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Analysing Silvicultural Regimes using the 300 Index Growth Model in Forecaster

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EXECUTIVE SUMMARY

This report, the second part in a series of technology transfer papers, uses the 300 Index growth model in Forecaster to design silvicultural regimes that integrate biological as well as economic criteria. We modelled stand development and profitability for different regimes, which consisted of different combinations of silvicultural treatments such as timing and intensity of thinning, final stocking and rotation age. The purpose of the report was to highlight the steps required to undertake regime analysis within Forecaster and provide a guide to interpreting the results from this modelling system. As an aid to interpreting these results, we introduced a number of biological metrics, including mean annual increment (MAI), current annual increment (CAI), Reineke's Stand Density Index (SDI) and Curtis's relative density (RD). These metrics quantify the rate of biomass accumulation and the degree of site occupancy. In combination with economic criteria, they provide a means for evaluating and comparing regimes.

Recent analysis of data showed that the maximum SDI for radiata pine in New Zealand is approximately 1200. This means that a site can only support a maximum of 1200 stems of 25.4 cm diameter per hectare. This can vary on very fertile sites, such as ex-farm sites, to approximately 1500. The typical maximum value of RD for New Zealand radiata pine is approximately 12. Both of these metrics, SDI and RD, can be illustrated in a stand density management diagram (DMD), a convenient tool for planning silvicultural interventions from a biological perspective. Classical silvicultural theory suggests that stands should be left to grow to 55% of maximum SDI, then thinned to 35% of maximum SDI and left to grow again in order to achieve the optimum balance between site occupancy and individual tree vigour. The region between 35% and 55% of maximum SDI is referred to as the "management zone". The upcoming release of Forecaster (v1.12.0) will allow users to compare regimes using a density management diagram, so these concepts were covered in some detail in the report.

Three broad regimes were analysed in this study to illustrate the process and the application of these metrics. These regimes – clearwood, framing and framing with production thinning – differed in their degree of stand development and site occupancy trajectories. For the clearwood and framing regimes, thinning occurred well below the management zone of the DMD. This indicates that the stands were considerably under-stocked, and hence under-utilised, for a considerable period of the rotation. The higher stocked regimes (i.e. 450 stems/ha) also incurred significant natural mortality later in the rotation, when the SDI exceeded 55% of the maximum SDI. Earlier thinnings at mean top height (MTH) 12 m in the framing with production thin regime generally followed the "55-35 rule" but were not economically viable. Regimes that fully occupied the site for longer periods of time achieved higher economic returns compared with regimes thinned to a lower residual stocking. These regimes were clearwood regimes thinned to 450 stem/ha, framing waste thinned to 450 stems/ha at MTH 8 or 10 m and framing production thinned to 450 stems/ha at MTH 16 or 18m. For the production thin regimes, delaying production thinning to MTH 18 would result in an overstocked stand, which could be vulnerable to damage by wind or pests and diseases.

Ultimately, the aim of regime analysis is to develop silvicultural regimes that will be profitable for the owner. In the absence of perfect information about future prices and trends, this becomes a balancing act between fully utilising the potential of the site through maintaining full site occupancy and producing the right log grade mix. Maintaining a healthy and vigorous forest and reducing the risk of wind damage are also important considerations. The intention of this report was not to make recommendations on the types of regimes that FFR members should consider – these will of course be a company-specific decision – but to highlight how Forecaster can be used to generate the information necessary to evaluate a series of potential regimes. In order to achieve optimal growing conditions, foresters should ideally adopt regimes that fully occupy the site for longer periods of time, and ensure the stand is kept in the "management zone" between 35% and 55% of maximum SDI. However, economic and risk considerations (such as windthrow and forest health) will ultimately dictate a less intensive or lower stocked regime.

INTRODUCTION

Regime analysis within a modelling system is a process where silvicultural regimes undergo iterative simulations to allow comparisons of model outputs under varying inputs such as initial and final stockings, timing and intensity of silvicultural treatments, or rotation lengths. These analyses focus mainly on comparisons of log yield and profitability, and test if the current prescriptions are giving the best balance of these aspects.

Biological metrics are not often used by New Zealand foresters, but with an increasing focus on improving biological productivity, their use will become more widespread as foresters want to know whether they are utilising the full potential of a given site. Moreover, with the release of new functionality within Forecaster v1.12.0 that enables the reporting of such biological metrics, it was considered useful by FFR to demonstrate how these could better support foresters considering inclusion of biological productivity as part of regime analysis and help them refine their regimes.

This report focuses on using the 300 Index growth model in Forecaster to help design silvicultural regimes that integrate biological as well as economic criteria. This report describes how stands develop over time in response to different silvicultural treatments such as timing and intensity of thinning, final stocking and rotation age.

Useful concepts for quantifying stand development and site occupancy, such as mean annual increment (MAI), current annual increment (CAI), Reineke's stand density index (SDI), Curtis's relative density (RD), and density management diagrams (DMD) are introduced.

Forecaster allows users to have a high degree of flexibility providing them with a wide range of user-defined inputs. While this is seen as one of the strengths of Forecaster, users also need to be aware of the correct usage of these features. This report provides a simple starting point by discussing how users can check the validity of measured or generated stem lists to ensure sensible outputs. The sensitivity of model outputs to changes in stem selection criteria for pruning and thinning operations and the randomness of this setting are also discussed.

Feedback from FFR members has highlighted the need for technology transfer papers that compare the different modelling systems that are available and provide guidance on using the 300 Index growth model within Forecaster, including the impacts of various parameter settings on the final modelled outcome. In response to this feedback, FFR is producing a series of technology transfer papers that address the following key topics:

1. Comparison of radiata pine growth modelling systems
2. Analysing silvicultural regimes using the 300 Index growth model in Forecaster
3. Modelling the influence of silviculture on wood quality and log-grade outturn
4. Modelling long rotations for carbon sequestration

This report addresses the second topic, and future papers will focus on wood quality and carbon modelling.

Background

Metrics for Quantifying Stand Development and Site Occupancy

MAI (the average rate of volume accumulation up to a given point in a rotation), and CAI (the amount of volume that is added in a given year) describe stand growth and development. The peak in MAI corresponds to the biological rotation age, that is the age at which volume production is maximised[5] (Figure 1). The CAI curve intersects the MAI curve at this maximum MAI value. Understanding the relationship between MAI and CAI and how this is affected by silvicultural treatments is crucial to understanding forest productivity.

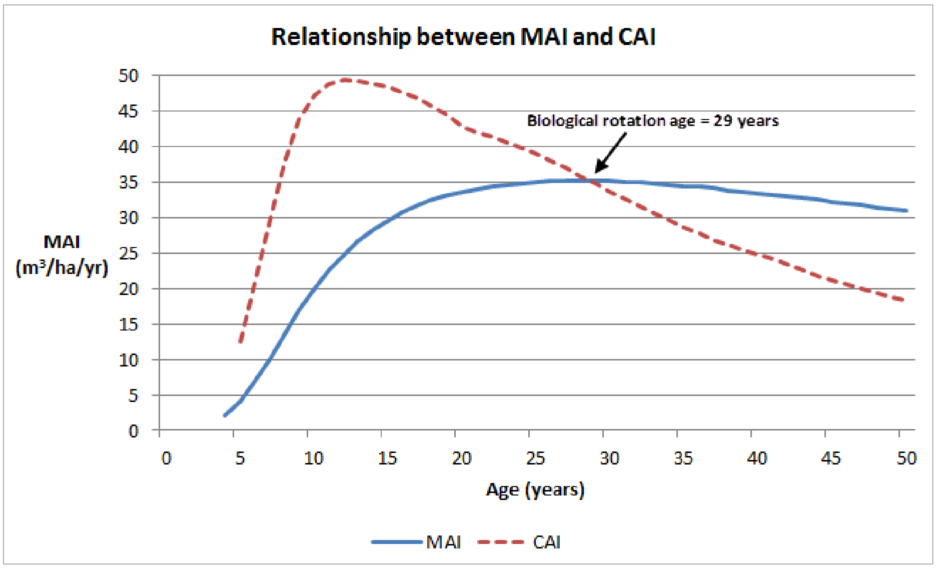


Figure 1: Relationship between MAI and CAI showing the biological age at peak MAI (when CAI is equal to MAI)

Another important component of forest productivity is site occupancy. This can be defined as the degree to which an area is utilised by trees. A number of metrics have been used to quantify site occupancy. In New Zealand, foresters have often used stocking to describe site occupancy, but the degree of site occupancy will depend on the size of these trees, e.g. 500 stems/ha that are 15 cm in diameter will not occupy as much of the site as 500 trees that are 30 cm in diameter. Basal area (BA) overcomes this limitation and has the advantage that it is also linearly related to volume. However BA only provides limited information on stand structure.

Reineke's Stand Density Index (SDI) is commonly used in North America where it was originally applied to single-species, even-aged stands, but has since been generalised for use in uneven-aged stands[6]. In North America, SDI corresponds to the equivalent number of 10 inch trees per acre, while in metric units it corresponds to the equivalent number of 25.4 cm diameter trees per hectare. The exponent of 1.605 has its basis in the -3/2 self-thinning rule that defines the relationship between the number and size of individual trees within a stand[7].

SDI is calculated by:

$$SDI = SPH \left(\frac{QMD}{25.4}\right)^{1.605} \qquad [1]$$

Where SPH is the number of stems/ha and QMD is quadratic mean diameter (cm).

Perhaps the greatest advantage of SDI and similar indices is their independence from site quality and stand age. This means that stands with the same quadratic mean diameter and number of trees per hectare are "more alike in every way than stands of the same site and age"[8].

Recent analysis of data[5] has shown that the maximum SDI for radiata pine in New Zealand is approximately 1200 (Figure 2), that is, a site can only support a maximum of 1200 stems of 25.4 cm (10 inch) diameter per hectare. The maximum SDI on very fertile sites (e.g. ex-farm sites) is slightly higher (~1500) and more work to determine whether the maximum SDI is related to site factors is currently being undertaken.

