THE IMPACTS OF SPECIES, PHYSIOLOGICAL AGE AND SPACING ON TREE FORM AND BRANCHING

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Abstract

This dissertation examined the impact of species, physiological age and spacing on tree form and branching at a Nelder experiment located near Rolleston, Canterbury. Two species were compared, *Pinus radiata* and *Eucalyptus nitens*, at a range of stockings from 271 stems/ha to 40,466 stems/ha. Within the *P. radiata*, two different physiological ages were compared.

Stocking and species significantly affected (p-value <0.05) tree height, diameter at breast height (DBH), crown depth, branch mortality, branch angle, branch size and internode length. Only stocking was statistically significant for crown width, and height from the ground was also statistically significant for branch angle and branch mortality.

DBH, crown width, crown depth, branch size and branch survival decreased with increasing stocking for both species. Branch angle and average internode length increased as stocking increased for both species, and branch angle and average internode length also increased as you moved away from the base of the tree. DBH, average internode length and branch size were significantly larger for *P. radiata* across all stockings, however branch mortality and branch angle were significantly larger for *E. nitens.*

Physiological age was not statistically significant for any aspects of tree form or branching examined in this study.

Key words: *Pinus radiata, Eucalyptus nitens,* species, initial stocking, physiological age, tree form, branching, significant

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1. Introduction

The Rolleston Nelder experiment was established in 2007/2008 to study the growth patterns of *P. radiata* and *E. nitens* over a range of stockings, along with two different physiological aged parents in the *P. radiata.* The stockings range from 271stems/ha to 40,466 stems/ha, which the latter is considered to be extreme stocking rates in terms of typical New Zealand forestry plantations.

An understanding of how *P. radiata* and *E. nitens* are affected by stand density at a young age is important for the management of forests throughout New Zealand. Branching and tree form can have a big influence on pruning costs and product values, with initial stocking affecting tree growth and development. The aim of many forest managers is to produce a crop which has large and valuable trees in a short time frame with minimal costs. Initial stocking can have a large influence on this, and an understanding of how branching and tree form are affected by stocking at a young age is essential in producing a valuable crop.

A number of papers found that DBH, crown width, crown depth, branch size and branch survival decrease with increasing stocking. Studies have generally been inconclusive regarding tree height response to stocking, and there is little information on branch angle response to stocking. There is also little information comparing the two species.

Physiological aging has the potential to improve stem form and growth. Studies have found mixed results with many finding little benefits of using physiologically aged stock. This study aims to determine if physiological aging has any effect on *P. radiata* in the Nelder experiment.

Studies of tree growth in response to initial stocking can aid forest managers to make silvicultural decisions in order to maximise crop production and quality. This study aims to determine how *P. radiata* and *E. nitens* tree form and branching is affected by initial stocking, and proposes to add to the current knowledge of tree growth and to facilitate future research.

2. Literature review

2.1 Initial Stocking

Initial stocking is one of the most important silvicultural decisions to be made during plantation establishment. There is a growing trend for wider spacing in New Zealand (Mason, 2004), and currently 800-1000 stems/ha is common for initial stocking. This is so managers can investment more into each tree, with an increase in growth per tree at the expense of growth per hectare. Initial spacing can have a major influence on stem characteristics because of intra specific competition (Waghorn, 2006), with less foliage being carried on trees which are planted in highly stocked areas.

2.2 Physiological aging

Physiologically aged cuttings are propagated from trees of a certain age, and these cuttings retain the characteristics of the aged tree. Trials with cuttings found that propagules from older trees showed an improvement in stem form, but exhibited slower early diameter growth (Lausberg, Cown, Gilchrist, Skipwith & Treloar, 1995). There are a number of advantages of physiological aging, and these include improved stem form and branching habit, less malformation and being less prone to toppling (Menzies, Holden, & Klomp, 2001). However, in order to avoid the diameter growth losses, Waghorn (2006) recommends confining physiological aging of planting stock to three years or less, and Menzies, et al. (2001) recommend to confine physiological aging to 4 years. There is limited research into the significant trends of younger physiologically aged cuttings with mixed results; however Gee (2002) found that the branches on *P. radiata* one year old cuttings had significantly higher angles than those of three year old cuttings.

2.3 Tree Height

Research into the effect of initial stocking on tree height has resulted in mixed outcomes for both *P. radiata* and *E. nitens*. It is generally accepted that tree height is unaffected by initial stocking, however this is not always the case. For example, Maclaren, Grace, Kimberley, Knowles, & West (1995) found that tree height increased with increasing stocking. Sjolte-Jorgensen (1967) found that mean height of trees in the Northern Hemisphere decreased in extremely high stockings due to suppression from competing trees.

2.4 DBH

The effect of initial spacing on DBH is much more evident than the effect on tree height. (Waghorn, 2006 and Mason, 2004) found that for *P. radiata*, a decrease in initial stocking resulted in an increase in diameter. Cairns (1986) and Fearon (1997) also found this effect of stocking on *E. nitens*. With an increase in stocking comes an increase in competition for resources, and diameter increment is the first type of growth to be affected by competition (Lanner, 1985). This is widely accepted for many species, but little research has been conducted to see if the rate at which stocking affects DBH differs between *P. radiata* and *E. nitens.*

2.5 Crown Width

Tree crowns play an essential role in tree productivity, as this is where the physiological processes such as photosynthesis, respiration and transpiration occur (Crecente-Campo, Marshall, LeMay, & Diéguez-Aranda, 2009). These processes lead to growth and development of the tree, so the larger the green crown is, the more productive the tree can be. There has been little research on crown width for *E. nitens*, but it is generally known that less foliage is carried on each tree at higher stockings due to crown competition (Waghorn, 2006). At higher stockings, the distance between trees becomes smaller so crowns are unable to expand as they are restricted by the neighbouring trees. This is only applicable where a stand canopy is closed. Until canopy closure occurs a tree crown will grow as it needs to in order to intercept the maximum possible amount of light.

2.6 Crown Depth

Crown depth is another measure of crown development, and a number of studies on both *P. radiata* and *E. nitens* have found crown height decreases with increasing stocking (Beekhuis, 1965; Waghorn, 2006; Neilson & Gerrand, 1999). Light is the main factor that contributes to crown depth and Beekhuis (1965) states that:

"The green crown level will diminish when the light penetrating through the upper canopy to the lower branches of the living crown falls below a certain level for survival of the needles."

As discussed earlier, a longer green crown will result in more light capture, thus leading to a more productive tree. However, with increasing stocking, increasing competition from neighbouring trees will cause lower branches to die off and will decrease the length of the green crown. Alcorn et al. (2012) emphasise that canopy closure (when all gaps of the canopy are filled and the canopy is one green mass of foliage) results in leaf area distribution being more concentrated towards the upper crowns. *E. nitens* is known to be crown shy, where new shoots are sensitive because they lack protective bud scales (Jacobs, 1955). This causes *E. nitens* crowns to avoid contact or interlocking with neighbouring plants, so they are very sensitive to high stocking rates.

2.7 Branch mortality

Branch mortality increases as planting density increases (Alcorn et al., 2007) as a result of competition for resources. Pinkard (2002) reported that loose knots occur when a dead branch is encased by a growing stem. Dead eucalypt branch stubs can become trapped and expelled out by growing stems, which can leave kino traces in eucalyptus trees. These traces and loose knots can result in a reduction in the production of appearance grade timber, lowering the value of a tree.

Green pruning is preferred to dead branch pruning, especially in *E.nitens* as this species retains its dead branches. Alcorn et al. (2012) also noted that it is considered desirable to remove dead branches before the live crown rises above the ground. Beekhuis (1965) found that bark and branch encasements are most pronounced in the lower part of the stem as this is where branches die off first, which stresses the need for early pruning to a level which is economically justifiable.

2.8 Branch size

Many studies have demonstrated that stocking had an impact on branch size. Gunn (2000), Gee (2002) and Waghorn (2006) found that for *P. radiata,* branch size increased with decreasing stocking. Neilsen & Gerrand (1999) also found this was the case for *E. nitens.* Branch size is a very important factor when it comes to assessing wood quality, with larger branches creating larger knots in timber, decreasing strength and stiffness (Mason, 2004), thus decreasing the value of the timber.

