Assessment of wood stiffness by species and aging: a Nelder experiment

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Abstract

Pinus radiata timber is inherently hindered by low stiffness due to high microfibril angle in the corewood zone. Determining how foresters can manipulate microfibril angle in plantation forests to increase stiffness is of high economic and silvicultural importance. A Nelder systematic spacing design in Canterbury was used to assess the stiffness and tree dimensions of 16-year-old *P. radiata* (n = 344) and 15-year-old *Eucalyptus nitens* (n = 211) at stocking levels ranging from 271 stems per hectare to 40,466 stems per ha. Using regression modelling independent variables species, aging and stocking were used to predict response variables outerwood stiffness, diameter at breast height (DBH) and tree height. Stocking, species and physiological aging had a significant effect on modulus of elasticity (MOE). Outerwood MOE significantly increased with increasing stocking for *P. radiata* up to 17,564 stems per hectare and up to 1,023 stems per hectare for *E. nitens* (P < 0.001). There was little stiffness gain in planting *E. nitens* at a greater stocking than 1,023 stems per hectare. By planting *P. radiata* at 2,505 rather than 823 stems per hectare, stiffness can increase by 14%. Stiffness was 41% greater for *E. nitens* however, *P. radiata* stiffness can be significantly (P < 0.001) increased by up to 1.2 GPa by planting physiologically aged clones. Stocking had significant effects on tree dimensions (P < 0.001) for both species: DBH decreased in an exponential trend, whereas tree height decreased more linearly. Physiological aging significantly affected DBH (P < 0.0067) but not tree height (P = 0.31). Wind direction was a significant predictor of MOE and as such standing tree stiffness should be measured on the windward and leeward sides of the tree to account for compression wood. At present, the potential of *E. nitens* as an alternative structural timber species is limited by its poor sawing and machinability due to growth stresses. However, the increasing trend of MOE seen with increasing stocking demonstrates that foresters have a lot of control over the stiffness of a tree crop through the choice and manipulation of stocking, seed stock and species.

Keywords: Pinus radiata, Eucalyptus nitens, outerwood modulus of elasticity, IML Micro Hammer, Nelder experiment, stocking, physiological aging, maturation status, wind, tree dimensions.

Table of Contents

List of Figures

List of Tables

List of Appendices

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1.0 Introduction

1.1 Wood quality

Pinus radiata (*P. radiata*) is the most common plantation species grown in New Zealand making up 90% of the total forest estate and covering nearly 1.6 million hectares (Ministry for Primary Industries, 2023). It is the most favourable plantation species for forest growers due to its good stem form and high growth rates, excellent machinability and high permeability.

There have been rapid advances in breeding and silviculture to improve *P. radiata* in New Zealand. While enhanced growth and form initially provided significant advantages in increased yield and shorter rotation lengths, they have been accompanied by a wide range of wood quality issues such as a larger proportion of corewood, increased branching and greater between-stem variability (Cown, 2005). Corewood has been said to constitute the first 10 annual rings from the pith at the base of the tree (Cown et al., 1991) but corewood has low utilisation for structural timber and its characteristics include high microfibril angle, low wood basic density, and greater grain spirality (Cown, 1992). Microfibril angle refers to the angle at which cellulose microfibrils are oriented with respect to the longitudinal axis of wood cells in the secondary cell wall (Walker & Butterfield, 1996). Wood basic density is the oven-dry weight divided by the green wood volume and is a common indicator of wood quality as it correlates with stiffness and pulp yield (Kimberley et al., 2015). Spiral grain is commonly expressed as the angle at which wood fibres or tracheids are oriented in relation to the longitudinal axis of the stem and correlates with poor wood utilisation and drying (Moore, Cown, & McKinley, 2015). Timber containing corewood negatively impacts end product value due to the aforementioned aspects causing low stiffness and increased longitudinal shrinkage (Zobel & Sprague, 2012).

For *P. radiata* the microfibril angle is highest, about 35 to 45°, in the corewood close to the pith and decreases rapidly toward the outerwood as the tree matures, typically 5 to 20° (Donaldson, 1992, 2008; Moore et al., 2014; Walker & Butterfield, 1996). Outerwood microfibril angle is much more stable than corewood microfibril angle and changes in stiffness occur at a slower rate from pith to bark (Walker & Nakada, 1999). It is widely understood that a high microfibril angle is directly correlated with low stiffness (Walker, 2006). Influencing the wood quality of *P. radiata* timber comes down to reducing the initial microfibril angle as this will have a downstream effect on decreasing the microfibril angle of outerwood in which a large proportion of structural timber will be utilised. While the main forest management objective of large-scale forestry companies is increasing site productivity, it is thought that increased growth rates adversely affect microfibril angle and thus stiffness (Dumbrell & McGrath, 2000; Herman et al., 1999; Sarén et al., 2004; Watt et al., 2011). However, this has been shown to be false and the only way to influence the microfibril angle and stiffness of *P. radiata* is through silviculture and tree breeding (Mason, 2023), which this study will explore.

Conversely, hardwoods have quite a low microfibril angle typically around 10° in *Eucalyptus spp.* (de Lima Melo et al., 2018; de Souza et al., 2021). This means *Eucalyptus spp.* are expected to be stiffer than softwoods. However, *Eucalyptus spp.* and most angiosperms are hindered in wood processing by prominent growth stresses which cause end-splitting, checks, warp, collapse and high shrinkage (Balasso et al., 2022b; Derikvand et al., 2017; Rozas et al., 2023; Suontama et al., 2016; Yang & Waugh, 2001). Growth stresses help trees survive and restore vertical growth by controlling the orientation of their limbs in space (if asymmetric), increasing their bending strength (by prestressing the outside of the tree axially in tension will increase compression strength which is 2 to 3 times lower than tension strength), and helping avoiding fracture by closing wounds with the outside in compression in tangential direction (Alméras & Clair, 2016). Gymnosperms also have growth stresses, but they are smaller (typically not causing problems); and their reaction wood works the other way (compression rather than tension) compared to that of most angiosperms (Alméras & Clair, 2016). Growth stresses influence microfibril angle, where tension wood in angiosperms have a low microfibril angle and gymnosperms have a high microfibril angle (Alméras & Clair, 2016). This study will help determine whether foresters can use spacing to influence the microfibril angle of *E. nitens* and in turn increase stiffness.

1.2 Stiffness

Stiffness, commonly expressed as modulus of elasticity (MOE) or Young's Modulus, is a measure of resistance to bending of a material (wood) in response to an applied load. For structural applications, wood with higher stiffness has greater utilisation in construction. Producing stiffer wood will also help New Zealand increase the use of wood products in midrise or commercial construction by 25% by 2030 (Ministry for Primary Industries, 2022). The majority of lumber made from *P. radiata* in New Zealand usually meets stiffness specifications for machine stress grade (MSG) 8, typically used for structural applications (Bayne, 2015; Moore, Cown, McKinley, et al., 2015). However, higher timber grades such as

MSG10 are much harder to achieve with *P. radiata* but easily achieved with alternate species such as *Eucalyptus* (Cown, 2005; Warren et al., 2009). For New Zealand to maintain its competitiveness in the global structural timber market, it is imperative that we enhance the stiffness of wood, aligning with the ability demonstrated by Australian and Chilean *P. radiata* plantations to meet MSG10 stiffness requirements (Bayne, 2015). Moreover, *P. radiata* structural timber exhibits lower average strength and stiffness compared to European and North American timber species (Moore, 2012).

Unpruned and unthinned forest area made up 55% of the total *P. radiata* forest estate as of 2022 (Ministry for Primary Industries, 2023) and that statistic is increasing each year. This emphasises the importance of planting an improved seed stock at an optimal spacing to improve stiffness in our minimally tended forests. A structural log index has been suggested by Mason (2012) to increase the value of structural regimes through more effective silvicultural planning as currently there is little understood about what or which processes lead to the low stiffness of timber. Understanding how to manage these unpruned forests for structural timber production is of high industry importance (Bayne, 2015; Cown, 2005). Moreover, assessing wood properties prior to processing for increased stiffness is valuable for forest owners (Apiolaza et al., 2013; Cown, 2005; Harris & Andrews, 1999; Mason, 2012).

Forest investments are unique in that a majority of the costs of investment are in the establishment and tending phase a long time before any income is earned (Hughes & Wong, 2021). A report by Sorensson and Shelbourne (2005) revealed a non-linear relationship between stiffness and timber value, emphasising the substantial financial penalties incurred when the stiffness thresholds of MSG6 and MSG8 are not met. Moreover, they also stressed the importance of improving value through manipulating stand density and the use of physiologically aged seed stock. Physiological aging or maturation status is the concept where cuttings are taken from older trees and then grown in a nursery. This makes the 1- and 5-year-old cuttings in this study different in chronological age (time grown from seed) (Menzies et al., 2000). The expectation is that the aged cuttings should have better wood properties because older trees have increased stiffness (Moore et al., 2018; Toulmin & Raymond, 2007; Waghorn et al., 2007; Watt et al., 2011). Therefore, the outcomes of this study should influence the way foresters use stand density and tree stock to increase the stiffness and value of their tree crop.

1.3 Acoustic tools

To understand why foresters use acoustic tools to measure the stiffness of standing trees, it is important to understand how to grade timber. Stress grading methods for structural timber in New Zealand are qualified using standard AS/NZS 1748.2 (Standards New Zealand, 2011). Qualification is defined as a process for demonstrating the ability of a grading method to reliably allocate structural timber to a specified stress grade(s) prior to the normal commercial use of the grading method. There are two qualified grading methods: mechanical stress grading and customised grading. The method for mechanical stress grading is set in accordance with AS/NZS 4063:1992 or AS/NZS 4063.2 (Standards New Zealand, 1992, 2010). While it is permissible to evaluate the highest and lowest grades and the largest and smallest sizes, and then interpolate for intermediate grade/sizes (extrapolation is not permitted), the procedure requires that timber be kiln dried and fully dressed and a destructive static four-point bending test undertaken. Sawmills are unlikely to use this procedure as it is cost-ineffective and time-consuming.