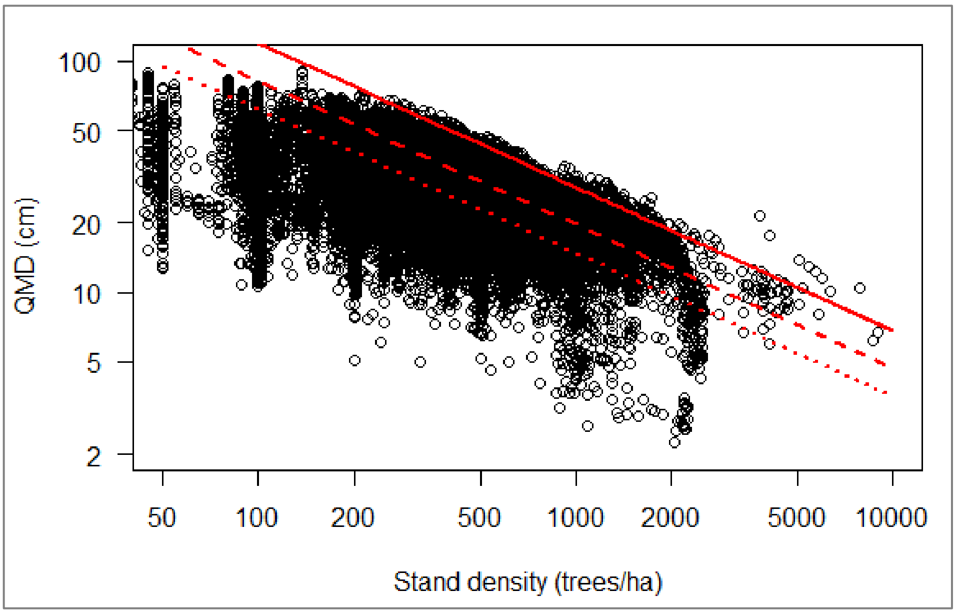


Figure 2: Relationship between stand density and quadratic mean diameter for radiata pine stands in New Zealand. Data are from approximately 27000 PSP measurements. The solid red line represents the maximum SDI (1200), while the dashed and dotted lines represent 55% and 35% of this maximum value, respectively.

SDI can be illustrated in a stand density management diagram (DMD), which shows the relationship between quadratic mean diameter and stand density over time plotted on logarithmically scaled axes. DMDs graphically depict relative density (i.e. current stand density expressed as a proportion of the maximum SDI) and stand dynamics, and provide a convenient tool for planning silvicultural interventions[6] to capitalise on the growth potential of a site.

Classical silvicultural theory suggests that stands should be left to grow to 55% of maximum SDI, then thinned to 35% of this maximum value and left to grow again. Above 55% of maximum SDI, mortality will occur and the stand will approach the maximum SDI line asymptotically, i.e. an increase in tree size will be accompanied by a significant reduction in the number of trees (Figure 3). Hence, when designing thinning regimes to achieve optimal growing conditions, foresters should ideally ensure the stand is between 35% and 55% of maximum SDI – the so-called “management zone”. This ensures that a good balance between maintaining site occupancy and individual tree vigour is achieved[9]. Note however, that economic (i.e. the cost of multiple thinnings) and windthrow (i.e. the risk of late or heavy thinnings) and forest health considerations (such as *Sirex noctilio* or *Dothistroma pini)* will ultimately dictate a less intensive or lower stocked regime.

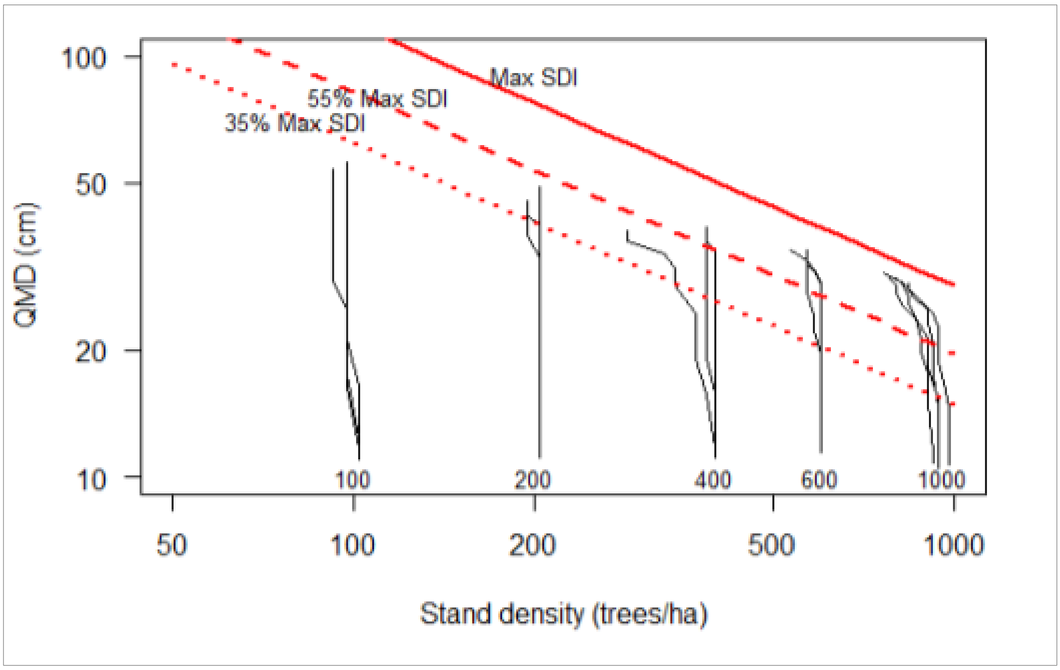


Figure 3: Example of a density management diagram showing the stand development of selected plots at an installation of the FR121 trial. Each plot was thinned to a target stocking at age 5 and allowed to grow. The post thinning stocking is indicated at the start of each stand development trajectory. Measurements are available up to age 19 years.

Curtis's relative density (RD) is broadly equivalent to other diameter-based measures of stand density, but is not as widely applied. Its use has mostly been confined to Douglas-fir stands in the Pacific Northwest of North America.

RD is calculated by[10]:

$$RD = \frac{BA}{\sqrt{QMD}} \qquad [2]$$

Where BA is the basal area (m^2/ha) and QMD is quadratic mean diameter (cm).

For radiata pine growing in New Zealand, the typical maximum value of RD is approximately 12. The management zone corresponds to the region between 35% and 55% of this maximum value.

Study Objectives

The objectives are to:

- Provide explicit guidance and examples of how to undertake regime analyses using the 300 Index growth model in Forecaster;
- Introduce useful metrics for quantifying stand development and site occupancy;
- Investigate how the timing and intensity of thinning, final stocking and rotation age affect stand development and site occupancy;
- Provide guidance on checking the validity of starting crop stemlists;
- Investigate the effect of changes in stem selection criteria for silvicultural events on outputs.

METHODOLOGY

Three broad silvicultural regimes (clearwood, framing and framing with production thinning) were modelled on a Bay of Plenty (BOP) site. Each regime consisted of a base simulation with variations in final stocking, timing and intensity of thinning, and rotation age.

Site and Crop data

For the BOP site, typical 300 Index and Site Index values were obtained from national look-up tables (Table 1). These look-up tables, which contain information on average site and productivity indices, altitude and latitudes for each of sixteen growth modelling regions, were derived in 2006 using data from 4,608 permanent sample plots (PSP) (M. Kimberley, personal communication, February 1, 2011).

Table 1: Site characteristics of BOP forest

Name	**Latitude** (dec deg S)	**Longitude** (dec deg E)	**Altitude** (m)	**300Index** (m^3/ha/yr)	**Site index** (m)	**GF rating**
BOP Forest Med	38.2	176.6	260	27.2	32.5	GF7

Forecaster allows a crop to be created from three different information sources, namely; a stem list, whole stand summary or stand subset. For each base regime in this exercise, stem lists at ages 4 to 5 years were generated from permanent sample plot (PSP) data. A starting age crop was also generated at ages 3 to 4 years using the Generate Start Age Crop[1] functionality in Forecaster. The distributions of stem diameters and heights for these measured and generated stem lists (Appendix 1) were checked to ensure that they were sensible and valid.

Regimes

Base clearwood and framing regimes were set up.

- The clearwood regime consisted of an initial stocking of 1000 stems/ha and three pruning lifts to 6 m and a final thinning to 250 stems/ha.
- The framing regime consisted of an initial stocking of 833 stems/ha, and either waste thinned to 450 stems/ha at mean top height (MTH) 8 m or production thinned to 450 stems/ha at MTH 14 m (Table 2). Although first lift pruning a large number of trees that are subsequently waste thinned is not usual practice, this regime tests sensitivity to final stocking without the complication of different initial pruning regimes.

The effect of different final stockings, timing and intensity of thinning and rotation ages on stand structure, and log product outturn was examined for the regimes.

Forecaster offers the ability to modify the stem selection criteria and the randomness of this selection to allow a subset of stems to be selected for silvicultural events. This modification influences the relative size of trees that are thinned, and the effect of this on log yield was examined. This was done by choosing three different stem ordering criteria:

1. Smallest DBH × Height
2. Smallest DBH
3. Smallest Height

and varying the randomness factor between 0 and 9 in steps of 3 (the higher the randomness factor, the less strict the ordering criteria applied when selecting stems for thinning. This exercise was only carried out for the framing base regime.

Table 2: Description of base regimes and the variations to them

Clearwood base regime	**Variations**
Plant 1000 stems/ha	
Prune 500 stems/ha to 2.4m at DOS 16 cm (minimum green crown remaining 3.5 m, minimum lift length of 1.5 m)	
Thin to waste to 500 stems/ha	
Prune 250 stems/ha to 4.3 m at DOS 17 cm (minimum green crown remaining 3.5 m, minimum lift length of 1 m)	Prune 300 to 450 in 50 stems/ha increments
Prune 250 stems/ha to 6m at DOS 17 cm (minimum green crown remaining 3.5 m, minimum lift length of 1 m)	Prune 300 to 450 in 50 stems/ha increments
Thin to waste to 250 stems/ha	Thin to waste to 300 to 450 in 50 stems/ha increments
Clearfell at age 30 years	Clearfell at ages 25 to 40 years in 5 year increments

Framing base regime	**Variations**
Plant 833 stems/ha	
Thin to waste to 450 stems/ha at MTH 8 m	Thin to waste to 300 to 400 in 25 stems/ha increment Thinning timing at MTH 10 to 14 m in 2 m increments
Clearfell at age 30 years	Clearfell at ages 25 to 40 years in 5 year increments

Framing base regime with production thin	**Variations**
Plant 833 stems/ha	
Production thin to 450 stems/ha at MTH 14 m	Production thin to 300 to 400 in 25 stems/ha increment Thinning timing at MTH 16 and 18 m
Clearfell at age 30 years	Clearfell at ages 20 to 40 years in 5 year increments

Models

The models used in the analysis are described in Table 3.

Additional inputs required by the 300 Index growth model, and the values applied in this exercise include:

- Mortality addition to account for extra mortality not included in the model, for example windthrow – kept at the default value of 0.
- Mortality multiplier to adjust the predicted mortality to account for regions with above or below average mortality – kept at the default value of 0.
- Regional drift setting to allow a 300 Index drift correction function to be applied to adjust growth and account for subtle regional differences in growth trajectories. This was kept at the recommended setting of 0 for BOP[2].

Additional inputs required by the BLOSSIM branch model include:

- Breeding value branch habit is a measure of branch cluster frequency and can be used instead of GF plus branch habit – left blank

- GF plus branch habit is a measure of branch cluster frequency – kept at the default value of 0.3094
- Mean annual air temperature – values were derived internally from LENZ 2010 - 12.1°C for BOP
- Region – CNI for BOP

Table 3: Models used in Forecaster simulations

Model type	Model name	Model properties
Growth model	300 Index	Mortality addition, Mortality multiplier, Regional drift
Monthly adjustment	2 (Kaingaroa 1985)	-
Height/age table	112	-
DOS function	DOS1999	-
Sweep model	Generic	-
Forking model	Generic	-
Volume table	460 (All NZ 3-point)	-
Taper table	460 (All NZ 3-point)	-
Breakage table	17 (KANG 1997)	-
Branch model	BLOSSIM	Breeding value branch habit, GF plus branch habit, Mean annual air temperature, Region

Log Product Definitions and Cutting Strategy

Log product definitions and cutting strategies used were based on MAF's generic domestic log grade specifications[3] and prices[4] and are provided in Appendix 2 and 3.

