/ha. However, this could be due to the relative volumes of corewood and outerwood. Over the typical range of final thinned stocking for both regimes, the difference became negligible. Changes in initial stocking, initial pruned stocking, and timing of thinning also produced very small changes to the proportion of logs which passed the threshold, suggesting that more extreme regime variations are required to have an any appreciable impact on wood density. These results indicate that more in-depth analysis is required to understand the complex contributions to density from silviculture and environment.

Heartwood

Simulations using the FFRWQI2009 model showed that there was little difference in the heartwood content of logs grown under either the Clearwood or Framing regimes. The regime variations also produced a negligible difference in heartwood proportion, especially over the normal range of final thinned stocking (i.e., 250-350 stems/ha for the Clearwood regime and 400-500 stems/ha for the Framing regime). The minor differences that do occur are most likely caused by the stochastic element included in the model.

The main influences on the predicted log heartwood content were site location and rotation length. More southerly sites produced logs with less heartwood content than those grown on more northern sites. This was to be expected as the FFRWQI2009 model contains a latitude term and is also consistent with results from previous wood properties surveys[6]. Increasing the rotation length increased the proportion of heartwood for all regimes at all sites. As expected, heartwood content also varied with position up the stem; upper logs contained almost no heartwood while butt logs contained 30-40% heartwood by volume.

Juvenile Wood/Corewood

Longer rotations resulted in logs with lower proportions of corewood for both regimes on all three sites. Logs grown in Southland were predicted to have the lowest amounts of corewood under both regimes, while the Bay of Plenty site produced the most. Logs grown under the Framing regime were also predicted to contain greater proportions of corewood, compared with those grown under the Clearwood regime (6-8% difference).

Of the regime variations that were tested only the final thinned stocking variations resulted in any real difference in the predicted corewood content. Both the Clearwood and the Framing regime variations resulted in a decrease in the proportion of corewood with decreasing stocking after final thinning. These results are consistent with increased diameter growth of the outerwood; a reduction in the growing space available to the tree when it is producing outerwood will result in a smaller volume of outerwood and thus a higher proportion of corewood (as corewood volume is relatively insensitive to initial stocking). As expected there was a substantial difference in corewood content between logs cut from different positions within the stem. Logs that were cut from higher in the stem had correspondingly larger proportions of corewood, with those cut from the uppermost part of the merchantable stem being almost exclusively composed of corewood.

The simulations also raised the question as to the appropriateness of the corewood definition. Currently, it is described in Forecaster v1.12 as being the ten inner rings, yet different companies may have different definitions of juvenile corewood based upon their location or genetic material. Strictly speaking, corewood is defined as the region in which wood properties vary rapidly with increasing ring number (or distance) from the pith[14]. Studies in other species have shown that the extent of corewood differs depending on the wood property used to define it. For example, in lodgepole pine (*Pinus contorta*) growing in coastal British Columbia, Mansfield et. al.[25] found that the transition between corewood and outerwood occurred at 31, 18 and 15 years for density, fibre length and microfibril angle, respectively. As such, a future version of Forecaster will contain the [redacted]

Branch Model BIX

Some users are hesitant to accept output from the BLOSSIM v3.0 branching model because it does not predict enough larger branches over 8 cm, possibly resulting from stem damage (J. Grace, Pers. Comm.). While the position and size of “normal” branches are predicted reasonably well, the lack of abnormal (large) branches results in a grade-mix that favours structural grades (small-branched logs) over utility and industrial grades (large-branched logs). Branching is a core component of most log grades and model prediction of branch sizes influences the predicted log grade mix, which in turn influences predicted economic outputs. A future option is to develop functions to incorporate stem damage and its impact on branching into BLOSSIM. Also in a future release of Forecaster, an enhancement will be included that allows richer branching output information to be produced at the log level, e.g., maximum, minimum and average branch sizes for each log, and a standard deviation value.

Most recently, two properties were developed to augment BLOSSIM v3.0 in an upcoming version of Forecaster, i.e., Large Branch Probability and Large Branch Scale Factor (A. Gordon, Pers. Comm.). These two properties provide user-control over the frequency and size of large-branched clusters. This will modify Forecaster–BLOSSIM simulations to report predicted grade-mixes that will be closer to user-expected grade-mixes.

Pruned Log Index

Model simulations showed that Pruned Log Index is not affected by site, initial stocking or initial pruned stocking, however variations to the timing and severity of pruning options were not examined in this study. Aside from adjusting the timing and intensity of pruning, which has a strong influence on the size of the defect core, forest managers looking to increase the proportion of logs in the higher PLI categories should decrease their final thinned stocking, and/or increase the rotation length. Results of our simulations showed that, for the pruning regime specified, approximately one-third of all butt logs will not pass the threshold of PLI ≥ 4 (which denotes ‘satisfactory’ pruning), no matter what the other regime variations are.

The large proportion of logs in the lowest PLI category in every scenario was caused by two factors. Firstly, there are the logs with a PLI value of zero because the stems were not pruned high enough for Forecaster to calculate a PLI value (PLI is only calculated for logs which have a pruned length > 5 m) or the log was cut from an un-pruned follower stem. Secondly, logs with a low PLI are those logs which also had large amounts of sweep and/or a small SED. Any logs that meet these criteria are allocated to the lowest PLI class.