Acoustic tools are an example of a non-destructive evaluation (NDE) method where the mechanical properties of wood, in this case stiffness, are identified without altering its end-use capabilities. There are two acoustic methods used for measuring stiffness in wood: transit time and resonance. Transit time is also known as the time of flight (ToF) method. ToF tools measure the time it takes for an induced stress wave to travel from one point to another. Typically, this is between two transducers that are attached to the tree, separated by d (meters) in the tree’s longitudinal direction. By measuring the ToF (t) in seconds taken for the stress wave to travel to the upper transducer, the wave’s speed (v) in meters per second can be calculated using Equation 1.

$$v = \frac{d}{t} \tag{1}$$

Resonance tools are used by inducing a stress wave at one end of the specimen and measuring the time it takes for the stress wave to travel from one end to the other end. This stress wave is reflected back and forth from end to end until the signal can no longer be detected.

There are distinct uses, advantages and disadvantages associated with each acoustic measurement approach. ToF tools represent the most practical acoustic method available for measuring MOE in standing trees, but they only measure the velocity in the shortest distance between probes, and so mean velocity throughout a stem is not assessed. On the other hand, resonance tools exhibit a higher level of accuracy and measure mean velocity throughout a log. However, they are not suitable for standing tree measurement, as they require access to the ends of the log. In practical field applications, resonance tools are well-suited for assessing log stiffness on skid sites, and within sawmills as they accurately determine the stiffness of green lumber. Both acoustic methods are simple and compact, with minimal training required for operation (Dickson et al., 2003). By establishing statistical correlations between the stiffness of standing trees and that of lumber in the sawmill, forestry professionals can effectively map stiffness variations between trees. This valuable information aids in harvest scheduling, log allocation decisions, and determining the value of each stand based on the mean MOE of the expected structural lumber yield. Such data-driven insights empower foresters to optimise their approaches and enhance overall efficiency in the utilisation of timber resources.

Intrumenta Mechanik Labor (IML) originally developed the IML Micro Hammer to locate and measure decay in trees. In the study described here, the IML Micro Hammer was used to measure the acoustic velocity in standing trees by utilising the strong correlation between stress wave velocity and MOE (Matheson et al., 2002). MOE is calculated using a fundamental equation (Equation 2) that utilises Young's Modulus where MOE is stiffness, ρ is green density and V^2 is the measured acoustic velocity (m/s) squared (Lindström et al., 2002).

$$MOE = \rho V^2 \tag{2}$$

Over the past 20 years, the IML Micro Hammer has been used in many silvicultural studies to measure the standing stiffness of trees (Carson et al., 2014; Menzies et al., 2004; Moore, Cown, McKinley, et al., 2015; Watt et al., 2009). Similar tools such as the Fakopp 2-D (Fakopp Enterprises, Hungary) and the TreeTap (University of Canterbury, New Zealand) are commonly used in assessing the stiffness of standing trees (Grabianowski et al., 2006; Waghorn et al., 2007). Knowles et al. (2007) concluded that the IML hammer was the better tool to accurately predict the true stiffness (MOE derived from a static bending test) of standing trees compared to the TreeTap tool. Moreover, in a study comparing acoustic tools Guenole et al. (2003) concluded that the IML hammer standing tree MOE strongly correlated (R = 0.91, d = 1 m) with hitman MOE values with the Fakopp 2-D achieving a similar correlation value (R = 0.97, d = 1.5 m). Confirming that the IML Micro Hammer was a suitable tool to use in this study.

1.4 Comparable studies

Lasserre et al. (2004) assessed the stiffness of 11-year-old *P. radiata* in Dalethorpe Canterbury at initial stand densities of 833, 1,250 and 2,500 stems per hectare where initial stand density ($P < 0.01$) had a significant influence on MOE. Between the three stocking levels, there was a 44% increase in MOE, rising from 4.1 to 4.6 to 5.9 GPa. Lasserre et al. (2008) assessed the stiffness of 9-year-old *P. radiata* in Dalethorpe and 11-year-old *P. radiata* in Port Levy at initial stand densities of 833 and 2,500 stems per hectare where initial stand density ($P < 0.001$) had a significant influence on MOE. Between the two stocking levels, there was a 38% increase in MOE, rising from 4.8 to 6.6 GPa at Dalethorpe and a 31% increase, rising from 4.9 to 6.4 GPa at Port Levy. Lasserre et al. (2009) assessed the resonance stiffness of 11-year-old *P. radiata* logs from an experiment at Dalethorpe at initial stand densities of 833 and 2,500 stems per hectare where initial stand density ($P < 0.001$) had a significant influence on MOE. Between the two stocking levels, there was a 35% increase in MOE, rising from 3.4 to 4.6 GPa. In a study by Waghorn et al. (2007) assessing the stiffness of 17-year-old *P. radiata* in Burnham, Canterbury initial stand density ($P < 0.001$) had a significant influence on MOE. Between 209 and 2,551 stems per hectare, there was a 39% increase in MOE, rising from 5.4 to 7.5 GPa. Most of this increase (33%) was observed between 209 and 835 stems per hectare. Similarly, Moore et al. (2018) concluded the same result in end-of-rotation *P. radiata* in Rotorua and Napier where acoustic velocity was found to be significantly affected by final stand density ($P < 0.001$). The acoustic velocities of trees in plots with a final stand density of 200 stems per hectare were significantly lower compared to those with final stand densities of 400 and 600 stems per hectare. Moore et al. (2015) further studied 15-year-old *P. radiata* at Shellocks Forest, Dunsandel, Canterbury with final stand densities from 100 to 400 stems per hectare where a positive correlation between MOE and final stand density was observed. Conflicting with the results of all aforementioned studies, Grabianowski et al. (2004) observed no significant difference ($P = 0.33$) in MOE between 100 and 625 stems per hectare when assessing the impact of initial stand density on MOE of 27-year-old *P. radiata* at Eyrewell Forest in Canterbury.

In Waghorn et al.'s (2007) Nelder study the age effect was explored where 3-year-old cuttings displayed the highest MOE, reaching 7.7 GPa, which was significantly ($P < 0.001$) higher than the MOE (6.7 GPa) observed in 1-year-old cuttings; a 15% increase. Menzies et al. (2004) assessed the acoustic velocity of 12-year-old *P. radiata* in Rotoehu Forest Bay of Plenty at 400 stems per hectare with physiological ages ranging from 1 to 5 years for three different seedlots where physiological aging ($P < 0.05$) had a significant influence on acoustic velocity. Between the 1- and 5- year-old cuttings there was an increase of 14% in MOE, rising from approximately 3.6 GPa to 4.1 GPa.

Growing *Eucalyptus spp.* has been a hot topic in the New Zealand forest industry for a long time (Miller et al., 1992). Recent strategy documents such as the Forestry and Wood Processing Industry Transformation Plan and research groups such as the New Zealand Dryland Forest Initiative have called for increased planting of *Eucalyptus spp.* to diversify the forest estate and as a viable species for timber production (Millen et al., 2018; Ministry for Primary Industries, 2022). Haslett and Young (1992) is the earliest study stating the expected wood stiffness from *E. nitens* at 8.5 GPa green and 10.9 GPa at a moisture content of 12%. Warren et al. (2009) at a 6-year-old trial in NSW, Australia reported on a stocking and species study with four stocking levels (714, 1,250, 1,667 and 3,333 stems per hectare) and three species *E. cloeziana, E. pilularis* and *E. dunnii*. *E. colenziana* had stiffness levels ranging from 14.2 to 15.7 GPa, *E. pilularis* 12.2 to 13.5 GPa and *E. dunnii* 10.7 to 12.6 GPa. Between 714 and 1,250 stems per ha, there was an 11% increase in stiffness across all species. However, after this point, the disparities between stocking levels were not consistently significant which indicated forest managers should plant at 1,250 stems per ha to minimise cost while still producing high stiffness timber. Yang and Evans (2003) measured the stiffness of 15 to 29-year-old *E. nitens* with a standardised bending test and observed a mean of 11 GPa for 54 boards. A summary of further literature with mean stiffness values is presented in Table 1.

Table 1. Summary of mean Eucalyptus spp. standing tree stiffness from previous studies.

Author(s)	Location	Species	Age	Tool	Mean stiffness value
Sargent and Gaunt (2018)	SouthWood Exports Goldingham Forest	*E. nitens*	Pre-harvest	HITMAN ST-300	3.89 km/s (15.1 GPa)
Blackburn et al. (2019)	North-western Tasmania, Australia	*E. nitens*	20	HITMAN ST-300	4.04 km/s (16.3 GPa)
Blackburn et al. (2019)	North-western Tasmania, Australia	*E. nitens*	14	HITMAN ST-300	3.96 km/s (15.7 GPa)
Blackburn et al. (2019)	North-western Tasmania, Australia	*E. nitens*	19	HITMAN ST-300	3.77 km/s (14.2 GPa)
Balasso et al. (2022a)	Southern Tasmania, Australia	*E. nitens*	21	HITMAN ST-300	4.15 km/s (17.2 GPa)
Dickson et al. (2003)	Newry State Forest, NSW, Australia	*E. dunnii*	9	FAKKOP	1,837 m/s (3.4 GPa)
Dickson et al. (2003)	Newry State Forest, NSW, Australia	*E. dunnii*	25	FAKKOP	1,672 m/s (2.8 GPa)
Iyiola et al. (2022)	Wairarapa, New Zealand	*E. globoidea*	8	TreeTap	2.96 km/s (8.8 GPa)
Jones et al. (2010)	Rotoehu Forest, Bay of Plenty, New Zealand	*E. globoidea*	25	IML Micro Hammer	2.5 km/s (6.3 GPa)
Jones et al. (2010)	Rotoehu Forest, Bay of Plenty, New Zealand	*E. muelleriana*	25	IML Micro Hammer	2.5 km/s (6.3 GPa)
Jones et al. (2010)	Rotoehu Forest, Bay of Plenty, New Zealand	*E. pilularis*	25	IML Micro Hammer	2.5 km/s (6.3 GPa)
Jones et al. (2010)	Rotoehu Forest, Bay of Plenty, New Zealand	*E. fastigata*	25	IML Micro Hammer	2.7 km/s (7.3 GPa)
Suontama et al. (2018)	Kaingaroa Forest, Bay of Plenty, New Zealand	*E. fastigata*	8	HITMAN ST-300	3.43 km/s (11.8 GPa)

1.5 Research objectives

The driver of this study was to gain deeper insights into the silvicultural factors that influence wood quality within the outerwood zone of *P. radiata* trees. By doing so, forest managers might have the necessary knowledge to predict stiffness and tree dimensions for a range of stockings in plantation forests. This, in turn, would enable the New Zealand forestry industry to enhance the value of *P. radiata* plantations by increasing wood quality. Additionally, the impact of stocking on *E. nitens* was investigated to determine the potential of *E. nitens* as an alternative species to *P. radiata* in structural applications.