Economic Analysis

Discounted cash flow analyses were carried out as part of the regime analysis. A discount rate of 8% was used. The operational costs are outlined in Table 4.

Data Analysis

All analyses were done using Forecaster v1.12.0.1015. The annual crop condition tables produced from the simulations were exported and analysed. For each regime, SDI was calculated within Forecaster; while RD was calculated using equation [2] (see Background).

MAI, CAI and total standing volume were calculated for each year of the simulation period (i.e. up to stand age 40 years) using Forecaster. In addition, DMDs were also produced to show how the stands developed over time and whether they were in the management zone at time of thinning. The volume by log grade and the net present value (NPV) was compared for the variations to each of the three regimes.

Table 4: Operational costs used in the discounted cash flow analysis

Operation	Amount	Units	Year of operation
General costs			
Site preparation	80	$/ha	-1
Dothistroma spray	60	$/ha	4, 8
Annual costs			
Administration	5	$/ha	-1 to Clearfell age
Land rental	150	$/ha	-1 to Clearfell age
Property maintenance	10	$/ha	-1 to Clearfell age
Insurance	20	$/ha	-1 to Clearfell age
Rates	15	$/ha	-1 to Clearfell age
Management	30	$/ha	-1 to Clearfell age
Event costs			
Planting	0.15	$/stem	0
Planting stock	0.45	$/stem	0
Clearwood Prune 1	1.80	$/stem	
Clearwood Thin 1	0.90	$/stem	
Clearwood Prune 2	1.40	$/stem	
Clearwood Prune 3	1.40	$/stem	
Clearwood Thin 2	1.00	$/stem	
Framing Thin MTH 8	0.90	$/stem	
Framing Thin MTH 10	1.00	$/stem	
Framing Thin MTH 12	1.10	$/stem	
Framing Thin MTH 14	1.20	$/stem	
Harvesting costs			
Roading	2000	$/ha	1 year before Clearfell age
Harvesting ground-based	25	$/m^3	Clearfell age
Production thin – MTH 14	30	$/m^3	
Production thin – MTH 16	24	$/m^3	
Production thin – MTH 18	20	$/m^3	

RESULTS AND DISCUSSION

Effect of Silvicultural Regimes on Stand Development and Site Occupancy

Clearwood Regimes

The clearwood regimes tested were similar in their degree of site occupancy trajectories:

- The maximum SDI ranged from 925 to 1138 (Table 5).
- Thinning occurred well below the management zone of the DMD (Figure 4), indicating that the stands were considerably under-stocked at the time.
- The decision to thin early (the first and second thinning operations were carried out at ages 5.5 and 6.9 years, respectively for the base regime variations) was made to ensure that large pruned logs were produced quickly. This, however, resulted in a significant underutilisation of the site for a considerable period of the rotation.
- The higher stocked regimes incurred significant natural mortality later in the rotation. This can be seen by the reduction in stocking when the SDI exceeds 55% of the maximum SDI (Figure 4).
- The regime with thinnings delayed until ages 6 and 9 years resulted in higher log yields and NPV returns compared with the clearwood base regime (Table 6). However, optimum stand growth was still not achieved as the stand was thinned before it reached the 35% of the maximum SDI (Figure 4).
- The DMD (Figure 4) also shows that a 60 cm diameter tree can only be achieved when the stocking is less than 300 stems/ha.

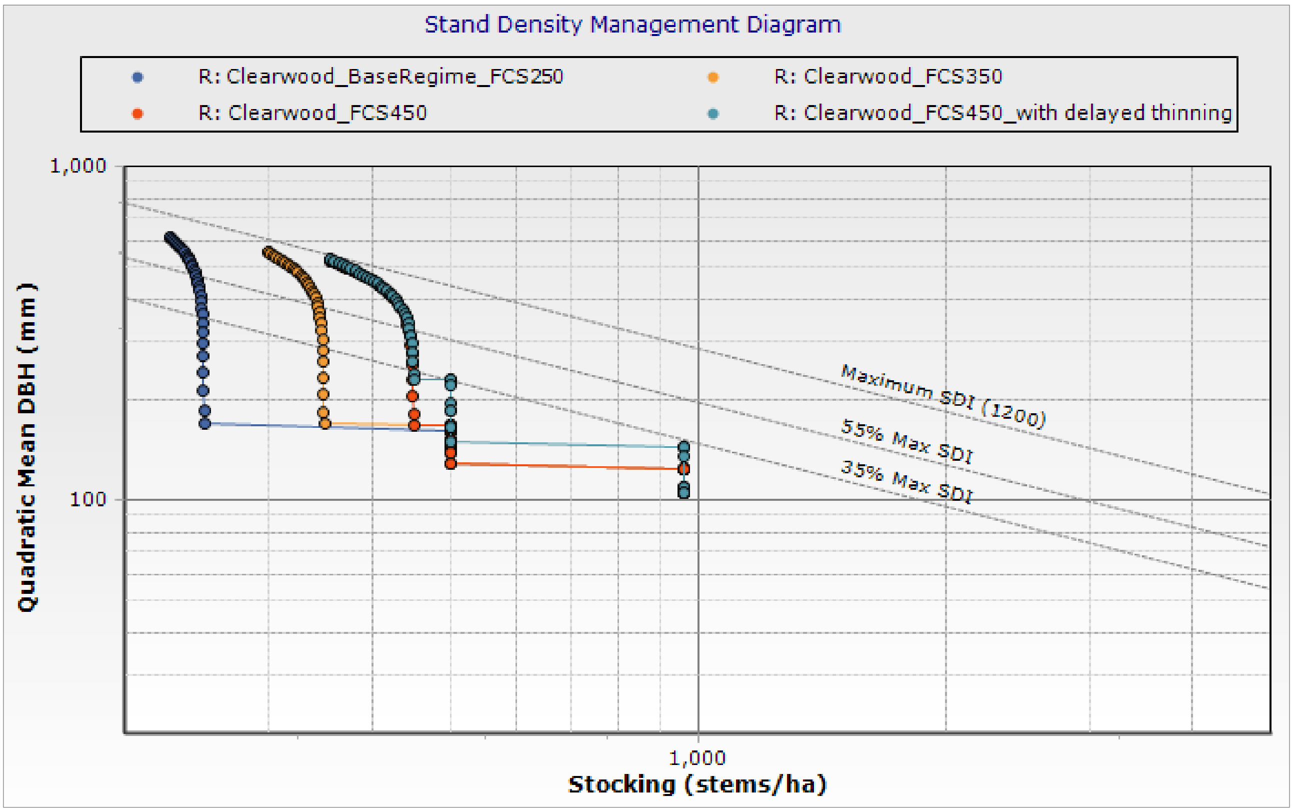


Figure 4: DMD showing stand development for clearwood regime under four variations. Starting crop is measured PSP data. (Source: Forecaster v1.12.0).

The maximum MAI increased with increasing final stocking, while the biological rotation age decreased (Table 5). The economic rotation age was 25 years and for the higher stocked stands there was only a small difference between the maximum MAI and the MAI at rotation age.

For example, the maximum MAI for a final stocking of 450 stems/ha was 31.7 m^3/ha/yr, while the MAI at harvest age (25 years) was 30.7 m^3/ha/yr (i.e. 768 m^3/ha ÷ 25 years). For a final stocking of 250 stems/ha, the maximum MAI was 27.1 m^3/ha/yr and the MAI at age 25 years was 24.8 m^3/ha/yr (i.e. 621 m^3/ha ÷ 25 years). There was little change in MAI after about 28 years (Figure 5), so a rotation length of 28 years would come close to achieving the maximum biological potential of the site and crop.

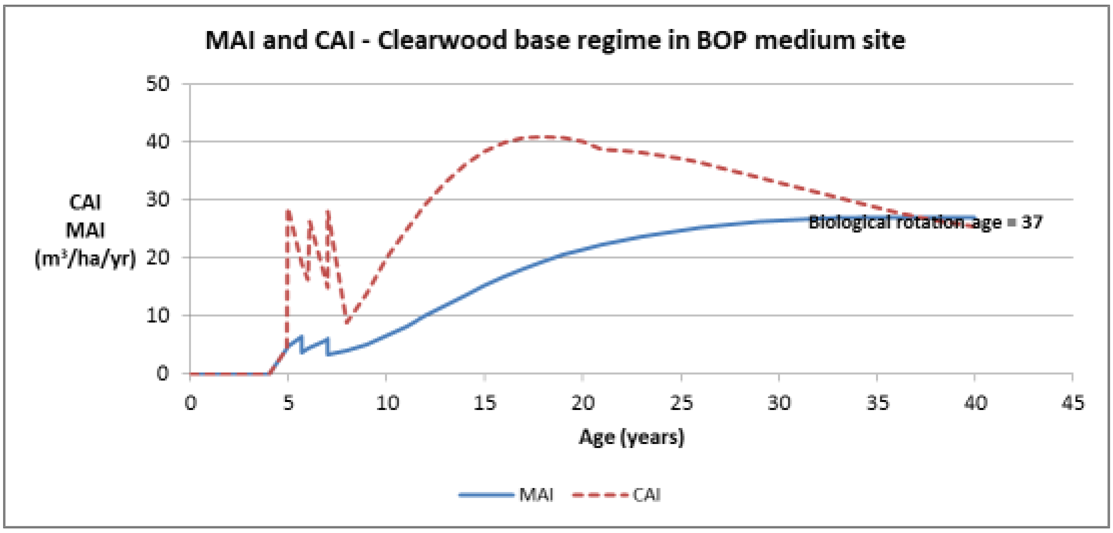


Figure 5: MAI and CAI for a clearwood base regime (final stocking of 250 stems/ha). Starting crop is measured PSP data.

Framing Regimes

The following were observed for framing regimes with respect to their degree of site occupancy trajectories:

- The maximum SDI ranged from 1162 to 1362 (Table 5).
- Stands were under-stocked when waste thinning was carried out at MTH 8 m (Figure 6). As expected this effect was most pronounced for the lowest residual stocking levels.
- Waste thinning at MTH 12 m to a residual stocking of 450 stems/ha almost followed the "55-35 rule". However, there was considerable mortality for this regime as the stand is above 55% of maximum SDI for much of the rotation (Figure 6). If the "55-35 rule" was followed then a second thinning to 300 stems/ha would be carried out, although economic and windthrow considerations might rule this out.
- When thinning was delayed until MTH 14 m, the stand exceeded 55% of maximum SDI and some mortality started to occur (Figure 6).
- Regimes that fully occupied the site for longer periods of time (i.e. waste thin to 450 stems/ha at MTH 8, 10 and 12 m) achieved higher economic returns compared with regimes thinned to lower residual stockings (Table 6).