2.9 Branch angle

There has been little research on branch angle (especially for *E. nitens*), with branch angle being measured from horizontal. Gunn (2000) found a strong trend for decreasing branch angles towards the base of *P. radiata* trees, and Gee (2002) found that branch angles increased with increasing stocking. These are both expected because there is more competition for light at higher stockings and lower down the tree, so the branches will grow up towards the light. Breeders prefer branches with flat angles to the stem (Raymond & Cotterill, 1990) as they leave smaller knots compared to branches with bigger angles. Pruning flat branches is also much easier for a pruner.

2.10 Branch distribution

Branching habits differ between *P. radiata* and *E. nitens. P. radiata* has distinct internodes which separate branch whorls (Lavery, 1986), whereas *E. nitens* branches are scattered up the tree stem. Gunn (2000) stated that yield of framing and clear cutting grades of saw timber are affected by distance between clusters, and clear, knot free timber is obtained from stems with long internodes (Raymond & Cotterill, 1990). Tree genetics can influence internode length, however Waghorn (2006) and Gee (2002) found that internode length was not affected by stocking.

3. Objectives

This study of young trees in a Nelder experiment aims to:

- Assess the effect of stocking on tree form and branching
- Compare tree form and branching habits between *Pinus radiata* and *Eucalyptus nitens*
- Determine whether or not *Pinus radiata* physiological age has affected tree form and branching

4. Methods

4.1 Experiment overview

The Rolleston Nelder experiment was set up by Euan Mason of the Canterbury University School of Forestry in 2007/2008. It consists of 24 rows of *P. radiata* and 21 rows of *E. nitens* planted at stockings ranging from 271stems/ha to 40,466stems/ha. The *P. radiata* is made up of two different physiological ages – from cuttings from one year old parents and cuttings from five year old parents.

The experiment was designed to compare the performance of *P. radiata* and *E. nitens* planted at a range of initial stockings in the Canterbury plains, and to determine if physiological age has any effect on *P. radiata* growth characteristics.

4.2 Experiment Site

The Rolleston Nelder is situated on Selwyn District Council land approximately 18km south west of Christchurch (latitude 43^{0}37.1' S, longitude 172^{0}20.5' E), New Zealand (Appendix 1). The region is dry and known for droughts and windy conditions in the summer. Frosts are common in the winter months and snow occasionally settles. The site is surrounded by *P. radiata* experiments with the North-east border in pasture, meaning that it is sheltered from the potentially damaging North-west winds. The predominant soil type is Lismore stony silt loam soil (Landcare Research, 2010), and there is a mean annual precipitation of 650mm. The experiment was established on land that was previously in pasture.

4.3 Experiment Design

The Rolleston Nelder consists of 45 spokes separated by eight degree intervals in 21 circular rings. Rings 1 and 21 were not included in the data as they are not under complete competition as they only had neighbours on one side, and so acted as buffer rings. This meant that a total of 19 trees were measured in each row (spoke), each with initial stockings as illustrated in Table 1.

Table 1: Rolleston Nelder ring spacing and stocking

Ring no	**Ring Spacing (m)**	**Ring Stocking (stems/ha)**
Buffer	0.43	**-**
1	0.50	40466
2	0.57	30639
3	0.66	23198
4	0.75	17564
5	0.87	13298
6	1.00	10069
7	1.15	7623
8	1.32	5772
9	1.51	4370
10	1.74	3309
11	2.00	2505
12	2.30	1897
13	2.64	1436
14	3.03	1087
15	3.48	823
16	4.00	623
17	4.60	472
18	5.29	357
19	6.08	271
Buffer	6.99	-

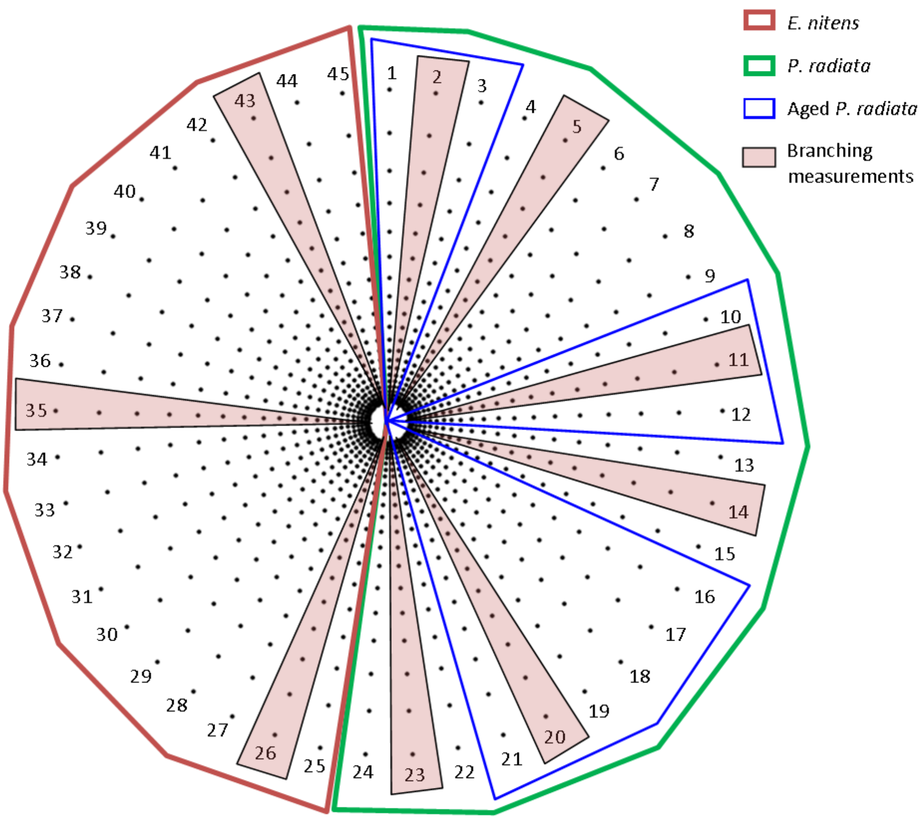


Figure 2: Nelder measurement components

Of the 45 rows, 24 rows are *P. radiata,* which were planted in 2007. The remaining rows are *E. nitens* (Figure 1) and these were planted a year later in 2008. Half the *P. radiata* trees planted were from cuttings with one year old parents, and half were from cuttings with five year old parents (rows encased in blue in Figure 1). Tree form was measured on all the trees from all 45 rows. However, branching was only measured on a selection of rows due to time constraints. In order to get a representative sample, three rows of *E. nitens* were measured and three rows from each of the physiological age classes in the *P.radiata* were measured in pairs. When selecting which of the physiological age class rows to measure, the middle rows in the tripe row age treatments were selected to ensure the neighbouring trees were of the same physiological age (Figure 1).

Genetics of the two different physiological *P. radiata* ages are very similar with identical GF ratings and very similar GF + ratings (Table 2).

Table 2: Genetics of two physiological age seed lots

				GF + Ratings					
parent age	# of parents	# of crosses	GF	Growth	Straightness	Branching	Dothistroma	Wood density	Spiral grain
1 year	43	66	24	22	20	22	18	23	21
5 years	10	9	24	22	21	22	20	26	21

4.4 Data Collection

4.4.1 Tree form measurements

For the purpose of this experiment, tree form refers to height, DBH, crown width and crown depth. Tree form measurements were collected from all trees within the Nelder experiment.

Height of trees was collected using a height pole to the nearest ten centimetres. The maximum the height pole could reach was 9.3 metres, so for any trees taller than this a vertex and transponder were used. DBH was collected using a diameter tape 1.4 metres up the tree stem, which was to the nearest millimetre. Where branching or swelling occurred at 1.4 metres, measurements were taken above and below the 1.4 metre height and averaged to gain a more representative measure of diameter.

Crown width was measured using a height pole for wide crowns and a one metre ruler for more condensed trees (generally in the areas of higher stocking). For each tree, the distance from the stem to the edge of the crown was measured. This was taken at four points around the tree, along the experiment spokes and at right angles to the spokes. An average of the four measurements was obtained, and this value was used for analysis.

Crown depth is the length of the live crown from the top of the tree to the first live branch. Crown height was measured as the distance from the ground to the first live branch using a height pole to the nearest ten centimetres. Crown depth was then calculated as height of the tree minus crown height.

4.4.2 Branch measurements

Of the selected trees, the diameter, height from ground, angle and survival of each branch between 0.2 metres and 2.2 metres was recorded. Below 0.2 metres was considered irrelevant as this would be below stump height, and above 2.2 metres was considered too time consuming and a safety hazard as a ladder would be required. The branches in this zone are the most relevant to measure as they are the largest so far and will be the first branches pruned in a pruning regime.