Primary Objectives

i. To test the hypothesis that as stocking increases, the stiffness of *P. radiata* outerwood increases, and is greater for cuttings taken from physiologically aged parents.

ii. To test the hypothesis that *E. nitens* outerwood stiffness is greater than *P. radiata* outerwood stiffness.

Secondary Objectives

i. To test the hypothesis that tree dimensions decrease with increasing stocking, and are significantly affected by the use of physiologically aged trees.

ii. To test the hypothesis that outerwood stiffness on the windward side of the tree is statistically different to that of the leeward side of the tree.

2.0 Methods

2.1 Site description

The Nelder trial was established in 2007 and 2008 on a predominantly flat site located 4 kilometres south-west of Rolleston (latitude 43°37'6.93" S, longitude 172°20'51.42" E, elevation 50 m a.s.l.) in Canterbury, New Zealand. The region is known for the predominant north-westerly winds and common soil moisture deficits. The soil at the site is characterized as Typic Orthic Brown Soils belonging to the Lismore series, a shallow, stony silt loam with low fertility and good drainage (Harris, 1948; Hewitt, 2010). The meteorological station closest to the site (Christchurch Airport) had an average annual rainfall of 618 mm, from 1981 to 2010 (Macara, 2016).

2.2 Experimental design and treatments

The experimental design was established using one of Nelder's (1962) systematic spacing designs. The experiment comprised 45 spokes separated by 8-degree intervals. In total there were 24 rows of *P. radiata* (456 trees) and 21 rows of *E. nitens* (399 trees). Due to mortality and windthrow, 344 *P. radiata* and 211 *E. nitens* trees were suitable for examination. There were 21 circular rings where the outermost and innermost rings were excluded from the analysis to ensure that each tree was subject to the same or similar conditions. Each ring represented a different stocking level ranging from 271 stems per ha in the second-most outer ring of the Nelder to 40,466 stems per ha in the second to innermost ring of the Nelder (Table 2). The experiment contained two species (*Pinus radiata* and *Eucalyptus nitens*). The *P. radiata* trees were planted in 2007 (16 years old when measured) while the *E. nitens* trees were planted in 2008 (15 years old when measured). The *P. radiata* trees were set up in a randomised complete block design, consisting of four complete blocks, each with three adjacent rows of cuttings taken from 1- and 5-year-old pine parents. The 1-year-old cuttings have a physiological age of 17 years, and the 5-year-old cuttings have a physiological age of 21 years. This facilitated the evaluation of the effect of physiological age on wood stiffness.

Table 2. Stocking design.

Ring Number	Stocking (stems/ha)
Buffer	-
1	271
2	357
3	472
4	623
5	823
6	1,087
7	1,436
8	1,897
9	2,505
10	3,309
11	4,370
12	5,772
13	7,623
14	10,069
15	13,298
16	17,564
17	23,198
18	30,639
19	40,466
Buffer	-

Table 3 displays individual trait ratings obtained from seed certificates of each aged *P. radiata* cutting used in this experiment. These cuttings were obtained from different seed orchards, with the 1-year-old cuttings from Proseed in Amberley, and the 5-year-old cuttings from Olsen Seed in Seddon. The 1-year-old cuttings were from 43 parents, resulting in 66 crosses, while the 5-year-old cuttings were from only 10 parents, which were crossed 9 times, resulting in a narrower range of genotypes. Both the 1-year-old and 5-year-old cuttings are rated as GF 24.

Table 3. Seedlot information.

	1-year old cuttings	5-year-old cuttings
Growth	22	22
Straightness	20	21
Branching	22	22
Dothistroma	18	20
Wood density	23	26
Spiral grain	21	21

2.3 Measurements and calculations

All trees in the experiment with green foliage and a diameter at breast height (DBH) greater than 3 cm (344 *P. radiata* and 211 *E. nitens*) were measured for stem height and diameter. The Haglof Vertex IV and T3 transponder were used to measure height. When measuring stem height, the transponder was placed at breast height (1.4 m), and then from the transponder, an ultrasound signal was emitted to the Vertex which calculated the distance to datum and measured the angle to datum. Then the Vertex was aimed at the top of the tree and the angle was recorded. Using trigonometry, the Vertex then calculated the height of the tree. The device was re-calibrated a minimum of three times per day to reduce the chance of temperature changes affecting distance measurements. If height measurements were obviously inaccurate, a second measurement was recorded as a replacement or to validate the first measurement to ensure no data was misrepresentative. Using a diameter tape, the DBH was measured at 1.4 m and recorded in centimetres.

All trees with a DBH greater than 3 cm had their stiffness measured and recorded. Due to the length of the probe required to be inserted into the tree, it was difficult to assess smaller diameter trees. As such, one *E. nitens* tree was excluded from the study.

The IML Micro Hammer was used to collect measurements of tree stiffness. The receiver and sensor screws were perpendicularly screwed into the stem. Then the sensor cap and the impact cap were attached to the magnetic ends of the screws. The probes were inserted 1.5 m apart either side of breast height (0.65 and 2.15 m from the ground). The impact cap was lightly tapped with the hammer at the end of the hammer lead to generate an acoustic stress wave. When the average value of the last three taps fell within a 10% tolerance range, the electronic unit saved this average value. This process was repeated on the windward and leeward side of every tree. To ensure low variation and accurate measurements, the impact probe was hit straight on, and the probes were regularly checked and cleaned to guarantee no foreign debris was in between the magnets and the sensor cap and impact cap. If taps were frequently inconsistent, a second measurement was recorded as a replacement or to validate the first measurement to ensure no data were misrepresentative.

The average value of the windward and leeward measurements was used for the analysis. To calculate stiffness (MOE), the measurement value (m/s) was then converted to acoustic velocity (km/s) by dividing the value by 1,000. Wood stiffness (in gigapascals, GPa) was thereby estimated for each tree using the acoustic velocity (Equation 3).

$$Stiffness\ (GPa) = (acoustic\ velocity)^2\ \times\ green\ density \tag{3}$$

Green density was assumed to be 1,000 kg/m^3. Non-destructive evaluation techniques to determine actual green density for every tree are time-consuming and expensive; so typically researchers assume a constant green density across all trees sampled (Lasserre et al., 2004; Lindström et al., 2004; Watt et al., 2009). Young et al. (1991) measured the green density of 25-year-old radiata pine to be 932 kg/m^3. Similarly, Chan et al. (2016) observed 943 to 1,023 kg/m^3 at a height of 1.3 m. *E. nitens* mean green density varies with disc height from 1,128 kg/m^3 at 0 m to 1,071 kg/m^3 at 20 m (McKinley et al., 2002). Moreover, Andrews (2000) stated that green density can be assumed as 1,050 kg/m^3 when using ToF tools. Therefore, 1,000 kg/m^3 was an appropriate assumption for the objectives of the study.

2.4 Data analysis

The height, DBH and stiffness data were collated in a Microsoft Excel spreadsheet alongside each tree's stocking. The dataset was prepared for statistical analysis using the R statistical package (R Core Team, 2023). Linear regression was used to determine if stocking had a statistically significant effect on each of the dependent variables (DBH, height and MOE) for both species (*P. radiata and E. nitens*). To analyse the impact of aging in *P. radiata*, a binary variable was developed for cuttings from aged and not-aged parents. Scaled power transformations were undertaken on both response and independent variables to achieve linearity, normalise the distributions of residuals, stabilise variance and reduce heteroscedasticity. This was done using a Box-cox transformation (4) or a logarithmic transformation. Shown below is an example of how these transformations are implemented within a model for DBH (5).

$$y(\lambda) = \begin{cases} \dfrac{y^{\lambda} - 1}{\lambda}, & if\ \lambda \neq 0 \\ \log y, & if\ \lambda = 0 \end{cases} \tag{4}$$

$$lm((I(dbh\text{^}0.66 - 1)/0.66) \sim I(\log(stocking))\ *\ spp \tag{5}$$

Both the windward and leeward sides of the tree were measured, where the north-westerly is the predominant wind direction, so an analysis of the impact of wind on MOE measurements was undertaken. This was done by using a linear mixed-effects model in R (Bates et al., 2015).

Similar to the linear regression analysis, scaled power and logarithmic transformations were used to meet the assumptions of a linear mixed-effects model.

Analyses of variance using R's car package were undertaken for all linear and mixed effects models using a significance level of 0.05 (Fox & Weisberg, 2019). To enhance the accuracy of the models, factors were removed if they were insignificant.