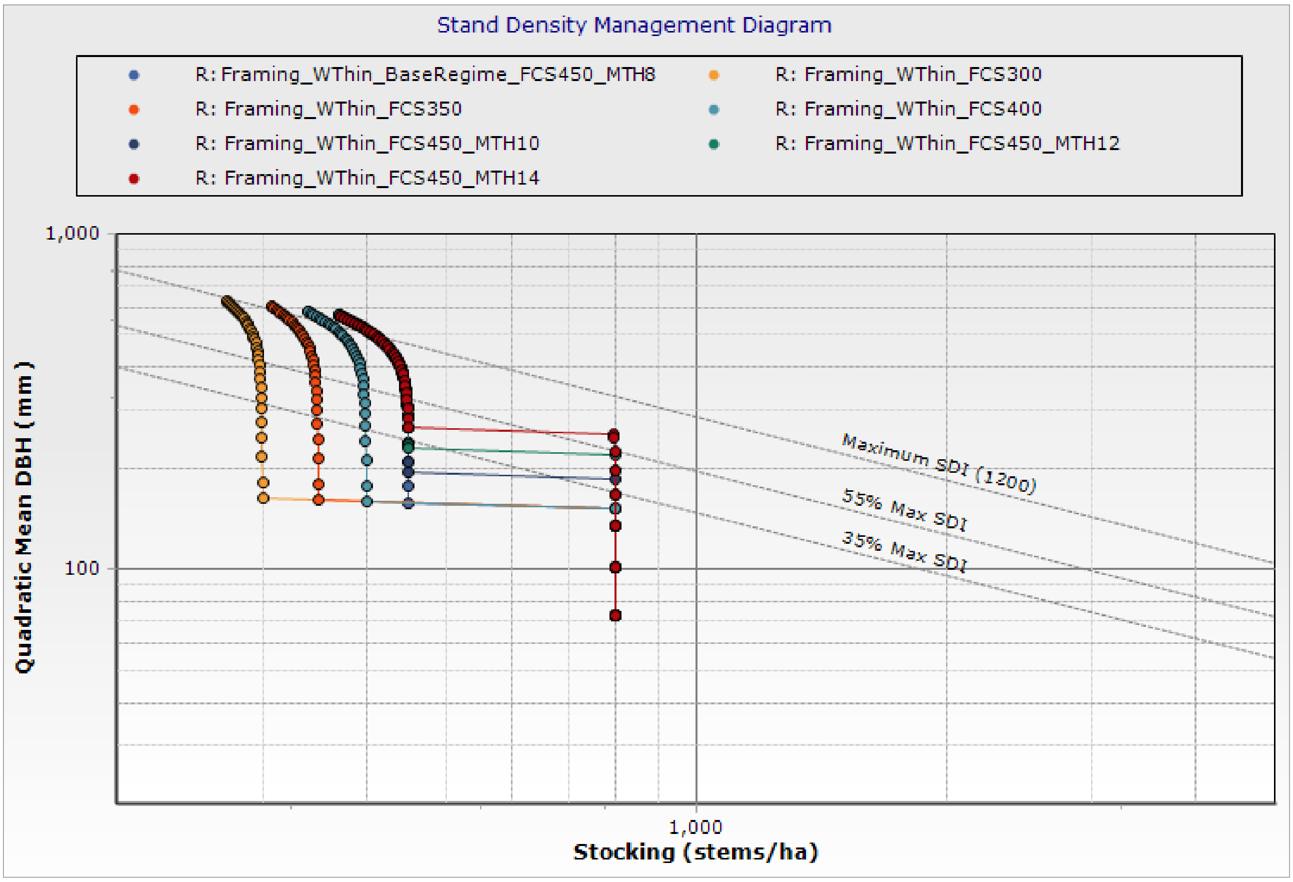


Figure 6: DMD showing stand development for framing regime under six waste thin variations. Starting crop is measured PSP data. (Source: Forecaster v1.12.0).

MAI for the majority of the framing regimes was approximately constant between ages 25 and 35 years, having a value of around 30 to 33 m^3/ha/yr (Figure 7). The biological rotation age of the different framing regimes was generally between 32 and 35 years, although the regime that had a residual stocking after thinning of 300 to 325 stems/ha had a slightly older biological rotation age of 36 to 37 years (Table 5). Delayed thinnings did not considerably affect the maximum MAI as well. The economic rotation lengths, based on the price set used and a discount rate of 8%, were well below the biological rotation length. In some cases the economic rotation length was as low as 20 years, which is highly questionable for a regime focussing on structural timber.

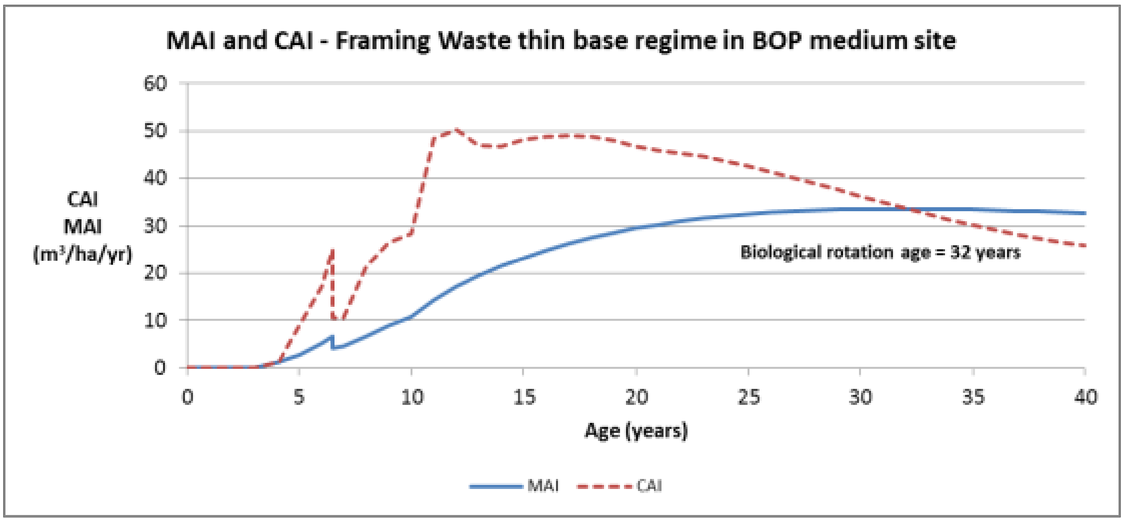


Figure 7: MAI and CAI for a framing waste thin base regime (final stocking of 450 stems/ha). Starting crop is measured PSP data.

Note: the “bump” in the CAI curve around age 12 is caused by the volume function used in Forecaster – when a volume function is required outside the range of its supporting data, Forecaster invokes a “safe calculation” method to simply extrapolate volume from the first volume within this range. At the point of switching models, a change in volume accumulation rate can occur.

Framing Regimes with Production Thin

The following were observed for framing regimes with production thin:

- The impact of delayed production thinnings on mortality can be seen in Figure 8. Above MTH 12 m, stands exceeded 55% of the maximum SDI and mortality started to occur. If the stand is above the 55% line, it may be too late to capitalise on the growth potential of the site. In this case, thinning may not be economic, or may increase the susceptibility of windthrow or pests/disease damage to the remaining trees[9].
- While thinning to a residual stocking of 450 stems/ha at MTH 12 m almost followed the “55-35 rule”, the production thinning needed to be delayed past this point in order to have sufficient piece size at time of thinning.
- At MTH 12 m, tree diameter is approximately 20 cm, while at MTH 18 m it is closer to 30 cm (Figure 8).
- The increased merchantable volume of material obtained from later production thinnings (i.e. MTH 16 and 18 m) is reflected in a higher NPV for these regimes, compared with those where thinnings were carried out earlier (Table 6).

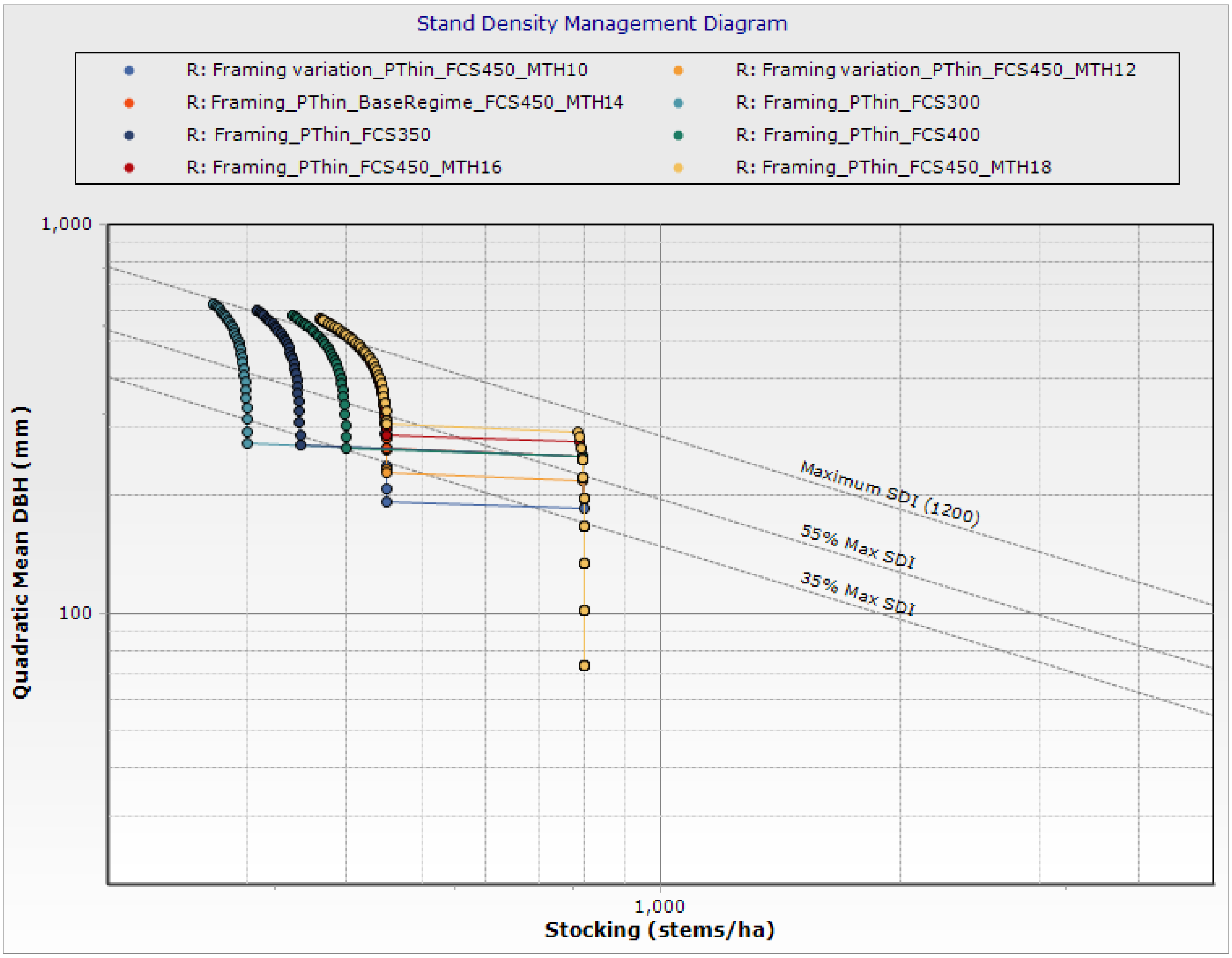


Figure 8: DMD showing stand development for framing production thin regime under seven variations. Starting crop is measured PSP data. (Source: Forecaster v1.12.0).