The height of the branch from the ground was measured using a height stick to the nearest five centimetres. In many cases there were a number of branches at one height which is known as a whorl, particularly for *P. radiata.* From this, the distance between these nodes was calculated and averaged for each tree, giving an average internode length per tree.

Diameter of each branch was measured to the nearest millimetre using a pair of electronic callipers. This was measured between one and three centimetres from the tree stem to avoid the branch collar. Any branch with a diameter less than five millimetres was not recorded. Branch angle from horizontal was measured along the first ten centimetres of the branch to the nearest five degrees using a clinometer. It was also noted for each branch whether it was alive or dead, and from this branch survival was calculated at each stocking for each species.

4.5 Analysis

4.5.1 Tree Form

The initial analysis consisted of linear regression modelling to see if stocking had an effect on dependent variables (DBH, height, crown width and crown depth) for the overall data set (both species). The effect of species was then included to see if this had a significant effect on each of the dependent variables.

Any bias in the models was examined by plotting the residuals against the predicted values, and in order to remove any curvature and reduce heteroscedasticity, scaled power transformation were applied to crown width, DBH and *E.nitens* height:

$$y_i^{(\lambda)} = \begin{cases} \dfrac{y_i^{\lambda} - 1}{\lambda}, & \text{if } \lambda \neq 0, \\ \log(y_i), & \text{if } \lambda = 0. \end{cases} \quad (1)$$

For *P. radiata* height, a double exponential model was applied where height (H) was described as a function of stocking (S = stocking/200) using the equation:

$$H = a \times S^{b \times S^{C}} \quad (2)$$

Where a = 6, b = 0.5, c = -0.95

For *P. radiata*, the effect of aging was analysed by representing aging as a dummy variable.

4.5.2 Branching

Linear regression modelling was carried out to examine the effects of stocking and species on the following dependent variables: angle, diameter, mortality and average internode length. Other relevant variables were also investigated to see if they had any effects, such as height from the ground. From branch survival data, percentage survival at each stocking was calculated and used to analyse branch survival across stockings and between species.

The effect of aging for *P. radiata* was also analysed as well as the effect of stocking by employing a dummy variable to represent aging.

5. Results

5.1 Tree form

5.1 .1 Tree form - both species

Spacing had a significant influence on tree height, DBH, crown height and crown width with p-values <0.001 for all variables (Appendix 2). Height (Figure 2a) decreased as stocking increased for *E. nitens*, with average height dropping from 8.9m at 271 stems/ha to 8.0m at 2,505 stems/ha (Appendix 3). Beyond this, there was a consistent decline as stocking increased. Height increased for *P. radiata* as stocking increased from 6.4m at 271 stems/ha to 7.5m at 1897 stems/ha, but beyond this stocking there was a depression in height. A similar pattern was observed for crown depth for *P. radiata* (Figure 2c). Average crown depth increased from 6.3m at 271 stems/ha to 7.3m at 2505 stems/ha, then declined after this stocking. *E. nitens* crown depth consistently decreased, and is deeper than *P. radiata* until 1087 stems/ha from where *P. radiata* crowns are deeper. DBH (Figure 2b) declined at a fast rate as initial stocking increased, but this rate slows as initial stocking increased. This is the case for both species, but it is clear that *P. radiata* DBH is larger than *E. nitens* overall. Crown width rapidly decreased for both species as initial stocking increased, but this also flattens out as initial stocking becomes very high. Figure 2d also shows that *E. nitens* have wider crowns than *P. radiata.*

It was found that species has an effect on DBH and height and the interaction between stocking and species had a significant effect on crown depth (Appendix 2). Species did not have a significant effect on crown width, which indicates that stocking is the only variable that affects crown width. Analysis of this relationship found an amount of curvature in the residuals, so a scaled power transformation was performed in order to create a non-linear model. This improved the residuals significantly (Appendix 4), with a final model being created (Table 3). This model shows that the coefficient, intercept and overall model are all significant, with the stocking explaining 83% of the variation in crown width.

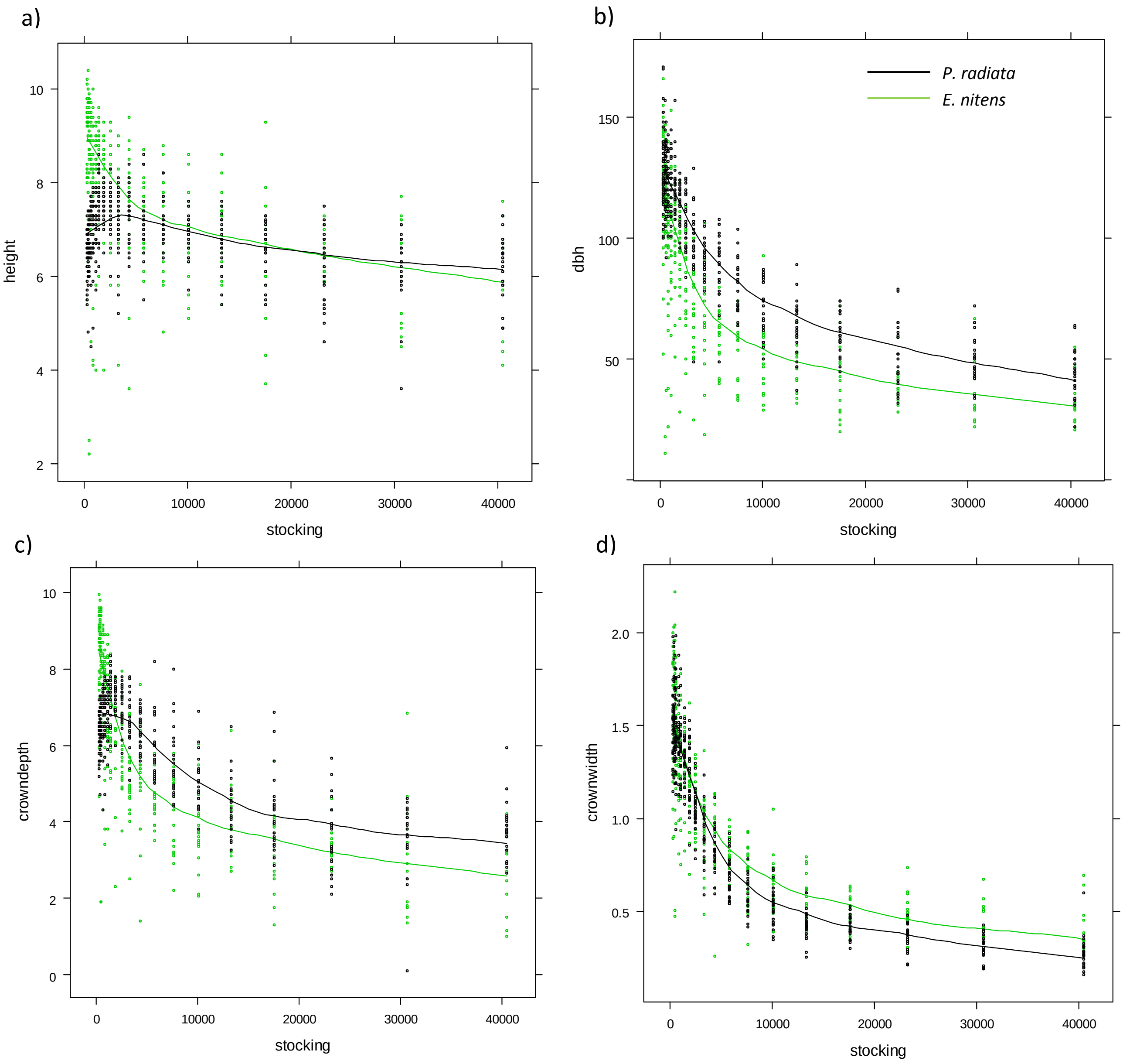


Figure 2: Tree form trends with stocking by species for a) height b) DBH c) crown depth d) crown width

Table 3: Summary statistics for crown width relationship with stocking using scaled power transformation

	Coefficient	t value	p-value	λ
Intercept	3.141	61.99	<0.001	1.1
stocking	-0.536	-62.82	<0.001	-0.08

Overall relationship	
p value	<0.001
r squared	0.827

5.1.2 Height

The relationship between stocking and height was significant for both species. Stocking explained 17% of variation in *P. radiata* in the general linear model, and 27% of the variation in height for *E. nitens.* Equation 2 was applied in order to improve the fit, and the residuals improved significantly (Appendix 5). Figure 3 shows how Equation 2 fits the raw data very well, so it is an appropriate model to use. The new model is also significant (p-value <0.05), along with each predictor being statistically significant (Appendix 6).