Final Recommendations and Observations

- Results from our model simulations showed that site, rotation length and final thinned stocking are the three main factors that forest managers can manipulate in order to influence wood quality in their stands.
- While site selection remains a critical consideration, in most cases foresters are stuck with the land they have. However, understanding the impact that a particular site has on wood quality is crucial for understanding what interventions (e.g. choice of genetic material and silvicultural regimes) might be required to improve wood quality. Increasing rotation length increases costs, so will only realistically occur if logs of better quality are sufficiently valued by the marketplace (though lower discount rates will also help).
- Other silvicultural variations produced a negligible effect on the wood quality distributions according to the results from the different models. However, in combination, these small increments can still contribute to improved wood quality, and a small increase in stiffness can

result in a significant increase in the pass rate for MSG8, which can be worth a lot of money to a structural sawmill.

- Intensive use of the wood properties models in Forecaster has revealed a number of areas in which the model output could be improved to provide better information for users. These include:
    - Output an outerwood density value for each log, as well as the average density value.
    - Produce a mature wood volume output, so that foresters can focus on maximising the premium wood, as opposed to trying to decrease the poorer (juvenile) wood.
    - Include richer branching output information in reports, namely maximum branch size in a log, average branch size and standard deviation. This would give users a better understanding of the silvicultural effects on branching.
- Further examination into the prediction of branches for normal trees by Forecaster's branching and BIX models, with the intent to further inform users as to how to get the best outcome from these models would be beneficial.
- Further studies could look at the impact of these models on standard log grades, and the subsequent effect on economics, which is ultimately what forest managers want to know.
- To enable forest managers to undertake similar analysis themselves, and thus tailor the regimes to suit their current practices and perform economic analyses that are specific to their situation, the project entities, used as inputs to Forecaster in this analysis, will be made available on the FFR website.

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APPENDICES

Appendix 1: Log product definitions[22]

Name	Description	Log price ($/$m^3$)	Min length (m)	Max length (m)	Min SED (mm)	Max SED (mm)	Max LED (mm)	Max live branch absolute (mm)	Max dead branch absolute (mm)	Max sweep relative to SED (%)
P1	Domestic large pruned	132	3.7	6.2	400	999	999	0	0	25
P2	Domestic small pruned	107	3.7	6.2	300	399	999	0	0	25
S1	Large, small-branched sawlog	92	3.7	6.2	400	999	999	60	60	25
S2	Med, small-branched sawlog	86	3.7	6.2	300	399	999	60	60	25
S3	Small, small-branched sawlog	73	3.7	6.2	200	299	999	60	60	25
L1	Large, large-branched sawlog	77	3.7	8.1	400	999	999	140	140	25
L2	Medium, large branched sawlog	77	3.7	8.1	300	399	999	140	140	25
L3	Small, large branched sawlog	73	3.7	8.1	200	299	999	140	140	25
Pulp	Pulp log	50	3.7	8.1	100	999	999	0	0	200

Appendix 2: Cutting Strategy[23]

Name	Description	Log Price $/m3	Priority
P1	Domestic large pruned	132	1
P2	Domestic small pruned	107	2
S1	Large, small-branched sawlog	92	3
S2	Med, small-branched sawlog	86	4
S3	Small, small-branched sawlog	73	5
L1	Large, large-branched sawlog	77	6
L2	Medium, large branched sawlog	77	7
L3	Small, large branched sawlog	73	8
Pulp	Pulp log	50	9

Appendix 3: Function sets used in the Forecaster simulations

* In order to better explain the effects of the wood quality models it has been decided to not use a Forking model, as this would introduce additional stochastic elements.

Model type	Models for growth modelling regions			Model properties
	Northland Forest	BOP Forest	Southland Forest	
Growth model	300 Index (Regional drift = 0.05)	300 Index (Regional drift = 0)	300 Index (Regional drift = 0.35)	1) Mortality addition = 0 2) Mortality multiplier = 0 3) Regional drift (as indicated)
Monthly adjustment	8 (Combined 1986)	2 (Kaingaroa 1985)	7 (Otago Coast Tennent 1986)	-
Height/age table	112 (mandatory for 300 Index)	112 (mandatory for 300 Index)	112 (mandatory for 300 Index)	-
DOS function	DOS1999	DOS1999	DOS1999	-
Sweep model	Generic	Generic	Generic	-
Forking model	None*	None	None	-
Carbon model	None	None	None	
Volume table	460 (All NZ 3-point)	460 (All NZ 3-point)	460 (All NZ 3-point)	-
Taper table	460 (All NZ 3-point)	460 (All NZ 3-point)	460 (All NZ 3-point)	-
Breakage table	2 (NZ No breakage)	2 (NZ No breakage)	2 (NZ No breakage)	-
Branch model	BLOSSIM v3.0 (Region = Clays)	BLOSSIM v3.0 (Region = CNI)	BLOSSIM v3.0 (Region = South)	4) Region (as indicated)
Acoustic velocity model	WQIAcousticVelocity (Density Index = 440)	WQIAcousticVelocity (Density Index = 420)	WQIAcousticVelocity (Density Index = 380)	Seeded using density index value as indicated below
Wood Density model	FFRDensity2011 (Density Index = 440)	FFRDensity2011 (Density Index = 420)	FFRDensity2011 (Density Index = 380)	Seeded using density index value as indicated.
Heartwood model	FFRWQI2009	FFRWQI2009	FFRWQI2009	-