MAI for the majority of the framing with production thin regimes was approximately constant from age 25 years onwards, having a value of around 30 to 33 m^3/ha/yr (Figure 9). The biological rotation age of the different framing regimes was generally between 32 and 33 years, although the regime that had a residual stocking after thinning of 300 to 375 stems/ha had a slightly older biological rotation age of 35 to 37 years (Table 5).

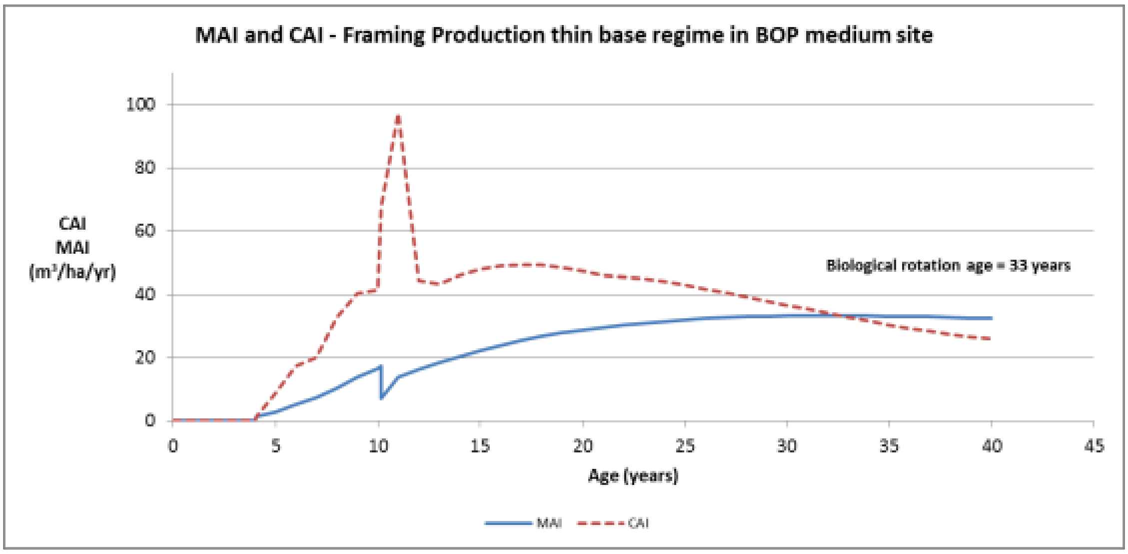


Figure 9: MAI and CAI for a framing production thin base regime (final stocking of 450 stems/ha). Starting crop is measured PSP data. Note the spike in the CAI curve which occurs at age 11 is an artefact of a partial year after the production thin at age 10.2 years.

Table 5: Summary of stand estimates and site occupancy for various clearwood and framing regimes in BOP

	Stand estimates at optimum clearfell age (age with max NPV)								
Regime	**SPH** (s/ha)	**MTH** (m)	**BA** (m^2/ha)	**TSV** (m^3/ha)	**Clearfell age** (yrs)	**Max SDI**	**Max RD**	**Max MAI** (m^3/ha/yr)	**Biological rotation age** (yrs)
Clearwood_BaseRegime_FCS250	243	39	46	621	25	925	8.5	27.1	37
Clearwood_FCS300	289	39	49	670	25	989	9.1	28.7	36
Clearwood_FCS350	333	39	53	702	25	1045	9.7	29.6	35
Clearwood_FCS400	376	39	56	738	25	1094	10.2	30.7	34
Clearwood_FCS450	418	39	58	768	25	1135	10.6	31.7	33
*Clearwood_FCS450_with delayed thinning	418	39	59	786	25	1138	10.6	32.4	32
Framing_WThin_BaseRegime_FCS450_MTH8	435	28	61	591	20	1362	12.6	33.6	32
Framing_WThin_FCS300	295	28	49	485	20	1162	10.6	29.3	37
Framing_WThin_FCS325	313	33	62	713	25	1201	11.0	30.2	36
Framing_WThin_FCS350	336	33	64	735	25	1238	11.4	30.9	35
Framing_WThin_FCS375	366	28	55	543	20	1273	11.7	31.7	35
Framing_WThin_FCS400	380	33	68	776	25	1305	12.0	32.3	35
Framing_WThin_FCS450_MTH10	423	33	72	812	25	1362	12.6	33.5	34
Framing_WThin_FCS450_MTH12	423	33	72	810	25	1361	12.6	33.5	34
Framing_WThin_FCS450_MTH14	424	33	71	801	25	1356	12.5	33.3	34
Framing_PThin_BaseRegime_FCS450_MTH14	437	28	59	578	20	1356	12.5	33.4	33
Framing_PThin_FCS300	296	28	48	472	20	1154	10.6	29.0	37
Framing_PThin_FCS325	314	33	61	700	25	1195	10.9	30.0	35
Framing_PThin_FCS350	337	33	63	722	25	1232	11.3	30.7	36
Framing_PThin_FCS375	367	28	54	530	20	1266	11.7	31.4	36
Framing_PThin_FCS400	381	33	67	763	25	1298	12.0	32.1	33
*Framing PThin_FCS450_MTH10	436	28	60	590	20	1362	12.6	33.6	32
*Framing PThin_FCS450_MTH12	436	28	60	588	20	1361	12.6	33.6	32
Framing_PThin_FCS450_MTH16	438	28	59	573	20	1355	12.5	33.3	33
Framing_PThin_FCS450_MTH18	427	33	70	792	25	1353	12.5	33.2	33

FCS= final crop stocking
*indicates additional runs carried out to determine regimes with optimal stand growth

Log Yield and Economic Analyses

Clearwood Regimes

The aggregated log yields and estimated NPV (at 8% discount rate) at age 25 years for various clearwood regimes in BOP increase with increasing final stocking (Figure 10). A final stocking of 450 stems/ha with delayed prunings and thinnings achieved a higher NPV ($421/ha) compared with other clearwood regimes. The proportion of pruned logs is similar across all regimes (Table 6), but the proportion of framing logs increases with increasing final stocking. There is a corresponding decrease in the proportion of utility grade logs with increased final stocking.

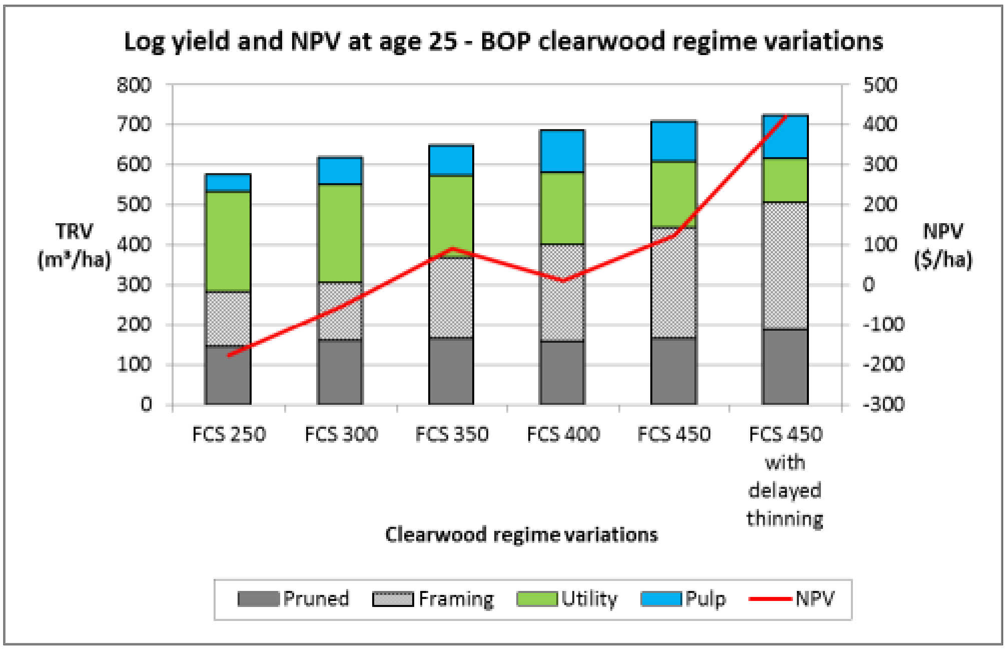


Figure 10: Aggregated log yield and NPV at age 25 for clearwood regime variations.

Framing Regimes

For the framing regimes with waste thinning, NPV was maximised when the thinning occurred at MTH 8 m (Figure 11). Thinning at MTH 8 m with a final stocking of 450 stems/ha and clearfell at 20 years gave the highest NPV ($1612/ha). The optimum rotation for the regime with thinning carried out at MTH 8 m was 20 years, which is unrealistically low for a structural regime. Delaying the thinning decreased the NPV. If clearfelling at 25 years, the optimum regime was thinning at MTH 10 – which also achieves optimal stand growth as illustrated in Figure 6 in the previous section – resulting in an estimated NPV of $1602/ha.

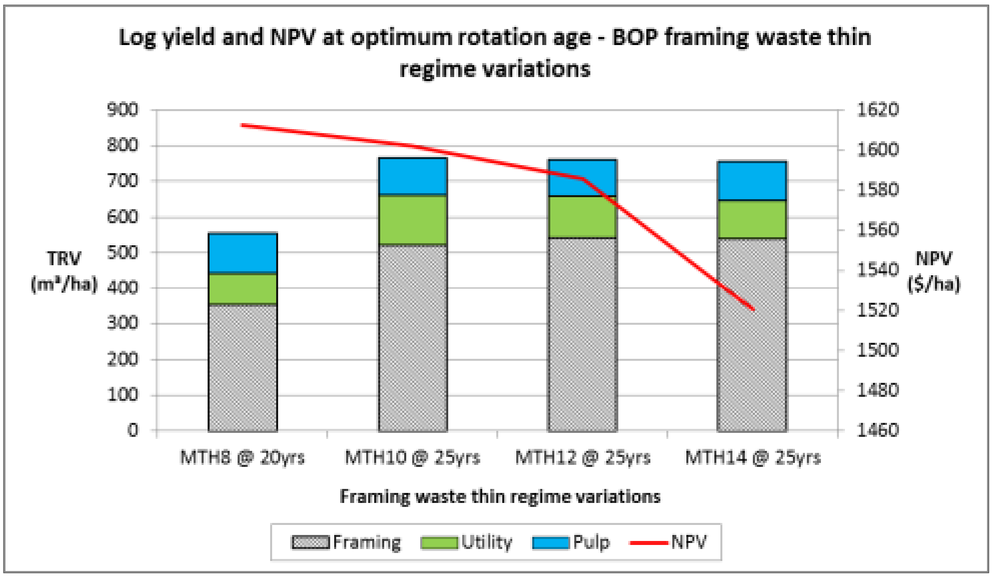


Figure 11: Aggregated log yield and NPV at the optimum rotation age for framing waste thin regime variations.