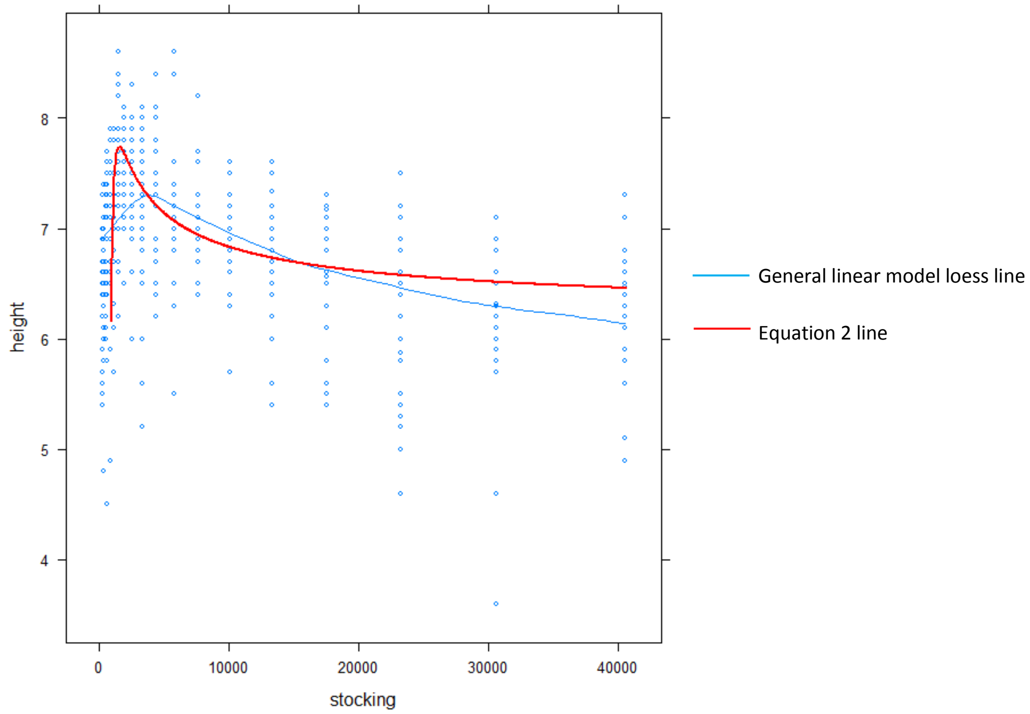


Figure 3: Loess smoothing line and Equation 2. Equation 2 is $H = a \times S^{b \times S^{c}}$

A scaled power transformation was applied to *E. nitens,* which also significantly improved the residuals (Appendix 7). This transformation improved the fit with 40% of the variation in *E. nitens* height being explained by stocking.

Table 4: Summary statistics for *E.nitens* height relationship with stocking using scaled power transformation

	Coefficient	t value	p-value	λ
Intercept	144.9	23.35	<0.001	0.8
stocking	-17.73	-15.66	<0.001	-0.1

Overall relationship	
p value	<0.001
r squared	0.4

5.1.2 DBH

The relationship between DBH and stocking was significant for both species. Bias in the residual plots and the shape of the curves in Figure 2b indicates that a non-linear transformation was appropriate for both species. A scaled power transformation was applied to each species separately, and this improved the fit of the residuals and removed any bias in the form of curvature (Appendix 8 & 9). The transformed models are highly significant (Table 5) and stocking accounts for 84% of the variation in DBH of *P. radiata*. Stocking accounts for 65% of the variation in DBH of *E. nitens*. The scaled power transformation showed that although the intercept for the *P. radiata* model was much higher than the *E. nitens* model (1082 compared with 61.46), the rate at which DBH declined as stocking increased is much faster.

Table 5: Summary statistics for DBH relationship with stocking using scaled power transformation a) *P. radiata*, b) *E. nitens*

a)

	Coefficient	t value	p-value	λ
Intercept	1082	77.68	<0.001	1.4
stocking	-51.04	-48.40	<0.001	0.1

Overall relationship	
p value	<0.001
r squared	0.838

b)

	Coefficient	t value	p-value	λ
Intercept	61.46	38.93	<0.001	0.6
stocking	-7.494	-26.02	<0.001	-0.1

Overall relationship	
p value	<0.001
r squared	0.647

5.1.3 Physiological Aging

Physiological aging was not significant for height, DBH, crown depth or crown width (Table 6). This analysis indicates that physiological aging has no effect on any aspects of tree form in *P. radiata*.

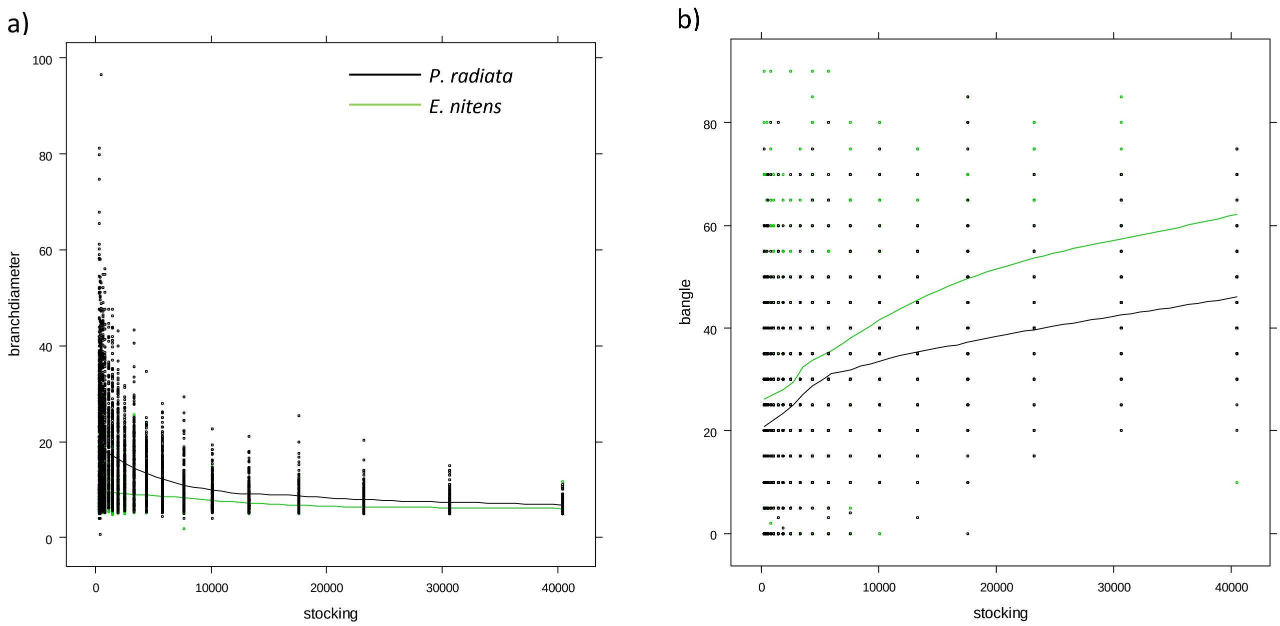
Table 6: Effect of physiological aging on tree form

Tree form aspect	p value
Height	0.13
DBH	0.06
Crown depth	0.11
Crown width	0.91

5.2 Branching

The interaction between stocking and species was significant for both branch diameter and branch angle. As stocking increased, *P. radiata* branch diameter decreased, but this trend is not as obvious for *E.nitens* (Figure 4a). It is also clear that *P. radiata* branches are bigger, especially in lower stocked areas. Branch angle increased as stocking increased for both species (Figure4b); however *E. nitens* branch angle is steeper than *P. radiata,* and increased at an increasing rate as stocking increased.