3.0 Results

3.1 The combined model for the stocking and species effects

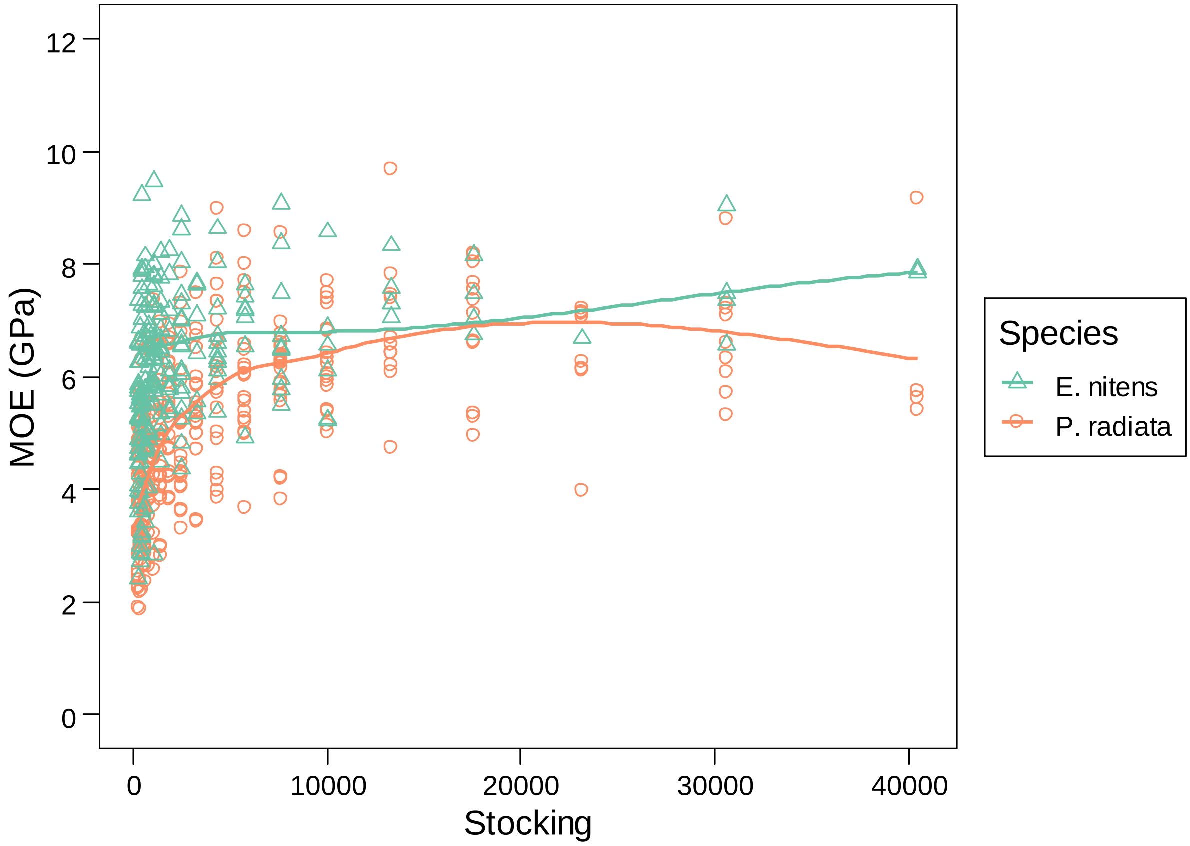

Figure 1. Stocking and species effect on MOE.

In the combined model investigating the stocking and species effect, MOE was significantly affected by stocking (P < 0.001) and species (P < 0.001). Both species exhibited a nonlinear increase in MOE to about 5,000 stems per hectare. At 17,564 stems per hectare, mean stiffness was quite similar between the two species, from this point the lines diverged with *E. nitens* increasing in strength at the higher stockings and *P. radiata* slightly decreasing. The model had some slight heteroscedasticity, and the residuals were normally distributed (Figures 2 & 3).

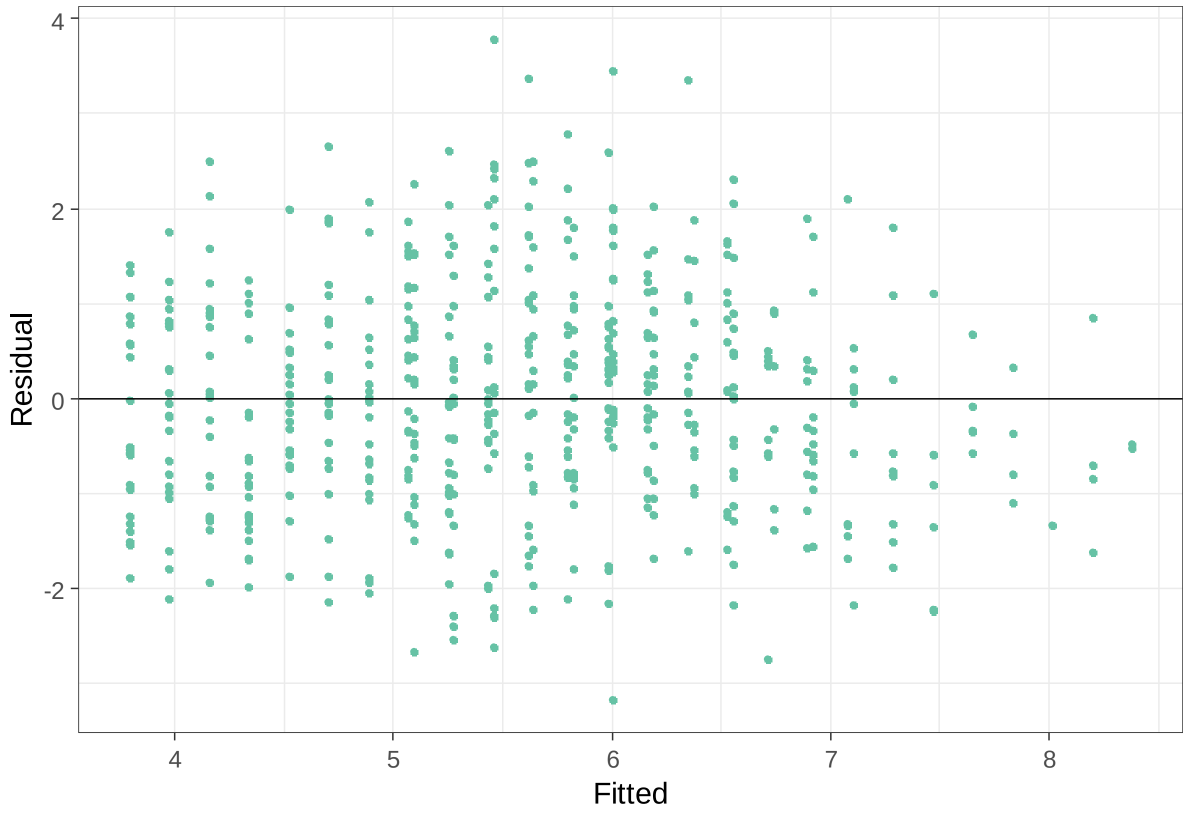

Figure 2. Residuals vs. fitted plot for the combined model.

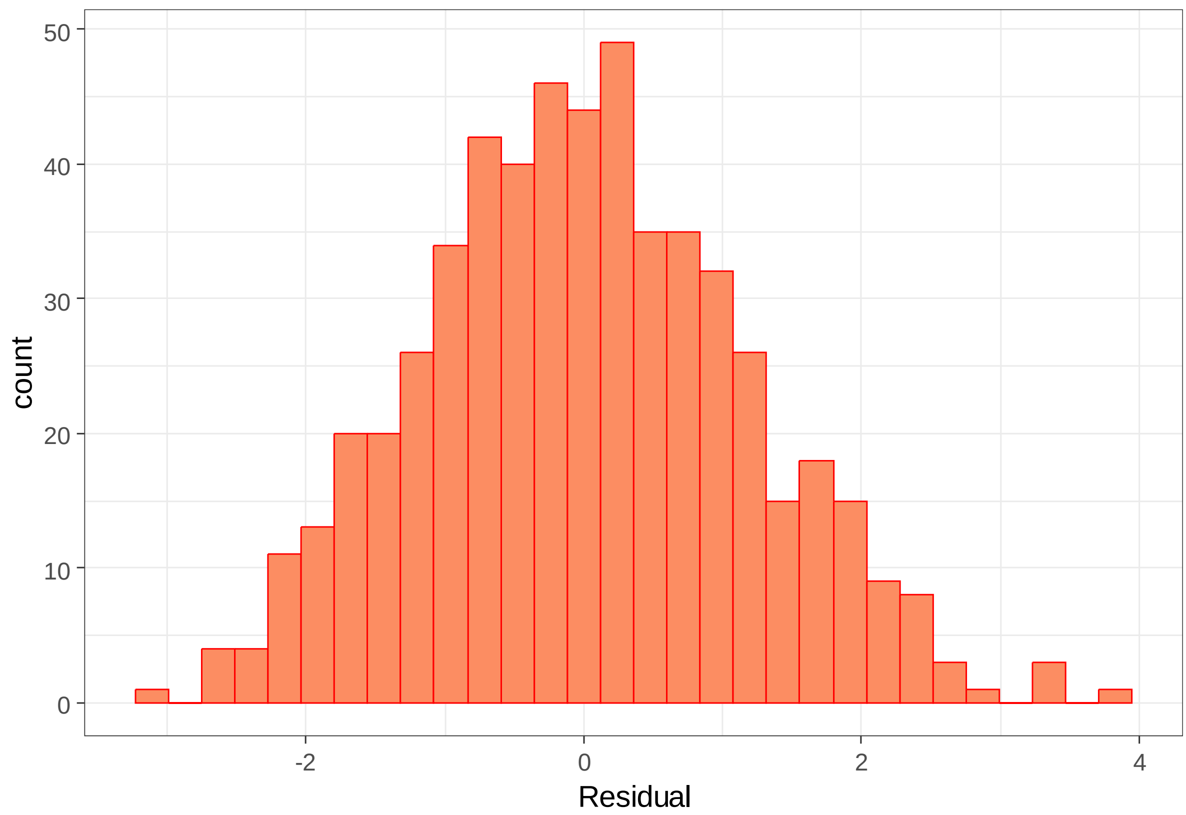

Figure 3. Histogram of residuals for the combined model.