Framing Regimes with Production Thin

For the framing regimes with production thinning, the NPV increased with increasing MTH at time of thinning (Figure 12). The optimum NPV for many of the regimes occurred when the clearfell age was 20 years. As already noted for the waste thinning regimes, a rotation length of 20 years is probably unrealistically short for a structural regime. Thinning at MTH 18 with clearfell at 25 years will achieve a maximum NPV of $2877/ha (Table 6), and hence is the ideal regime if we consider just the economic criteria. However, delaying thinning to MTH 18 results in an overstocked stand, which could be vulnerable to damage from wind and pests and diseases following thinning.

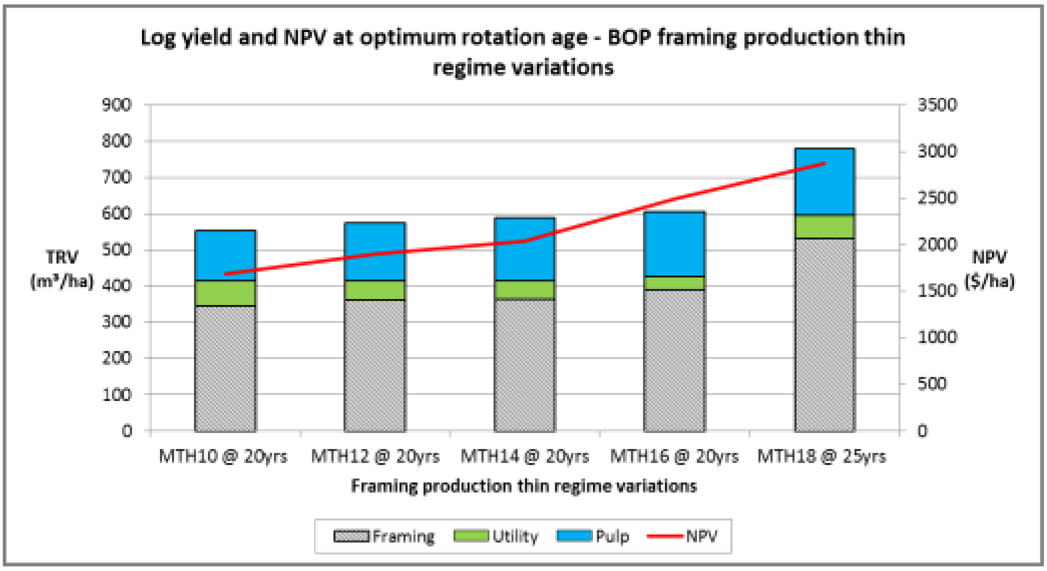


Figure 12: Aggregated log yield and NPV at the optimum rotation age for framing production thin regime variations.

Table 6: Comparison of log yield and NPV returns for various clearwood and framing regimes in BOP

Regime	**Clearfell age** (years)	**% Pruned**	**% Framing**	**% Utility**	**% Pulp**	**NPV** ($/ha)
Clearwood_BaseRegime_FCS250	25	25	23	43	8	-178
Clearwood_FCS300	25	26	24	40	11	-55
Clearwood_FCS350	25	26	31	32	11	91
Clearwood_FCS400	25	23	35	26	15	11
Clearwood_FCS450	25	23	39	23	14	124
*Clearwood_FCS450_with delayed thinning	25	26	44	15	15	421
Framing_WThin_BaseRegime_FCS450_MTH8	20		64	16	21	1612
Framing_WThin_FCS300	20		52	33	15	855
Framing_WThin_FCS325	25		53	35	12	962
Framing_WThin_FCS350	25		54	33	14	1048
Framing_WThin_FCS375	20		61	24	15	1299
Framing_WThin_FCS400	25		56	30	14	1296
Framing_WThin_FCS450_MTH10	25		68	19	13	1602
Framing_WThin_FCS450_MTH12	25		71	15	14	1586
Framing_WThin_FCS450_MTH14	25		71	14	14	1521
Framing_PThin_BaseRegime_FCS450_MTH14	20 (and 10.2)		62	9	29	2046
Framing_PThin_FCS300	20 (and 10.2)		58	16	26	1689
Framing_PThin_FCS325	25 (and 10.2)		60	15	25	1807
Framing_PThin_FCS350	25 (and 10.2)		60	12	28	1855
Framing_PThin_FCS375	20 (and 10.2)		62	12	26	1950
Framing_PThin_FCS400	25 (and 10.2)		62	11	27	2007
*Framing PThin_FCS450_MTH10	20 (and 7.7)		62	13	25	1693
*Framing PThin_FCS450_MTH12	20 (and 8.9)		63	10	27	1902
Framing_PThin_FCS450_MTH16	20 (and 11.5)		68	10	23	2491
Framing_PThin_FCS450_MTH18	25 (and 12.8)		68	8	23	2877

FCS=final crop stocking
*indicates additional runs to determine regimes with optimal stand growth

Checking the Validity of Starting Stemlists

This section describes how Forecaster users can check the validity of measured or generated stem lists to ensure sensible outputs. Figure 13 shows the stem height and diameter distributions for a crop generated in Forecaster using the Generate Start Age Crop functionality. This chart can be obtained by clicking on the "Preview Stem List" button on the Stem List tab of the Crop entity. All stems in the stemlist are plotted according to their DBH and Height values. The mean top height is indicated by the white diamond shape, and the arrows on the top axis indicate the mean top diameter and quadratic mean diameter[11].

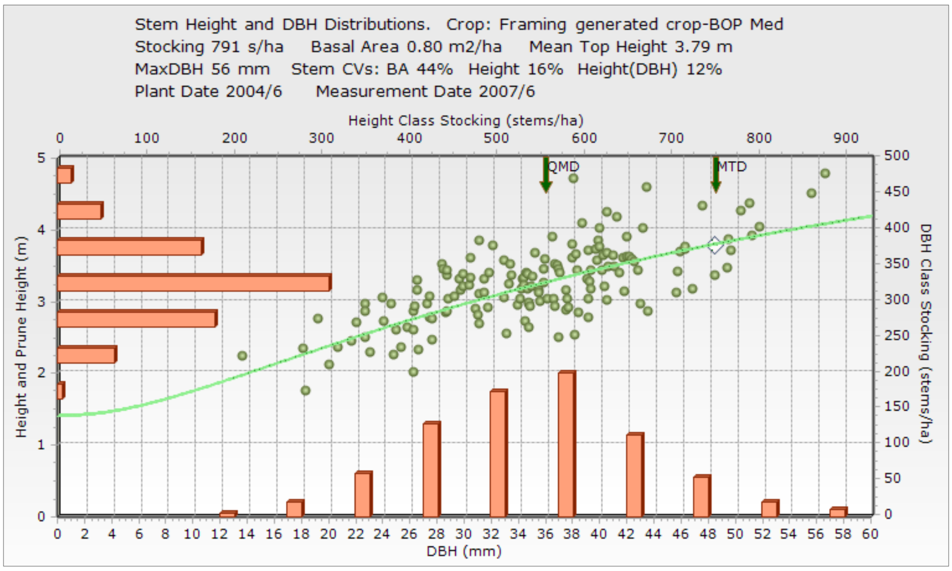
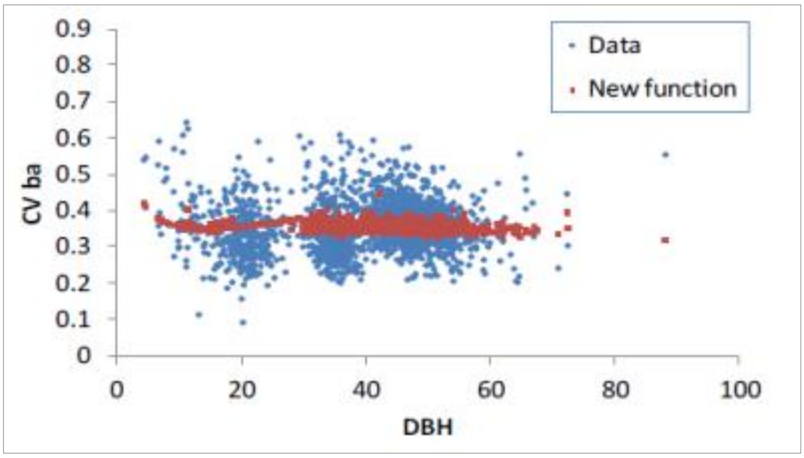


Figure 13: Stem height and diameter distributions for a crop generated in Forecaster (Source: Forecaster v1.12.0).

Users are advised to check the values for stem BA and height coefficient of variation (CV). These are important as they define the variation in stem diameter and height, and thus can have a big impact on log size distribution. Figure 14 shows the expected change in BA and height CV with increasing tree size[12] - BA CV averages 38%, and height CV is approximately 20% at early ages and declines rapidly to a 10% average.



(a)

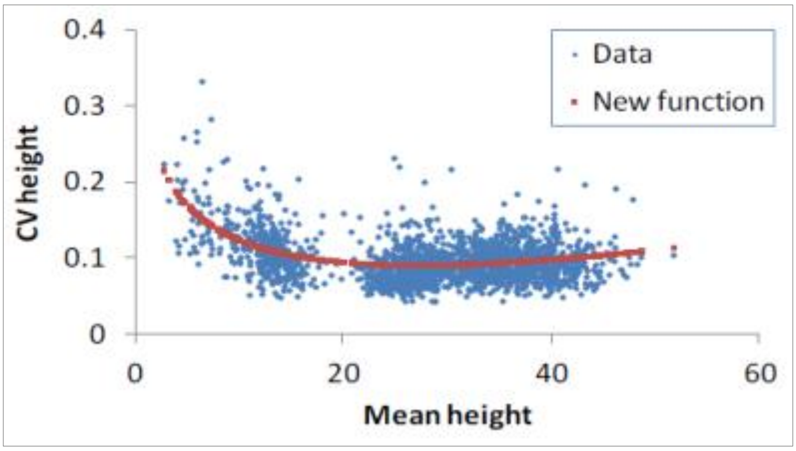
(b) 

Figure 14: Variation in the coefficient of variation (CV) for (a) basal area and (b) stem height with increasing tree size.