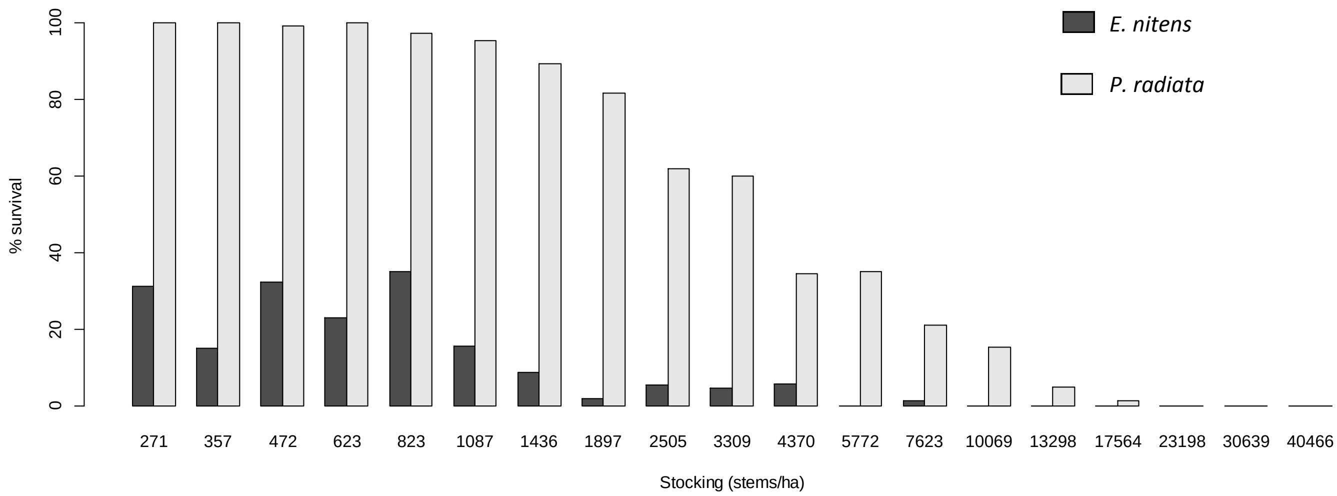
Figure 4: Branching trends with stocking for a) diameter b) angle



5.2.1 Survival

Interactions between stocking and species were significant for branch survival. Branch survival in *E.nitens* is noticeably different to that in *P. radiata* (Figure 5). For *P. radiata,* there is a 100% survival rate at lower stockings, with survival decreasing from 823 stems/ha. This is dissimilar to the distribution of branches in the *E.nitens.* At high stockings only approximately 30% of branches are alive, and this diminishes as stocking rates increased. Height of the branch from the ground also had a significant effect on branch survival (p value < 0.001) with branch survival increasing as you moved up the stem.

Figure 5: Branching survival across a range of stockings for both species



There is a correlation between survival of branches and stocking (Table 6) for both species. However, the χ^2 value for *E.nitens* is much lower than that of *P.radiata,* indicating that stocking and branch survival are correlated, but to a lesser extent than for *P. radiata.*

Table 7: χ^2 test for stocking and branch survival

	χ^2	df	p value
P.radiata	2291	18	<0.001
E.nitens	195.4	18	<0.001

5.2.2 Internode Length

Interactions between stocking and species were significant for internode length (Appendix 2). *P. radiata* internode length is much longer than *E.nitens,* but this is to be expected because branches are not in nodes like they are on *P .radiata,* and are scattered up the stem. Average internode length increased as stocking increased (Figure 6); however the distance is still relatively small. Average internode length varied from only 0.22m at low stockings to 0.31m at high stockings (Appendix 10).

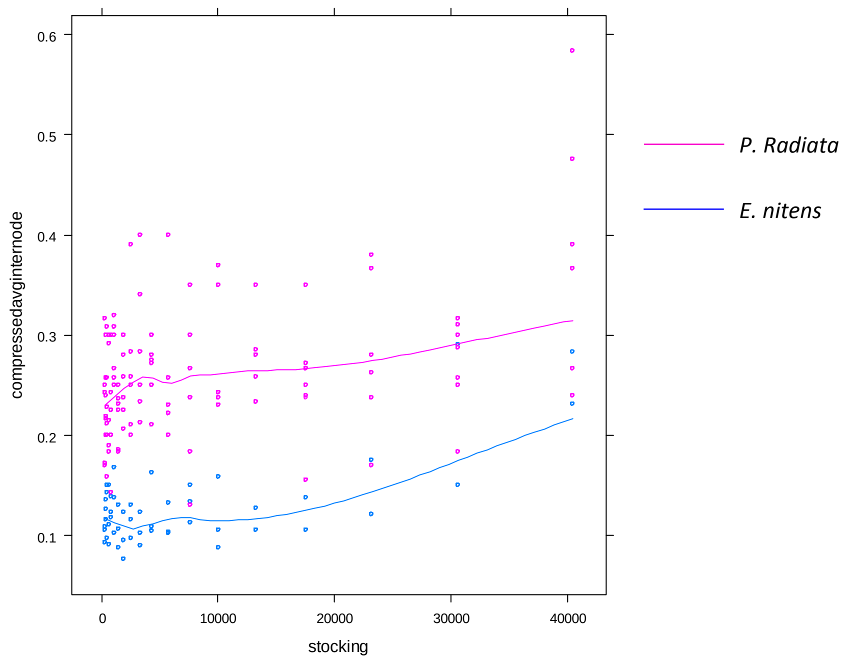


Figure 6: Average internode length trend with stocking for both species

5.1.3 Physiological Aging

Physiological aging did not have a significant effect on mortality, average internode length, branch diameter or angle (Table 8). This analysis indicates that physiological aging has no effect on any aspects of tree form in *P. radiata*.

Table 8: Effect of physiological aging on branching

Variable	p value
Mortality	0.08
Average internode length	0.08
Branch diameter	0.35
Branch angle	0.86

6. Discussion

6.1 Tree height

Species and stocking significantly affected height in the Nelder trial. *E. nitens* height dropped as stocking increased, which contrasts with Cairns (1986) who found that stocking did not have an effect on *E. nitens* mean height. Waghorn (2006) found no relationship between *P. radiata* heights and initial stocking, but my results found stocking was significant. Maclaren et al. (1995) found that mean top height increased with increasing stocking; however his experiment only tested up to 800 stems/ha, and this was with a consistent selection ratio. The results from my analysis found that height increased until a stocking of 1897 stems/ha, but as stocking increased after this, height decreased. There have been few experiments which include stockings as dense as this trial; however Sjolte-Jorgensen (1967) found that mean tree height decreased in extremely high stockings, which is consistent with my results. Because so few trials with stockings this high have been undertaken, there is little known as to why this phenomenon occurs.

6.2 DBH

In this trial, DBH significantly decreased as a function of stocking for both species, but DBH was consistently larger for *P. radiata* throughout the stockings. This is consistent with Lanner (1985) who stated that diameter increment is often the first type of growth to be affected by competition. This trend was also found by Waghorn (2006), Mason (2004), Cairns (1986) and Fearon (1997). Once stocking reached a certain level, the trees were under complete competition (canopy closure) so the rate at which DBH decreased as stocking increased began to decrease. As there is no literature that suggests that *P. radiata* trees have larger DBH's than *E.nitens*, it is unknown as to whether the size difference found between species was a result of the two different species or because the *P. radiata* were a year older than *E.nitens.*

6.3 Crown Depth

Crown depth significantly decreased as a function of stocking for both species, but varied slightly between the two species. Beekhuis (1965), Waghorn (2006) and Neilson & Gerrand (1999) found that crown depth decreases with increasing stocking, and this was clear for *E. nitens* throughout the stockings. However, *P. radiata* crown depth increased slightly as stocking increased at the lower stockings, but decreased as expected from a stocking of 1463 stems/ha. A similar pattern was observed for tree height. Because crown depth is calculated from tree height, this could have influenced the pattern observed for crown depth.

6.4 Crown Width

This study found that crowns were wider in lower stocked rings. Little research into crown width has been undertaken, but this result is consistent with the theory of Waghorn (2006), who stated that less foliage is carried on each tree at high stockings due to crown competition. Stocking had a significant effect on crown width; however species did not have a significant effect on crown width. This indicates that the space between the trees is a primary factor which influences how wide a crown can be. This makes sense as there is only enough space for the crown to expand, regardless of what species it is. Other factors such as genotype or fertility could have influenced crown width, but these were not analysed. It was interesting to find that species was not significant with *E. nitens* trees being crown shy. This characteristic could cause *E. nitens* crowns to be more sensitive than *P. radiata,* but this study did not show crown width differing between species.

6.5 Branch Size

Overall, stocking caused branch size to significantly decrease, but losses were larger in *P. radiata*. Moreover, even after controlling for DBH, the branches were still larger. The rate at which branch size decreased was much faster for *P. radiata,* particularly at the lower stockings. These findings are consistent with research conducted by Gunn (2000), Gee (2002), Waghorn (2006) and Neilsen & Gerrand (1999). While little research has compared branch size between the two species, these results could have been influenced by the age difference between the species, as the *P. radiata* was one year older than *E. nitens.* One year's growth can make a big difference in branch size, especially when the trees are still young.