3.2 Influence of stocking and tree dimensions on wood stiffness

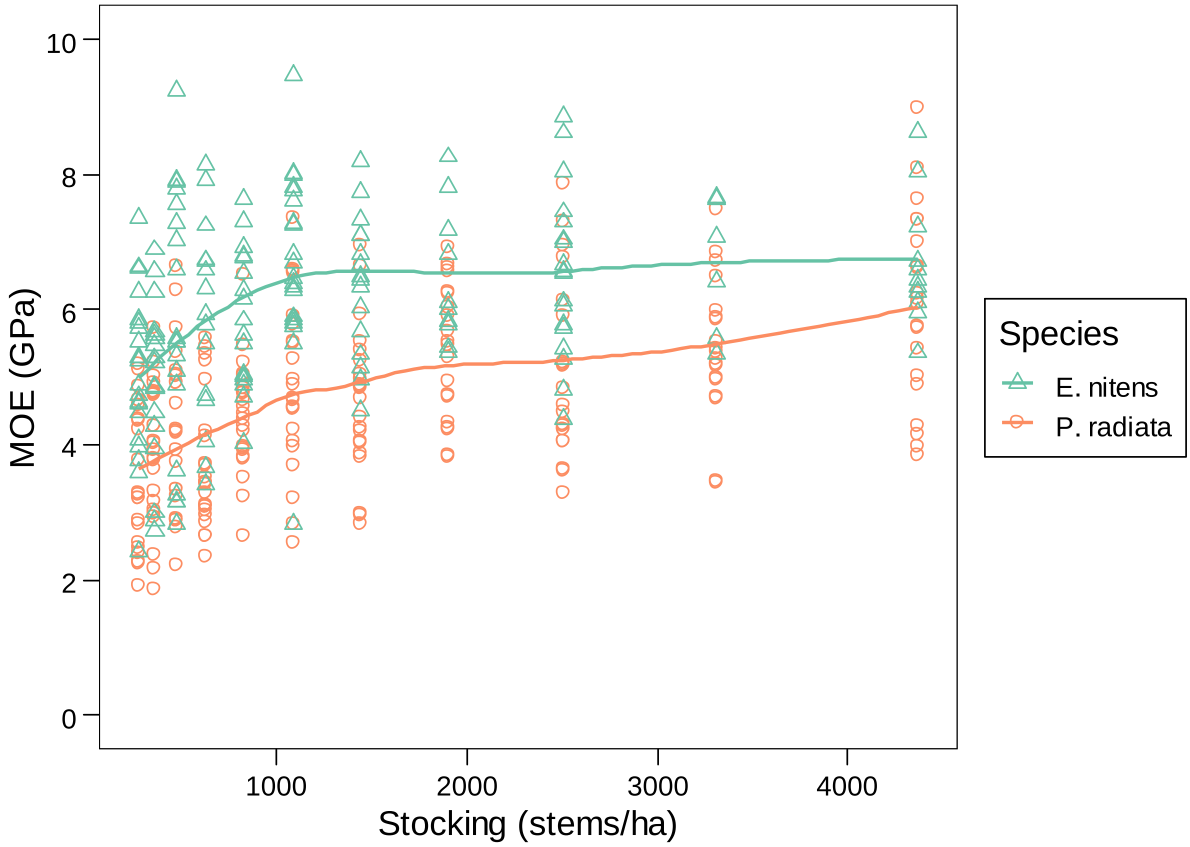

Figure 4. Stocking and species effect on MOE for stocking deemed realistic for forest growers.

The model shown in Figure 4 was reduced to 271 stems per hectare to 4,370 stems per hectare to analyse stiffness trends for stocking levels that forest growers in New Zealand typically plant. An increase in MOE was observed from 271 stems per hectare to 1,087 stems per hectare for *E. nitens* with no major difference in MOE from 1,436 stems per hectare to 4,370 stems per ha. *P. radiata* on the other hand increases in MOE up to 1,897 stems per hectare. The model had some slight heteroscedasticity, and the residuals were normally distributed (Figures 5 & 6).

Tree dimensions, DBH and tree height showed little trend in predicting MOE once stocking was taken into account. They were deemed unsuitable predictors of MOE and regarded as nuisance factors. See Appendix A for the DBH regression plot and Appendix B for the height regression plot.

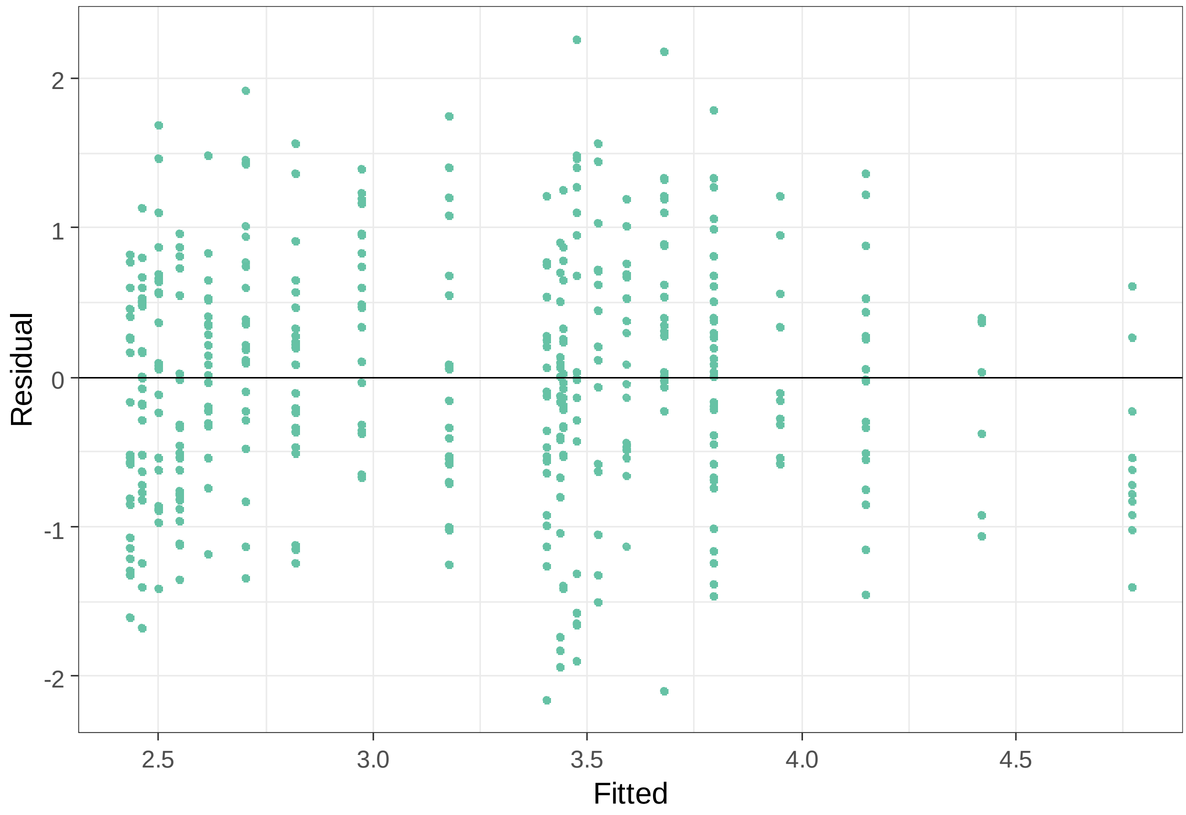

Figure 5. Residuals vs. fitted plot for the realistic stocking model.

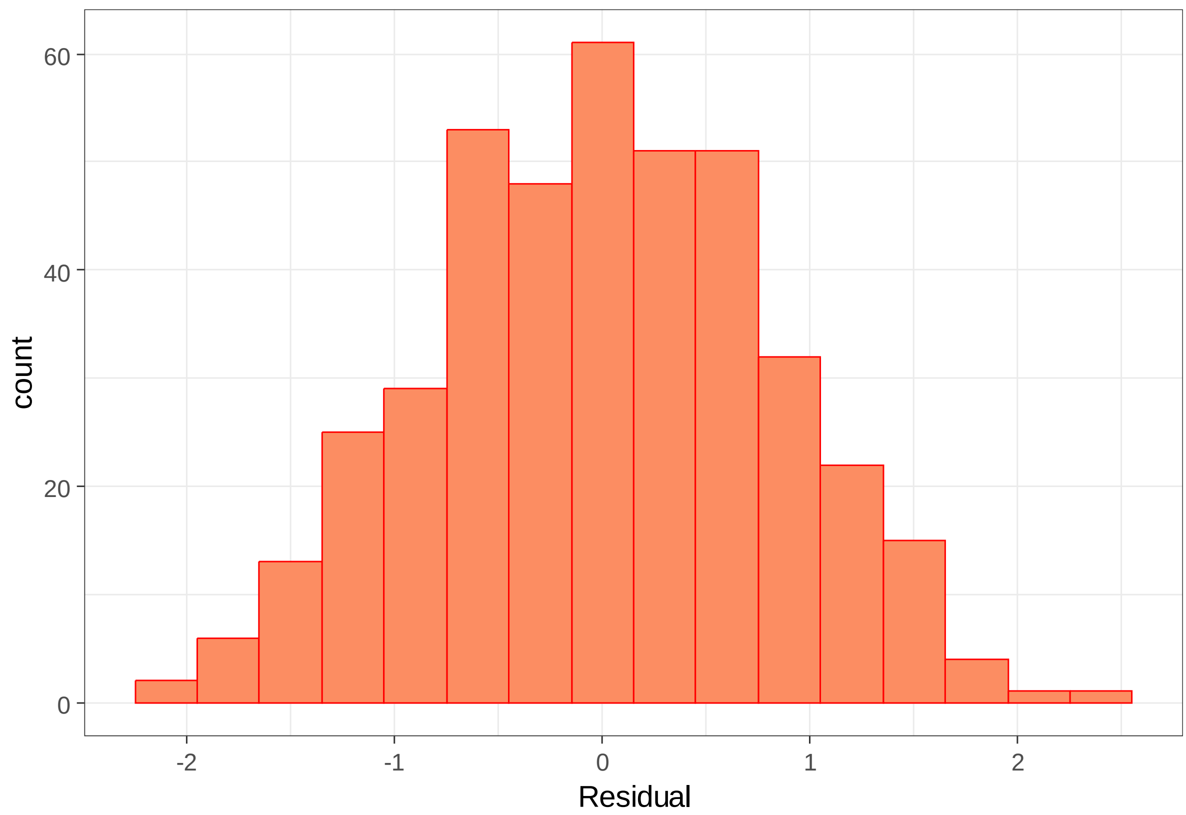

Figure 6. Histogram of residuals for the realistic stocking model.