The example in Figure 15 shows a stemlist which was made by combining measurements from two stands which were assumed to be of similar productivity. However, the plot of height against DBH shows that there are two apparent clusters of points (one at approximately DBH = 50 mm, and one at DBH = 100 mm), indicating a bimodal diameter distribution, while the height distribution also looks abnormal. This shows that the two stands were quite different and should not have been combined into a single stemlist. Such a stemlist would not be appropriate for use in a regime analysis, and we would recommend that the user return to the source data to check it, and perhaps find a new data source (ideally one which produces more of a normal distribution). Care should always be taken when combining stemlists from more than one source.

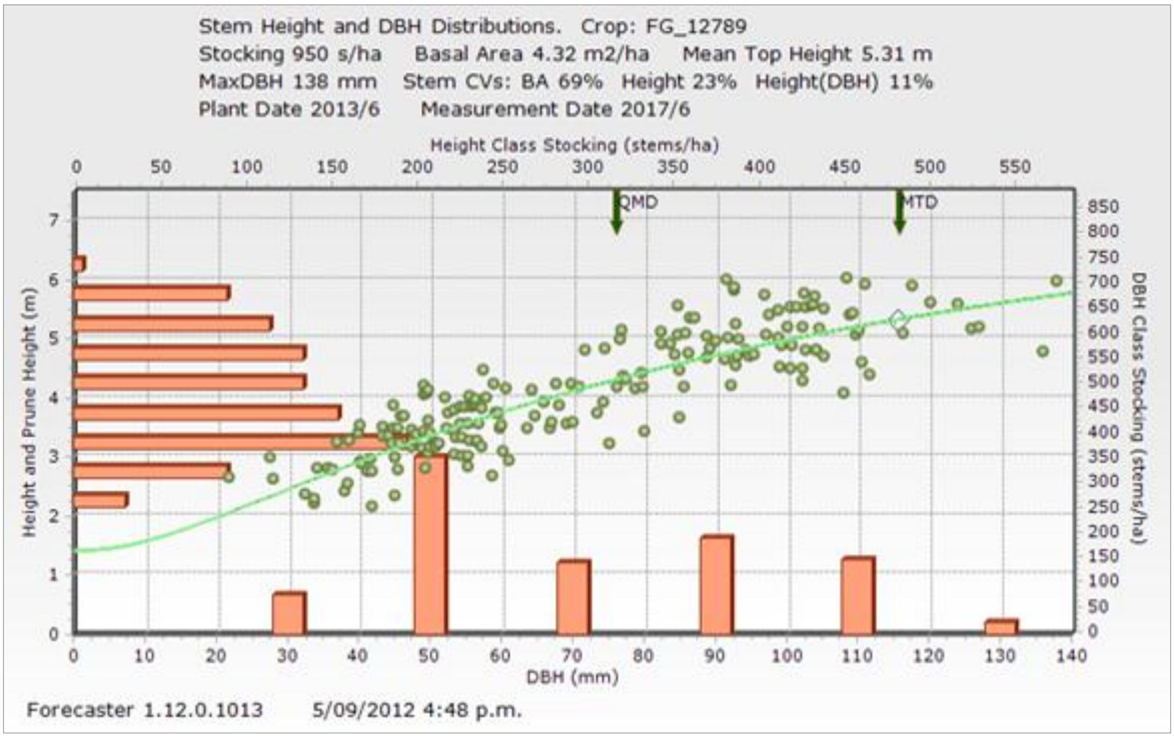


Figure 15: Example of stem list showing two clusters of points (Source: Forecaster v1.12.0).

Effect of Stem Ordering Criteria and Randomness Setting

Forecaster offers the ability to modify the stem selection criteria to allow a subset of stems to be selected for silvicultural events (Figure 16). The stemlist is ordered according to the required stem ordering as well as the level of randomness which is applied to this ordering. The event is performed when sufficient stems meet the specified criteria. The intent of this control is to allow the user to simulate operational realities of stem selection such as the need to maintain even spacing, and deal with malformation etc[13].

Figure 16: Stem selection criteria for a waste thin event in Forecaster

The stem ordering criteria and randomness setting influence the thinning coefficient, which is defined as the proportion of basal area relative to stocking that remains following a thinning and is calculated by:

$$= \frac{\log_e(BA\ after\ thin) - \log_e(BA\ before\ thin)}{\log_e(SPH\ after\ thin) - \log_e(SPH\ before\ thin)}$$

Where BA is Basal Area in m^2/ha and SPH is the number of stems per hectare.

This coefficient indicates the relative size of trees that are thinned:

- ≈1 = row thinning from beside (e.g. random thinning such as out-rowing)
- <1 = thinning from below (i.e. more of the smaller stems are removed)
- >1 = thinning from above [14] (i.e. more of the larger stems are removed, such as what could happen if removing unpruned followers which have out-grown pruned stems in the time since pruning).

When carrying out waste thinnings from below, we recommend using a thinning coefficient of 0.8. This value was obtained from the analysis of historical PSP data (M. Kimberley, personal communication, February 1, 2011). Forecaster reports the thinning coefficient for every thinning operation in the message viewer that appears straight after a simulation (Figure 17).

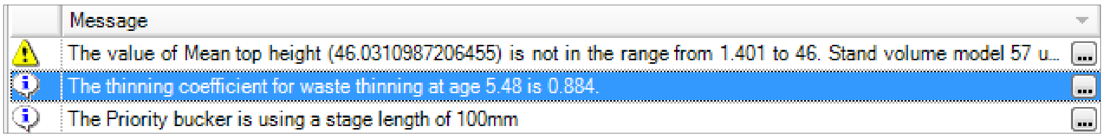


Figure 17: Thinning coefficient reported by Forecaster after a simulation

The effect of stem ordering criteria and randomness setting on the resulting thinning coefficients is shown in Table 7. As the randomness setting increases, the size of trees thinned, and hence the thinning coefficient, increases as well.

Table 7: Effect of stem ordering and randomness settings on thinning coefficient for a BOP framing waste thin base regime

	Randomness setting			
Stem ordering	**0**	**3**	**6**	**9**
Smallest DBH & height	0.646	0.810	1.043	1.050
Smallest DBH	0.629	0.803	1.034	1.050
Smallest height	0.751	0.857	1.018	1.050

The effect of increasing the randomness level (and hence the thinning coefficient) on log yield estimates is illustrated in Figure 18. While the proportion of S1 logs has increased, S2 and S3 log volume has decreased, resulting in an overall reduction of the proportion of framing (aggregated S grade) logs.

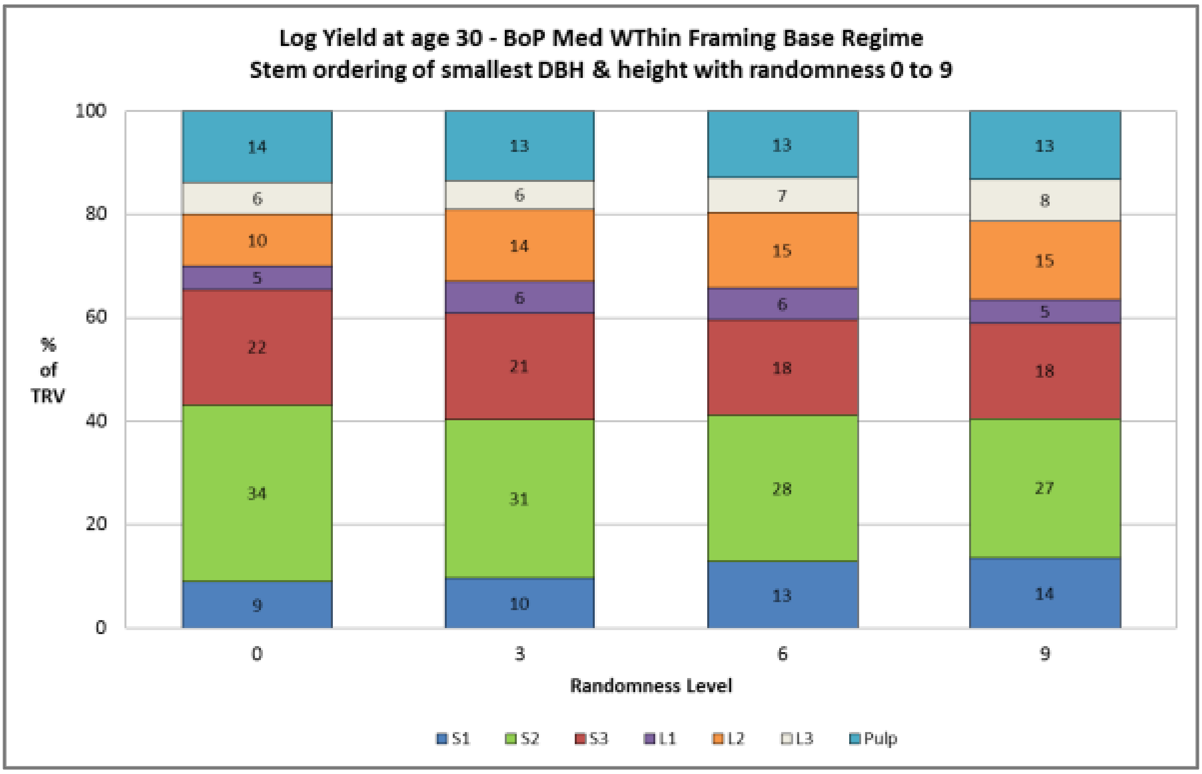


Figure 18: Effect of stem ordering criteria of smallest DBH and height with randomness setting of 0 to 9 on log yield at age 30

To examine this further, we looked at the resulting stem distributions at age 30 (Figure 19). Strictly thinning out the smallest stems (randomness setting=0) results in a skewed post thin distribution with less small sized and more large sized stems. Competition between the remaining larger stems restricts growth, and results in a narrower distribution of stem volume at age 30 with less S1 and more S2 and S3 logs. The lower proportion of L grade logs could be caused by less branching due to a higher number of large stems remaining after the thin.

On the other hand, by thinning at random (randomness setting=9), the post thin stem distribution remains basically the same as the pre-thin distribution, with a higher proportion of very small stems. The growth of these small stems will be restricted in favour of the larger stems, resulting in a wider distribution of stem volume at age 30 with more S1 logs.

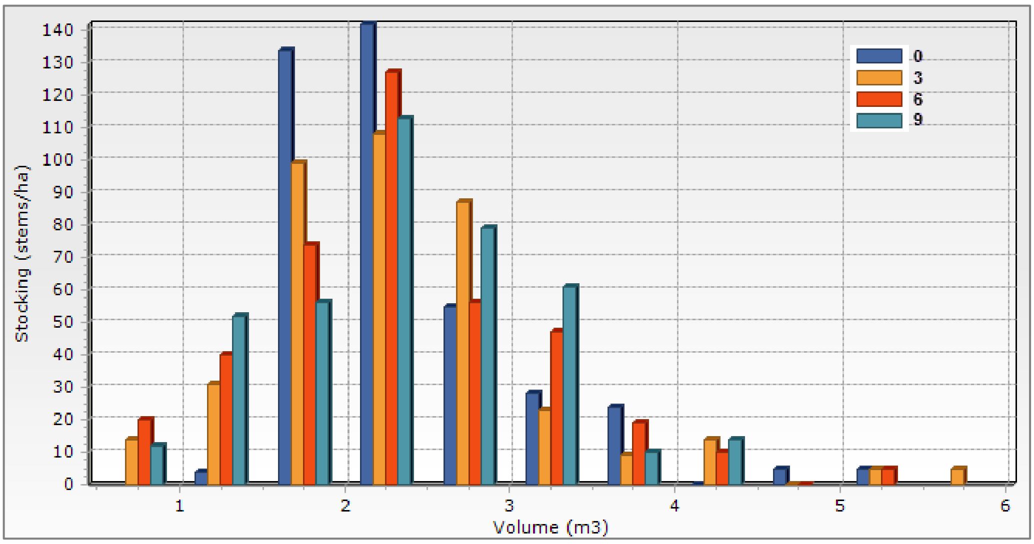


Figure 19: Distribution of stocking by volume at age 30 - stem ordering criteria of smallest DBH and height with randomness setting of 0 to 9 (Source: Forecaster v1.12.0).