These findings regarding the effect of stocking on branch diameter have important implications for managers. Larger branches create larger knots in timber, decreasing strength and stiffness of the wood (Bier, 1986), which lowers the value of the wood. This is also backed up by Alcorn et al. (2007), who stated that high quality timber can be produced by minimising or eliminating knots. Larger branches also and take longer to prune, so silvicultural costs can be increased. Net revenue can be increased by increasing the value of wood and decreasing silvicultural costs, and smaller branches could potentially drive this. This can be promoted by planting at higher initial stockings; however these high initial stockings will affect other growth characteristics.

6.6 Branch Angle

Stocking caused branch angle to increase, with larger branch angles found in *E. nitens.* Little research has been undertaken for branch angle; however the findings are supported by Gee (2002), who also found that branch angle increased with increasing stocking. There is a large amount of variance in the angle data, with a number of extreme branch angles recorded.

Although the trees were measured at a young age, there is evidence that some of the branch angle habits will have implications for managers. Branches with large angles can produce problematic knots and are harder to prune. Because of this, breeders prefer branches at right angles to the stem (Raymond & Cotterill, 1990). If thinning occurs around trees which have large branch angles, this could accentuate the problem by allowing these problematic branches to grow larger. Lower initial stockings may encourage branches at right angles to the stem, but these lower stockings will also affect other characteristics such as branch size.

6.7 Internode Length

Internode length significantly increased as a function of stocking for both species. This is in contrast with Gee (2002) and Waghorn (2006) who found that internode length was not affected by stocking. It was also found that internode length was much lower for *E. nitens,* but this was not a surprise as *P. radiata* has distinctively long internodes which separate the whorls of branches (Lavery, 1986). However, the internodes for *P. radiata* were only 0.26m on average, which is not useful when it comes to framing and clear cutting grades, where internodes of at least 0.6 m are desired. For the purposes of this report, branches were only measured to a height of 2.2 m. This does not provide an entirely accurate representation of internode length on a tree, and the relationship with stocking could have been a chance event. However, it clearly shows the difference in branching distribution between *P. radiata* and *E. nitens.*

6.8 Branch Mortality

The interaction between stocking and species had a significant effect on branch mortality, as did height up the tree. There has been little research into this, but the effect of stocking and height up the tree was also found by Alcorn et al. (2007), as green crowns rise earlier with increasing initial stockings. Branch mortality increased as stocking increase, and it was clear that branch mortality was much higher in *E. nitens,* with average percent survival being much lower even at low stockings. This could be due to the crown shy nature of *E. nitens,* where any touching of the naked buds can cause branch damage or mortality. However, at low stockings the trees weren't touching so this doesn't explain why mortality was so high in these rings.

As explained in the literature review, green pruning is preferred to dead branch pruning, especially in *E. nitens* as it retains dead branches and can leave kino traces (Pinkard, 2002). The apparent high mortality rates in *E.nitens* branches at this young age could create a need for early pruning, provided pruning is economically justified.

6.9 Physiological Aging

Physiological aging did not have any effect on tree form or branching in the Nelder experiment. Waghorn (2006) and Menzies et al. (2007) recommended confining physiological aging or 3 or 4 years in order to avoid diameter growth losses, so it is reassuring to see that DBH growth has not been affected by the older physiological age. Gee (2002) found branches with one year old cuttings had higher angles, than those from three year old cuttings, but these results do not show any difference between the aging treatments and branch angle. Because the trees in the trial are still young, it could be too soon to see any of the advantageous traits of physiological aging come through.

Although there was not any difference between the physiological ages, there may be some concern about genotype differences rather than aging differences because of the large number of parents. However when considering the law of large numbers, the large number of parents creates a large sample size, so it is more likely that they will converge to the average value.

6.10 Limitations

The following features of the study may have limited applicability of the findings reported here:

- There is a small amount of mortality throughout the *E. nitens,* with any dead or missing trees being excluded from the analysis. This means that not all the trees are under complete competition. Neighbouring trees to dead trees are able to use the resources from the space of the dead tree, so could possibly be larger than the typical tree at that stocking, changing the results. Further analysis could be undertaken into comparing the data with a 'perfect' dataset which only included trees which had all four competing neighbours, to see if the mortality had a major influence on tree form and branching.

- Trees in the middle of the experiment are not under complete light competition with an unplanted circle in the centre of the experiment. While measuring, it was evident that the first two or three rows from the middle had longer green crowns than the following trees further out the row.

- As pointed out earlier, branching was only measured up to a height of 2.2m. Although the trees are still young and some trends were coming through which will have implications for managers, measuring branching higher up the stem would be more beneficial for managers.

7. Conclusions

- Stocking and species significantly affected tree height
    - Height decreased with stocking for *E. nitens*
    - Height increased for *P. radiata* as stocking increased to 1897 stems/ha, then was followed by a depression as stocking increased beyond this
    - A scaled power transformation was applied to stocking and *E. nitens* height, improving the residual fit and eliminating bias
    - A double exponential model was applied to *P. radiata* height, which improved the residuals and eliminated bias

- Stocking and species significantly affected DBH
    - DBH decreased with increasing stocking
    - DBH was larger for *P. radiata*
    - A scaled power transformation was applied to stocking and both *P. radiata* and *E. nitens* DBH, which improved the residual fit and eliminated bias for both species

- Stocking and species significantly affected crown depth
    - Crown depth decreased as stocking increased for *E. nitens*
    - Crown depth increased for *P. radiata* as stocking increased to 2507 stems/ha, then decreased as stocking increased beyond this
    - Crowns were deeper for *E. nitens* until 1087 stems/ha, from which *P. radiata* crowns were deeper as stocking continued to increase.

- Only stocking had a significant effect crown width
    - Crown width decreased with increasing stocking
    - Crown width was larger for *P. radiata* at extreme stockings
    - A scaled power transformation was applied to stocking and crown width of both species. This improved the residual fit and eliminated bias for both species

- Stocking, species and height from ground significantly affected branch mortality
  - Branch mortality increased with increasing stocking
  - Branch mortality was significantly higher for *E. nitens,* particularly at low stockings
  - Branch mortality decreased as you moved up the tree for both species

- Stocking and species significantly affected internode length
  - Average internode length per tree increased with stocking
  - Average internode length much longer in *P. radiata*

- Stocking and species significantly affected branch size
  - Branch size decreased with increasing stocking
  - Branch size was larger for *P. radiata*

- Stocking, species and height from ground significantly affected branch angle
  - Branch angle increased with increasing stocking
  - Branch angle is higher for *E. nitens*
  - Branch angle increased as you moved up the tree