3.3 Influence of physiological age on wood stiffness

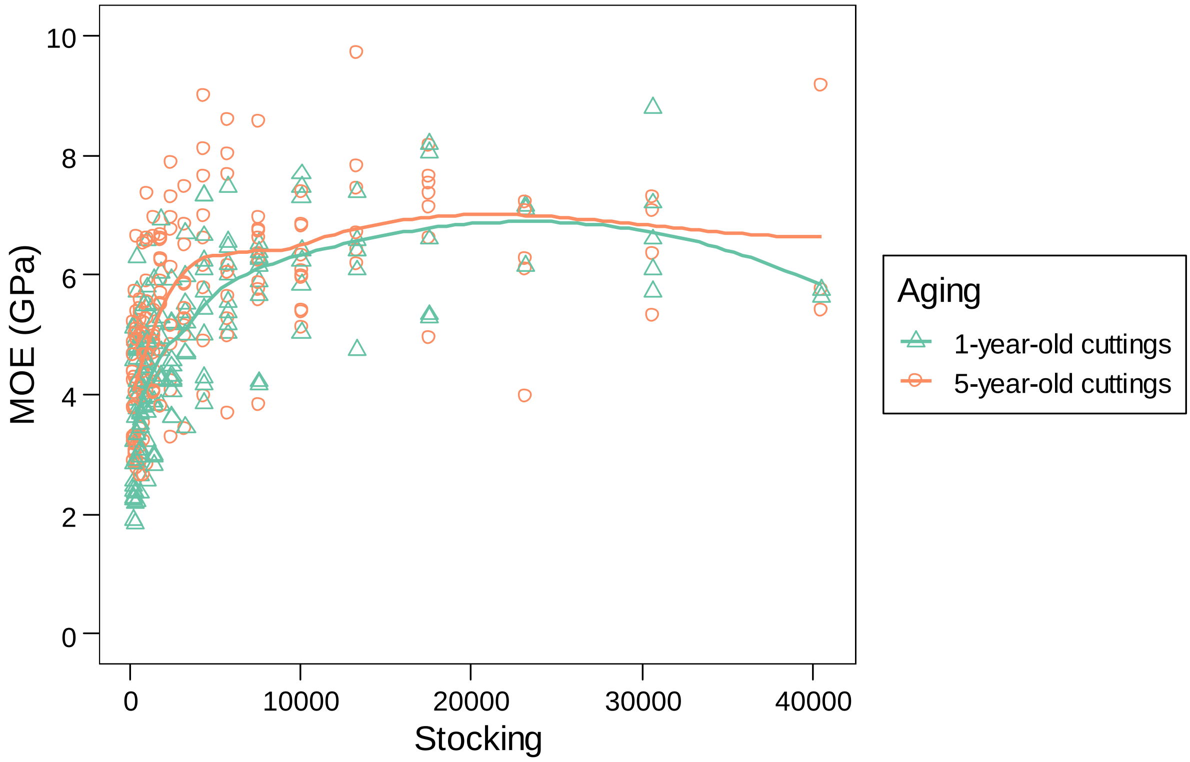

Figure 7. Stocking and aging effect on MOE for P. radiata.

In the physiological aging regression, the highest stiffness values were from 5-year-old parents (Figure 7). The greatest difference in MOE between the two seed stocks was between 271 and 623 stems per hectare. In a mixed effects model stocking and physiological aging had a strongly significant effect on MOE (P < 0.001). An insignificant interaction between stocking and physiological aging (P = 0.11) implies the main effects were additive, meaning the effect of aging did not depend on stocking and vice-versa. The model had equal variance, and the residuals were normally distributed (Figures 8 & 9).

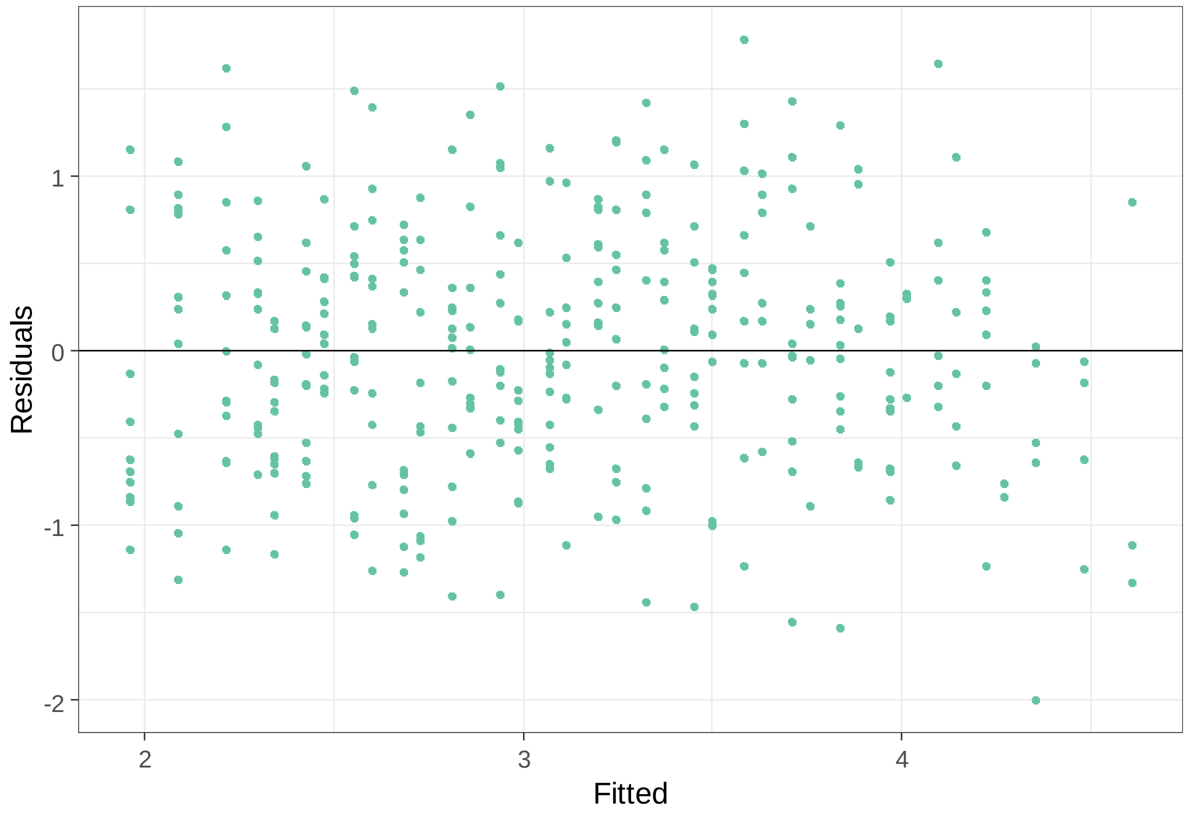

Figure 8. Residuals vs. fitted plot for the stocking and aging effect on MOE model.

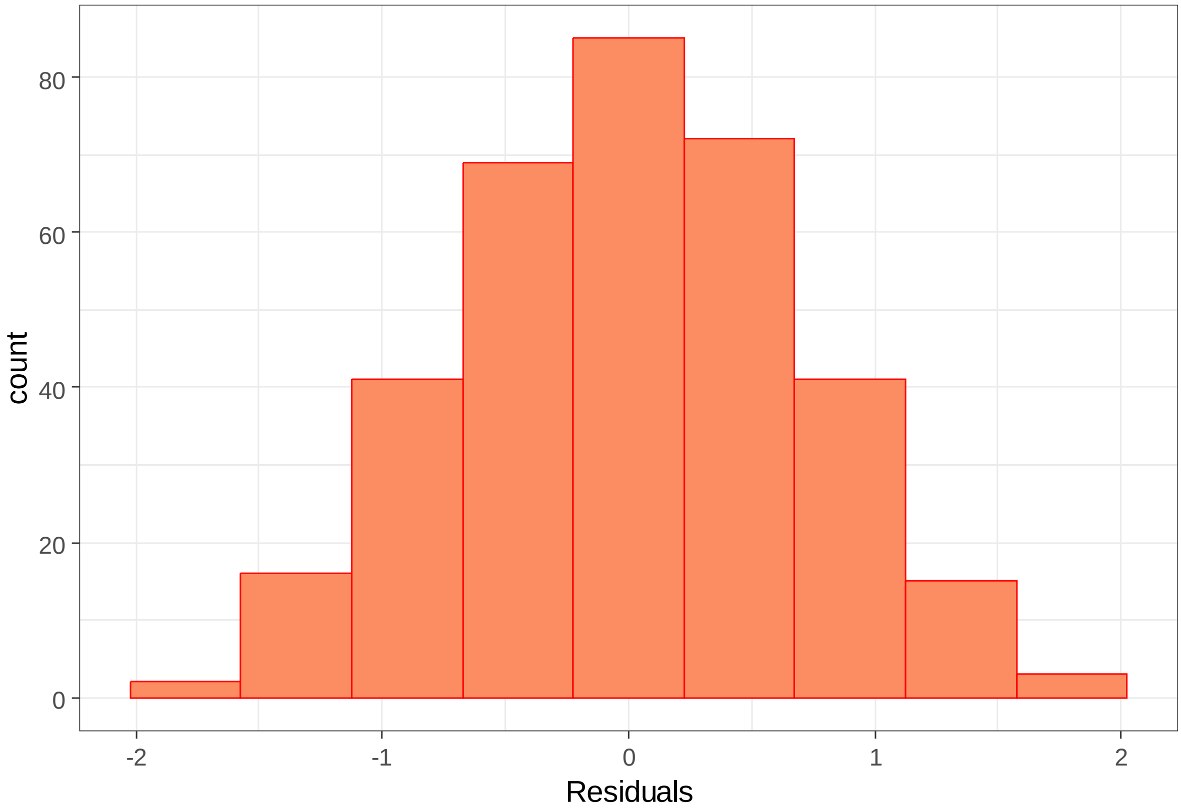

Figure 9. Histogram of residuals for the stocking and aging effect on MOE model.