CONCLUSIONS

Developing silvicultural regimes requires foresters to consider multiple factors, including the growth and development of stands over time in response to different treatments, the appropriate level of stocking to maintain and the overall profitability. Stand density metrics, such as Reineke's Stand Density Index (SDI) and Curtis's Relative Density (RD), and density management diagrams (DMD) provide useful means for evaluating stand development and site occupancy and complement the existing economic analysis tools that are available within Forecaster.

To achieve optimal growing conditions, foresters should ideally adopt regimes that fully occupy the site for longer periods of time, and ensure that, where possible, the stand is kept in the "management zone" between 35% and 55% of maximum SDI.

The three broad regimes evaluated in this report (clearwood, framing and framing with production thinning) did not follow this "55-35" rule. Instead, the first thinning was carried out well below 35% of maximum SDI and the stands were then left to grow beyond 55% of maximum SDI. This indicates that the stands were considerably under-stocked, and hence under-utilised, for a considerable period of the rotation. While production thinning to a residual stocking of 450 stems/ha at MTH 12 m almost followed the "55-35 rule", the operation needed to be delayed in order to have sufficient piece size at time of thinning. Higher merchantable volume obtained from later production thinning (i.e. MTH 16 and 18 m) was reflected in higher NPV for these regimes, compared with those where thinning was carried out earlier.

The NPV generally increased with final stocking levels for all three regime classes. These higher stocked regimes were also the regimes that had the highest level of site occupancy throughout the rotation. For framing regimes, NPV was maximised with early waste thinning or with later production thinning.

For all the regimes tested, the maximum MAI increased, as expected, with increasing final stocking, while the biological rotation age decreased. Delayed thinning did not considerably affect the maximum MAI. The economic rotation ages, based on the price set used and a discount rate of 8%, were well below the biological rotation ages.

To Forecaster users, we emphasise the importance of checking the validity of stem height and diameter distributions as well as the values for stem BA and height coefficient of variation for the starting crops to ensure sensible outputs. Understanding the implications of stem ordering for silvicultural events as well as the level of randomness applied to this ordering on resulting log yield is also advised.

Silviculture has a significant role to play in achieving the sector's goal of raising biological productivity. However, the example regimes that were evaluated in this study also highlight the trade-offs between maximising biological prodicitivity and economic profitability. The tools that are now available in Forecaster v1.12.0 will allow silviculturalists to better understand these trade-offs when designing their regimes.

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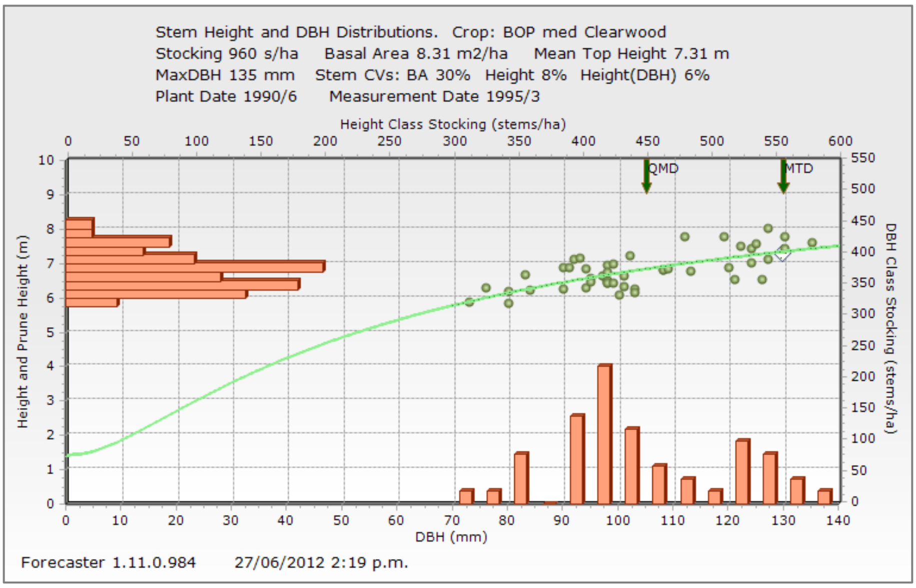
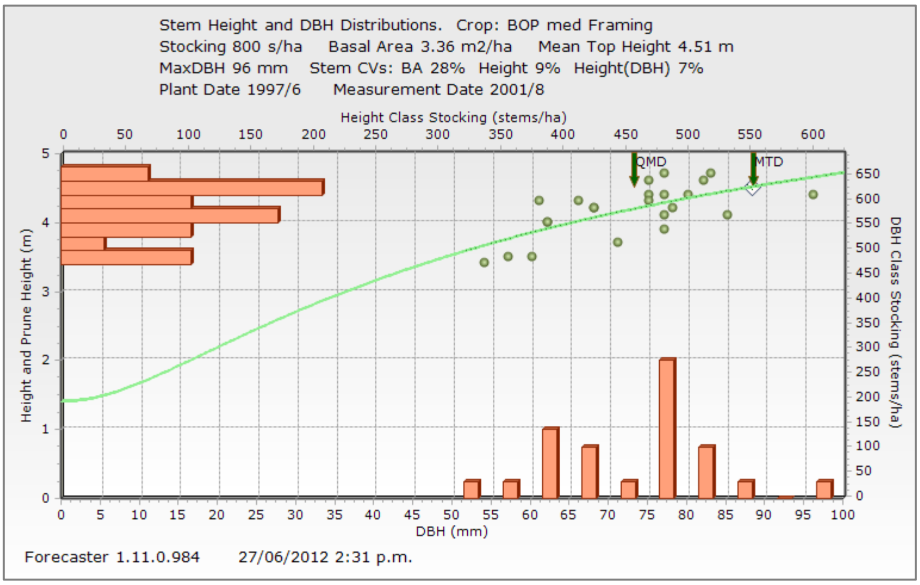
APPENDICES

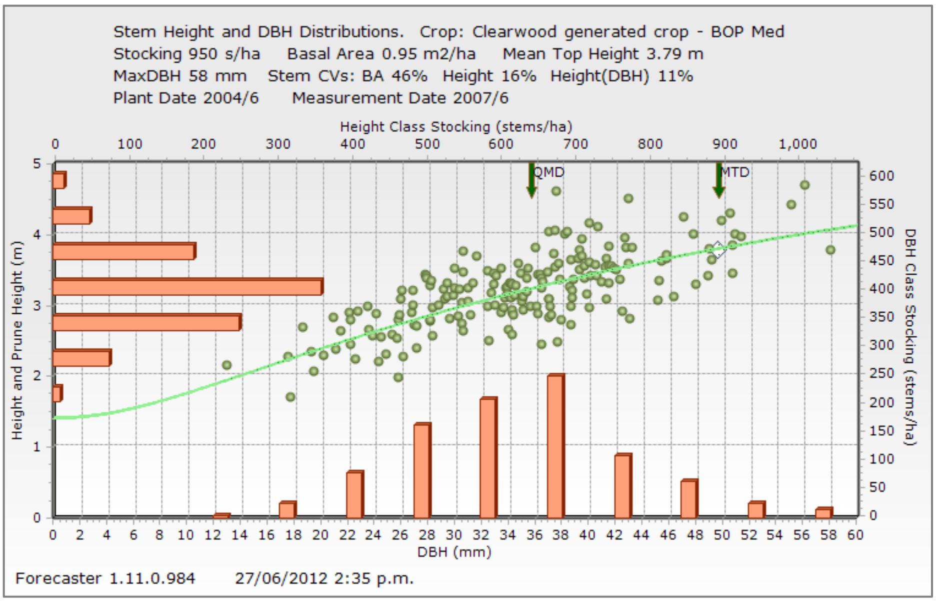
Appendix 1: Stem height and diameter distributions of the starting crops



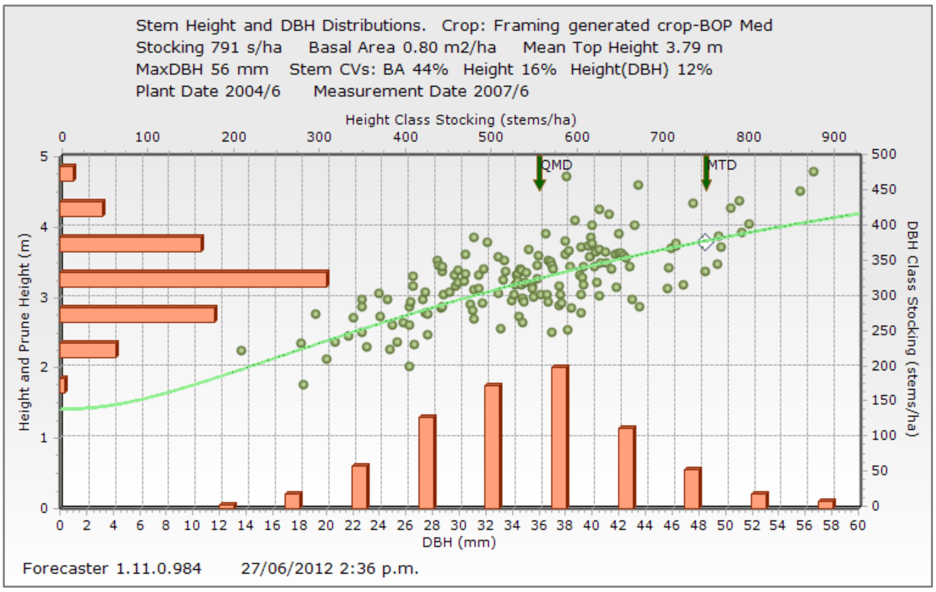
4.7 year old BOP medium clearwood crop from PSP data, with 48 stems in the stemlist



4.1 year old BOP medium framing crop from PSP data, with 23 stems in the stemlist



3 year old BOP medium clearwood crop generated from Forecaster, with 190 stems in the stemlist



3 year old BOP medium framing crop generated from Forecaster, with 158 stems in the stemlist

Appendix 2: Log product definitions

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	Pulplog	50	3.7	8.1	100	999	999	0	0	200

Appendix 3: Cutting Strategy

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	Pulplog	50	9