- Physiological age did not have a significant effect on tree form or branching

8. Acknowledgements

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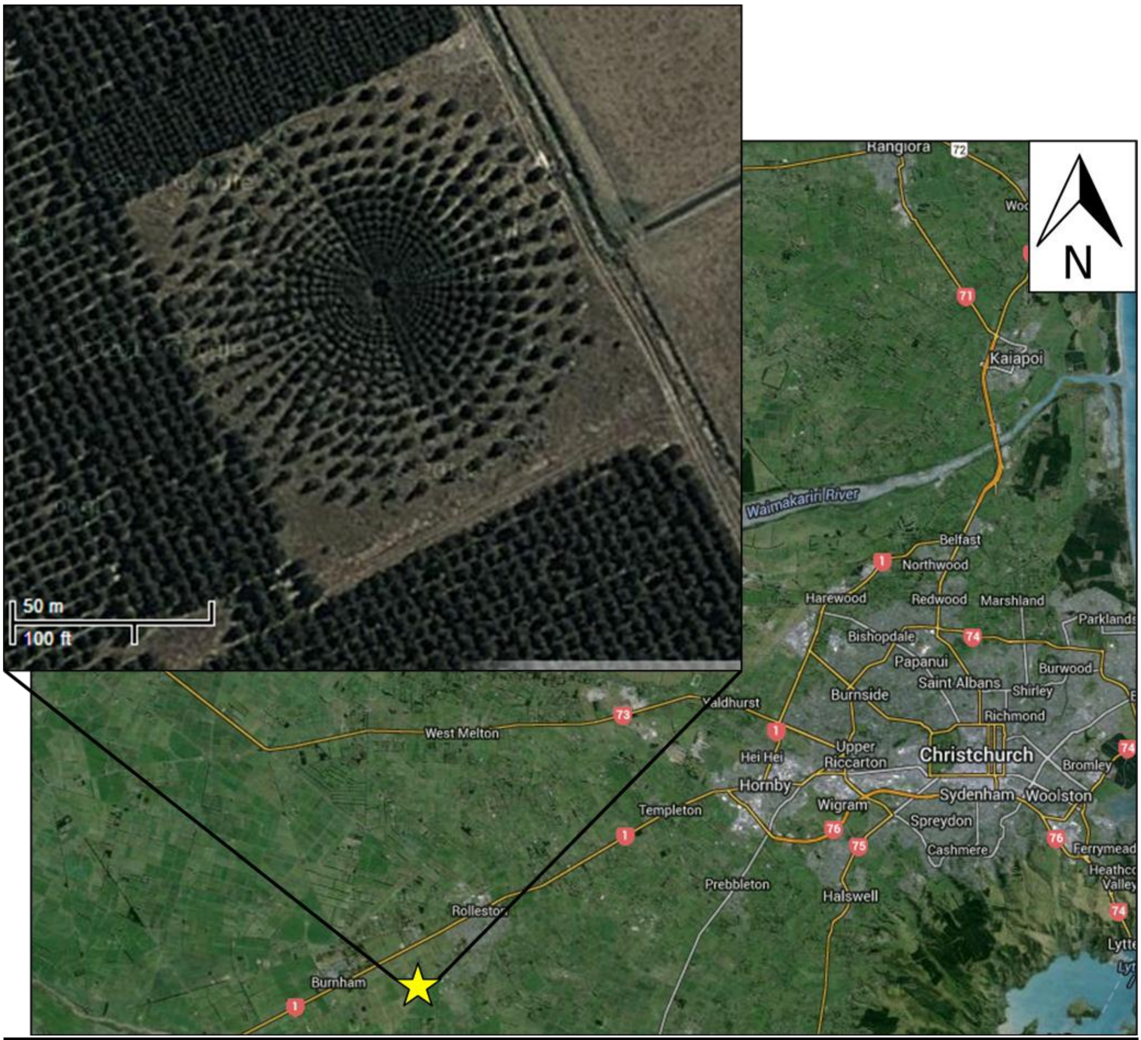
10. Appendix



Appendix1: Rolleston Nelder location

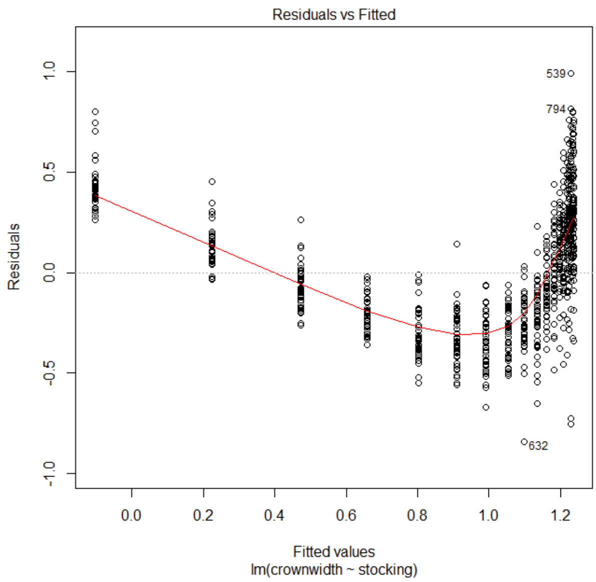
Appendix 2: Significant effects for tree form and branching

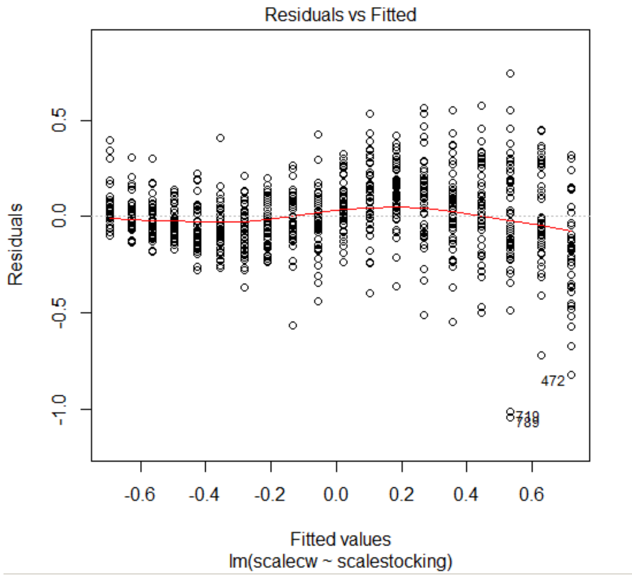
Variable	Significant Effect	P value
Tree height	Stocking	<0.001
	Species	<0.001
DBH	Stocking	<0.001
	Species	<0.001
Crown depth	stocking:species	<0.001
Crown width	Stocking	<0.001
Branch mortality	stocking:species	<0.001
	height from ground	<0.001
Average internode length	stocking:species	<0.001
Branch diameter	stocking:species	<0.001
Branch angle	stocking:species	<0.001
	height from ground	<0.001

Appendix 3: Tree form average values

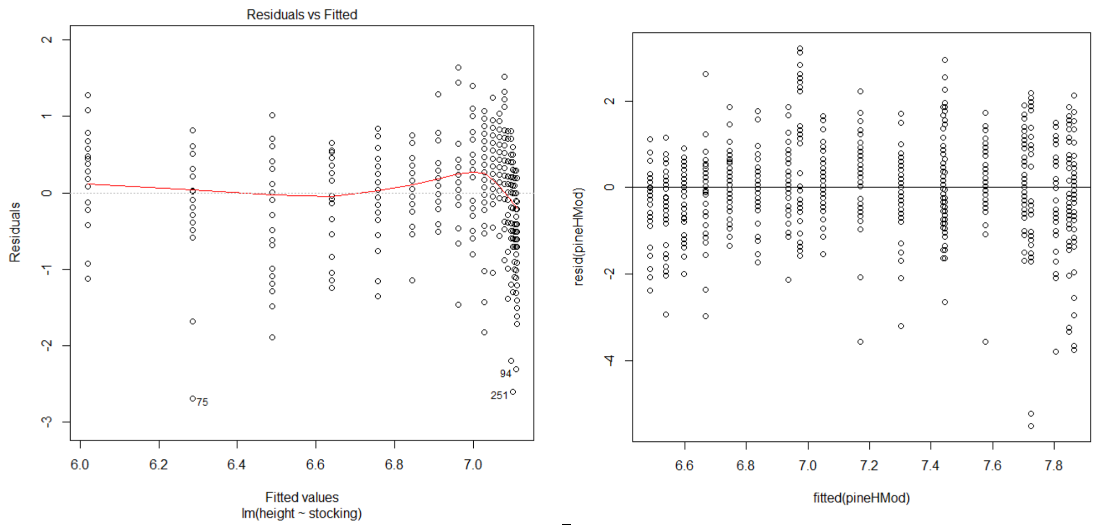
Stocking (stems/ha)	Height (m)		DBH (mm)		Crown Depth (m)		Crown Width (m)	
	P.radiata	*E.nitens*	*P.radiata*	*E.nitens*	*P.radiata*	*E.nitens*	*P.radiata*	*E.nitens*
271	6.48	8.92	125.6	119.6	6.36	8.37	1.53	1.49
357	6.53	8.90	133.3	124.7	6.41	8.53	1.66	1.55
472	6.72	8.36	127.7	115.9	6.59	7.90	1.48	1.51
623	6.97	8.45	126.0	108.0	6.81	7.92	1.49	1.45
823	6.98	7.80	123.7	94.2	6.84	7.02	1.30	1.48
1087	7.12	8.21	122.6	101.0	6.96	7.00	1.30	1.38
1436	7.52	8.40	121.1	99.0	7.34	6.70	1.28	1.34
1897	7.53	8.16	115.2	92.5	7.29	6.26	1.16	1.24
2505	7.47	7.98	107.2	84.2	7.04	5.88	1.11	1.05
3309	7.10	7.46	98.2	71.5	6.53	5.17	0.94	0.92
4370	7.33	7.53	92.5	69.5	6.42	5.23	0.90	0.82
5772	7.16	7.18	88.4	61.6	5.93	4.51	0.82	0.70
7623	7.17	7.13	79.9	55.5	5.55	4.25	0.70	0.58
10069	6.92	6.84	71.7	52.4	5.05	3.81	0.63	0.53
13298	6.69	6.98	63.2	49.1	4.40	4.00	0.58	0.43
17564	6.56	6.45	60.6	43.0	4.16	3.24	0.50	0.42
23198	6.14	6.46	51.5	40.0	3.54	3.36	0.47	0.35
30639	6.18	6.02	49.5	37.2	3.58	2.98	0.43	0.31
40466	6.18	5.98	43.8	33.2	3.72	2.80	0.40	0.28