3.4 Influence of stocking on tree dimensions

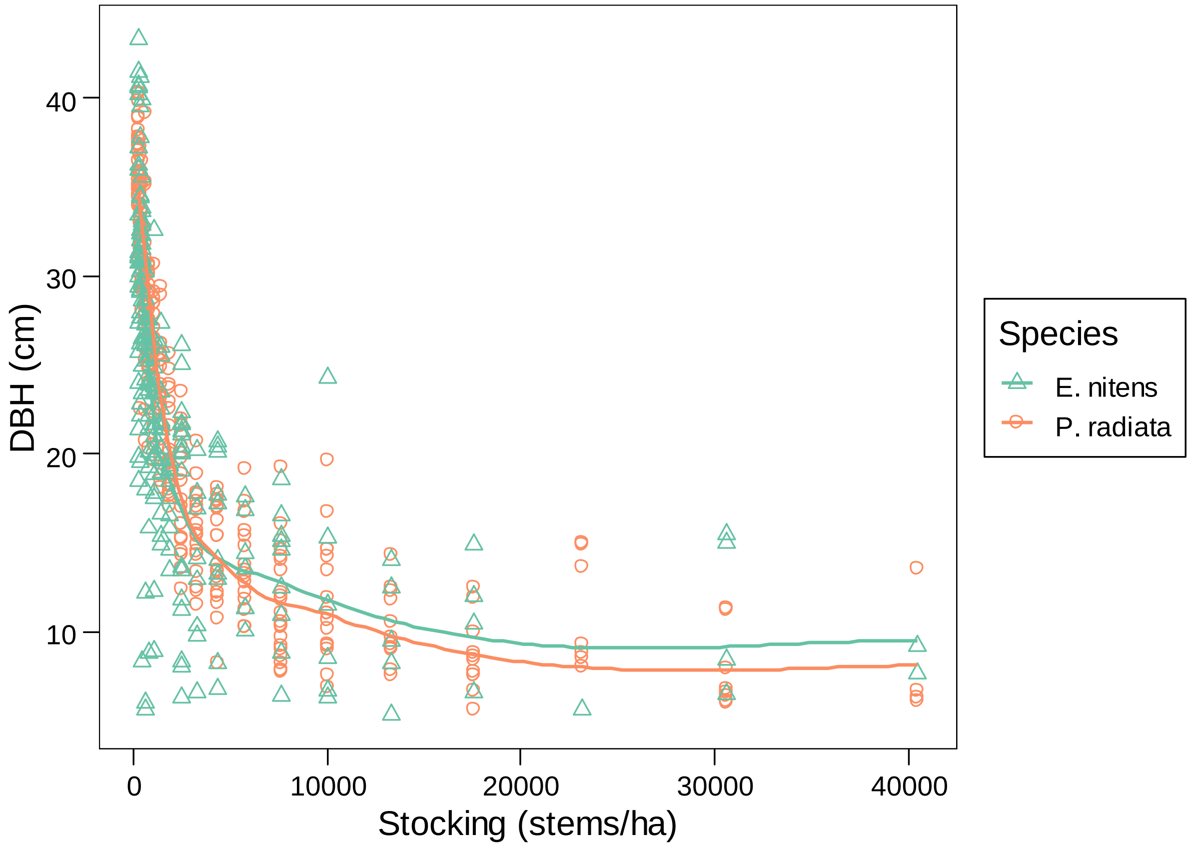

Figure 10. Stocking and species effect on DBH.

Stocking, species and their interaction were all significant predictors of DBH ($P < 0.001$). Both species decreased in stiffness in an exponential trend (Figure 10). The *E. nitens* trees were consistently larger, in DBH, than the *P. radiata* trees across all stocking levels. However, this could be due to high mortality amongst the *E. nitens* trees thus having less competition effects. There were also a lot of smaller *E. nitens* trees at lower stockings. The model had equal variance and some bias where smaller values were overestimated (Figure 11). The residuals were normally distributed (Figure 12).

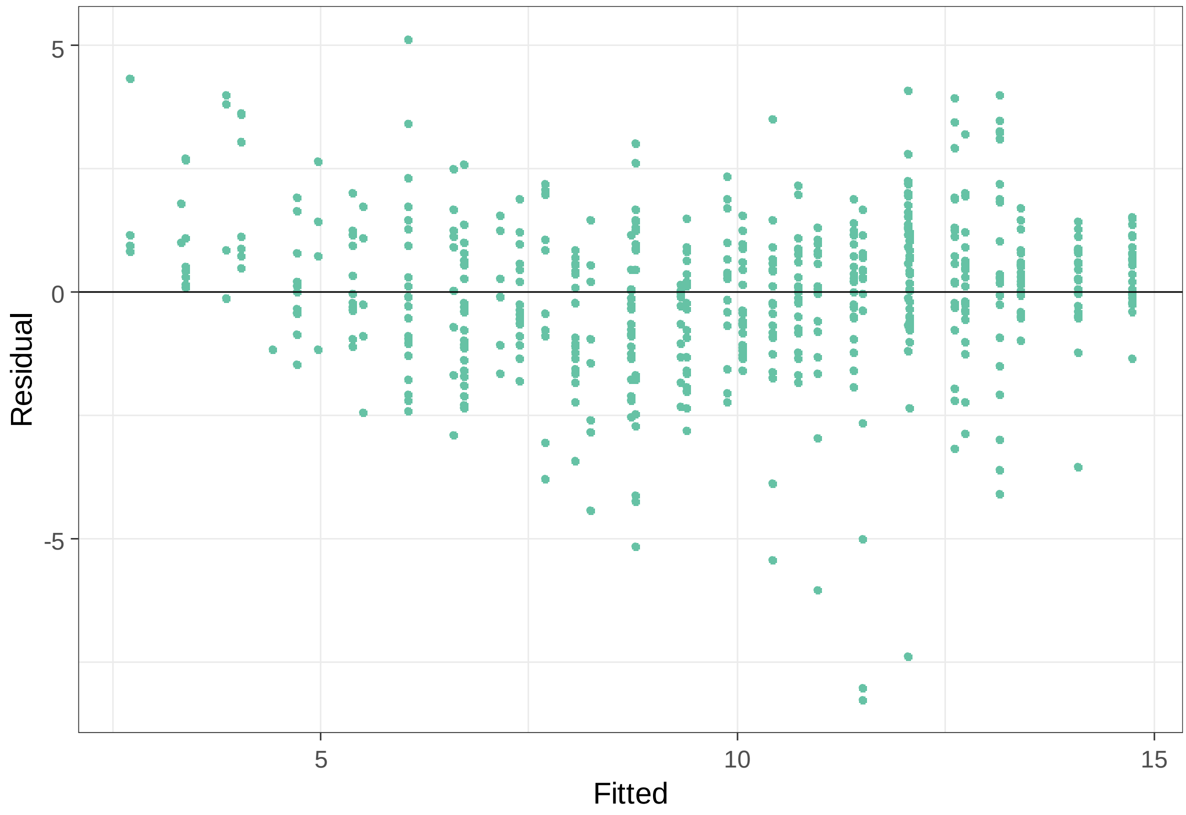

Figure 11. Residuals vs. fitted plot for stocking and species effect on DBH model.

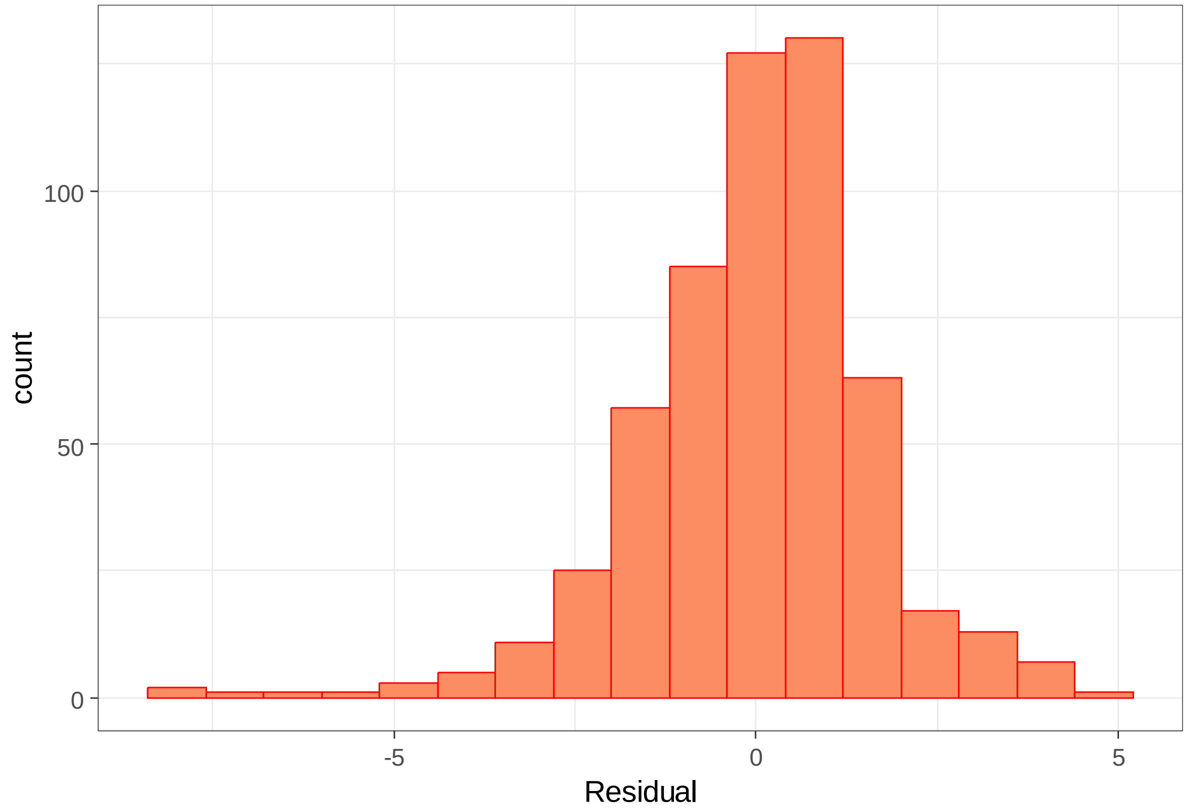

Figure 12. Histogram of residuals for stocking and species effect on DBH model.