Appendix 4: Linear model vs scaled power transformation residuals for crown width





Appendix 5: *P. radiata* height residual plots for linear model and Equation 2 transformation

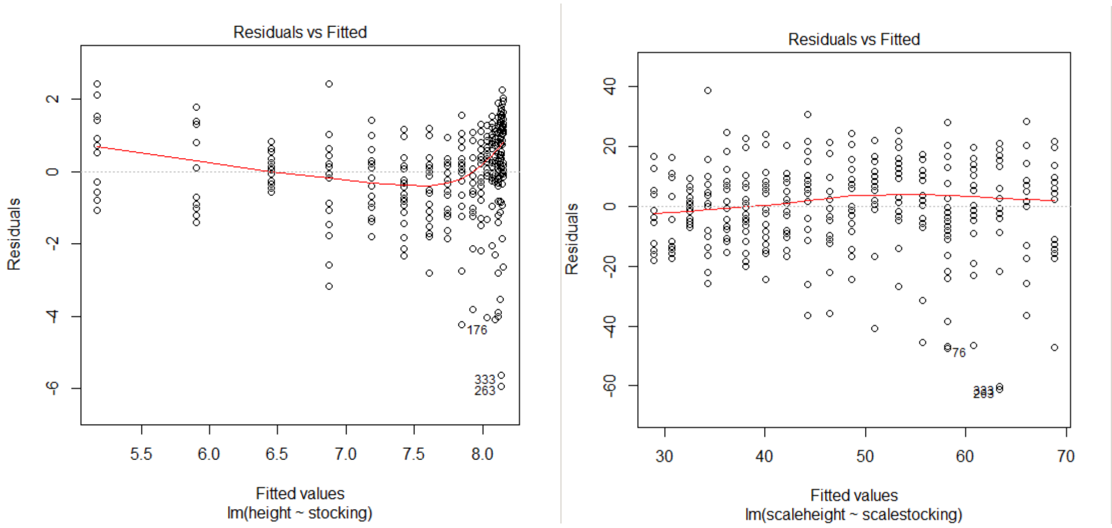


Appendix 6: Summary statistics for *P. radiata* relationship with stocking using Equation 2 transformation

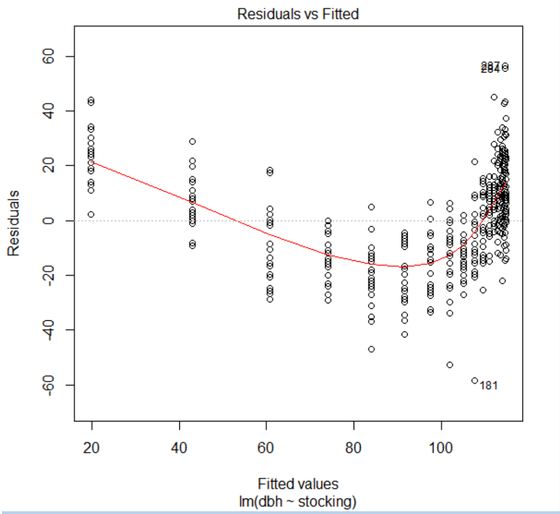
	Coefficient	t value	p-value
a	6.189	52.16	<0.001
b	0.495	12.29	<0.001
c	-0.758	-17.98	<0.001

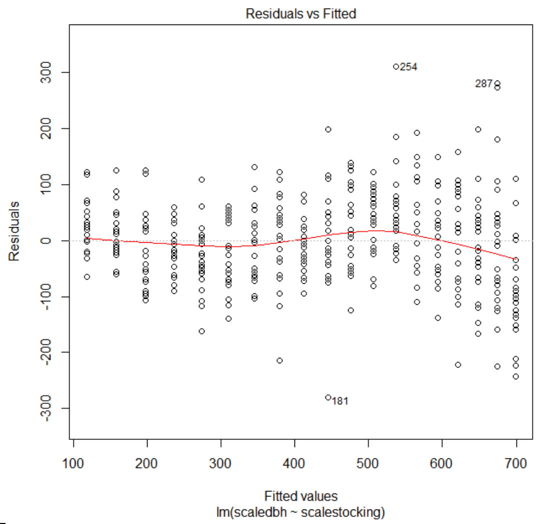
Overall relationship	
p value	<0.001

Appendix 7: *E. nitens* height residual plots for linear model and scaled power transformation

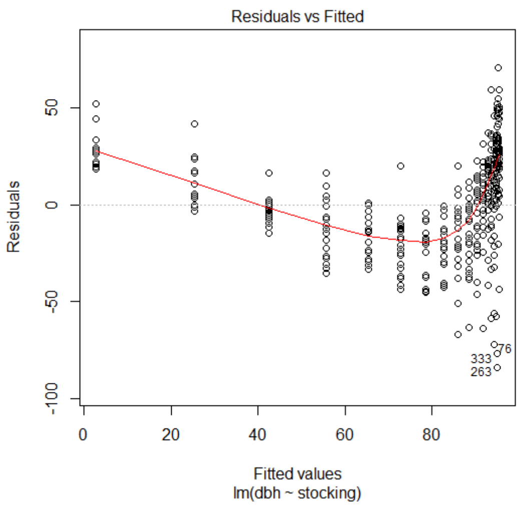


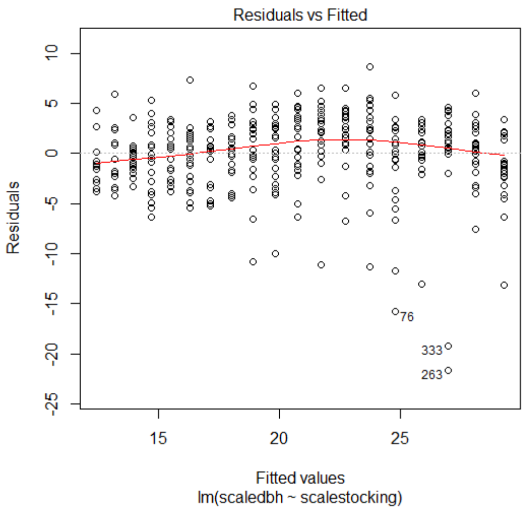
Appendix 8: *P. radiata* DBH residual plots for linear model and scaled power transformation





Appendix 9: *E. nitens* DBH residual plots for linear model and scaled power transformation





Appendix 10: Branching average values

Stocking (stems/ha)	Diameter (mm)		Angle (^{0})		Internode Length (m)		Survival (%)	
	P.radiata	*E.nitens*	*P.radiata*	*E.nitens*	*P.radiata*	*E.nitens*	*P.radiata*	*E.nitens*
271	23.8	12.7	23.6	30.1	0.22	0.10	100%	31%
357	23.0	11.1	20.7	22.9	0.23	0.13	100%	15%
472	22.5	13.7	25.5	30.8	0.23	0.13	99%	32%
623	22.4	11.0	24.4	20.0	0.25	0.11	100%	23%
823	19.5	11.2	18.4	33.3	0.22	0.13	97%	35%
1087	19.5	12.3	23.4	26.3	0.28	0.13	95%	16%
1436	18.6	10.7	20.8	31.9	0.22	0.11	89%	9%
1897	16.9	9.8	20.7	27.0	0.25	0.10	82%	2%
2505	14.5	9.6	24.8	27.1	0.26	0.11	62%	5%
3309	16.0	10.0	28.8	30.6	0.29	0.10	60%	5%
4370	13.2	9.7	29.9	39.9	0.26	0.13	34%	6%
5772	12.5	9.0	30.9	34.5	0.25	0.11	35%	0%
7623	10.9	8.3	35.5	35.9	0.25	0.13	21%	1%
10069	13.3	7.9	32.3	44.6	0.29	0.11	15%	0%
13298	9.0	7.1	36.3	41.9	0.27	0.12	5%	0%
17564	8.3	7.0	38.8	54.5	0.24	0.12	1%	0%
23198	8.5	6.5	38.9	56.6	0.29	0.15	0%	0%
30639	7.9	6.5	43.8	59.5	0.27	0.34	0%	0%
40466	6.8	6.5	45.4	55.9	0.40	0.25	0%	0%