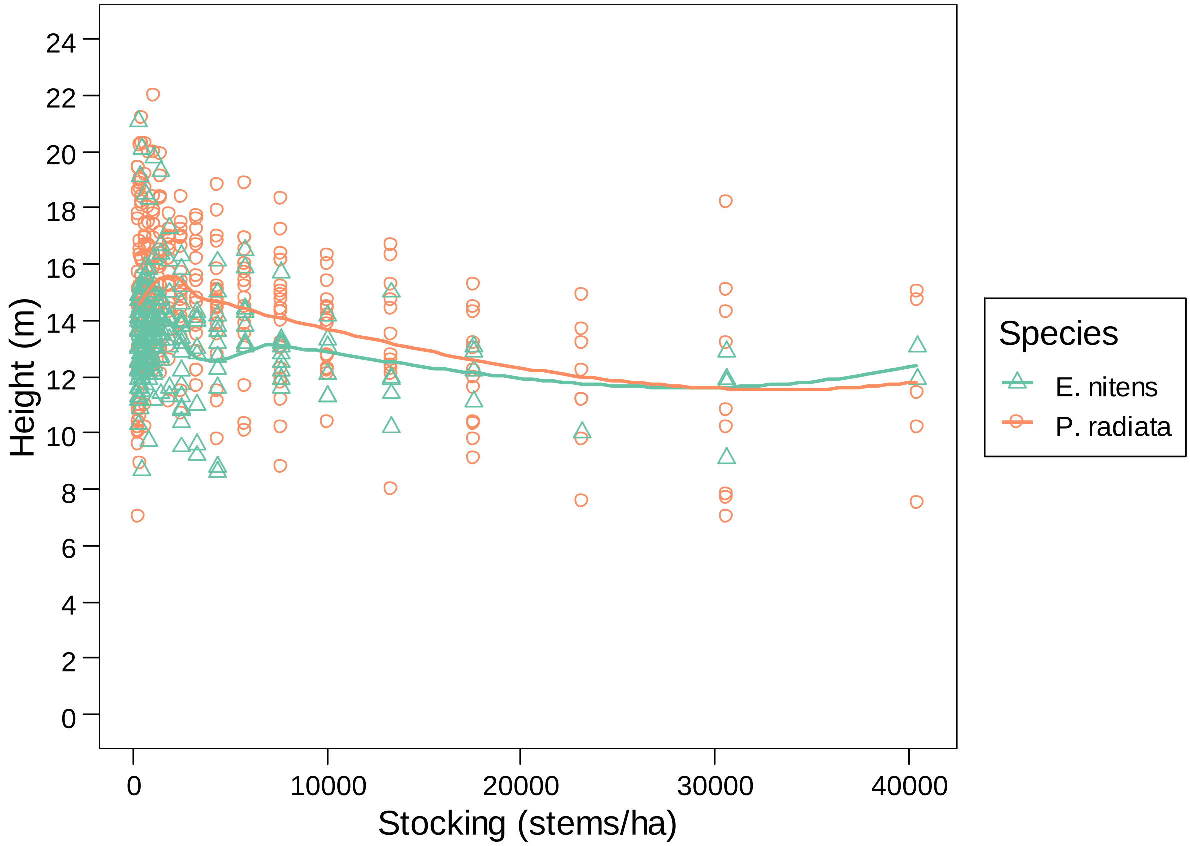

Figure 13. Stocking and species effect on tree height.

Stocking and species were significant predictors of height ($P < 0.001$). The *P. radiata* trees decrease in height in a nonlinear manner. *E. nitens* height was slightly less predictable, fluctuating in height at lower stockings (<10,000 stems per hectare) and increasing slightly in height at extremely high stockings (Figure 13). This could be due to a lower sample size than the *P. radiata*. The model had equal variance with slight heteroscedasticity and the residuals were normally distributed (Figures 14 & 15).

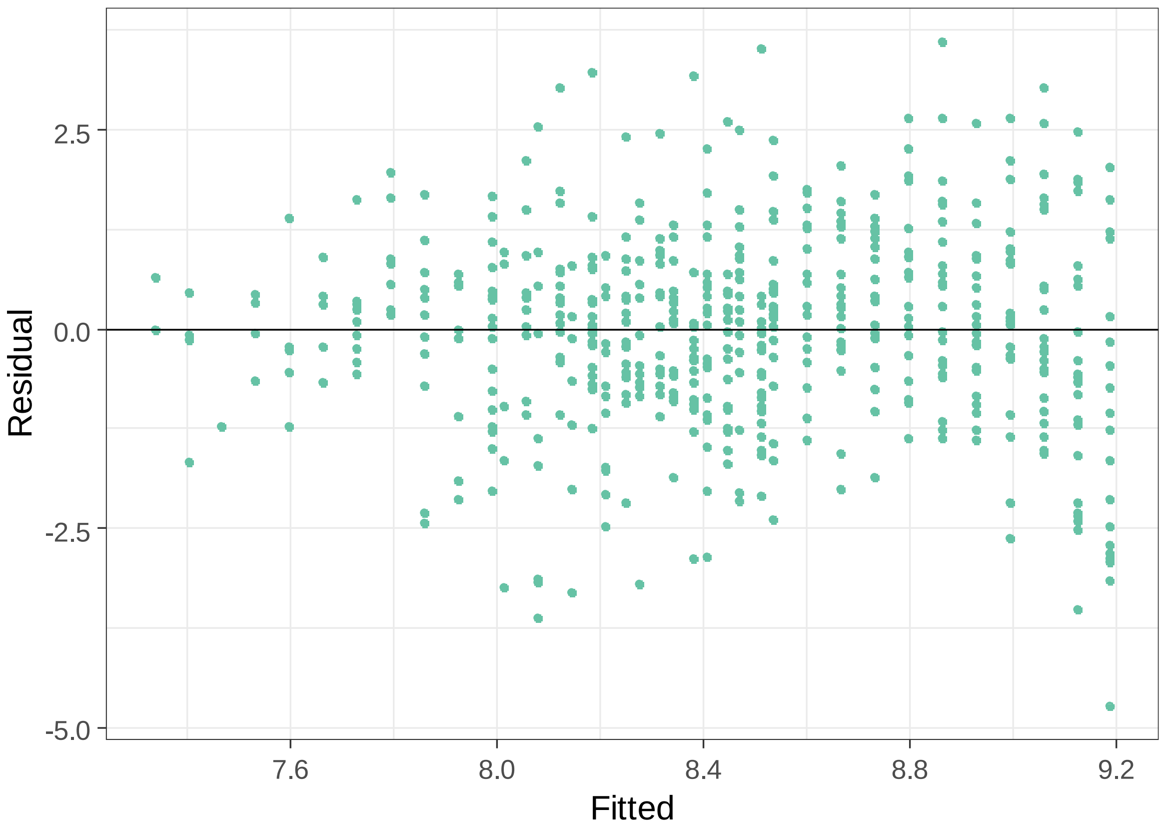

Figure 14. Residuals vs. fitted plot for stocking and species effect on tree height model.

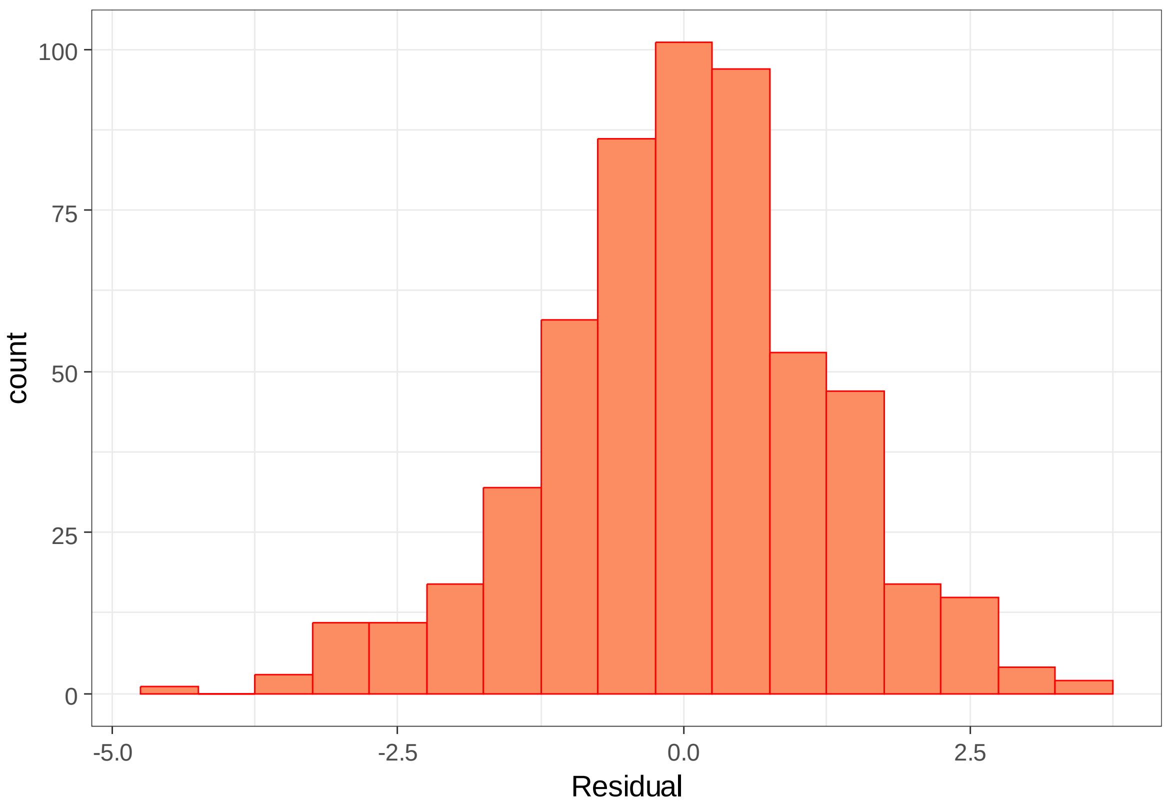

Figure 15. Histogram of residuals for stocking and species effect on tree height model.

3.5 Influence of physiological age on tree dimensions

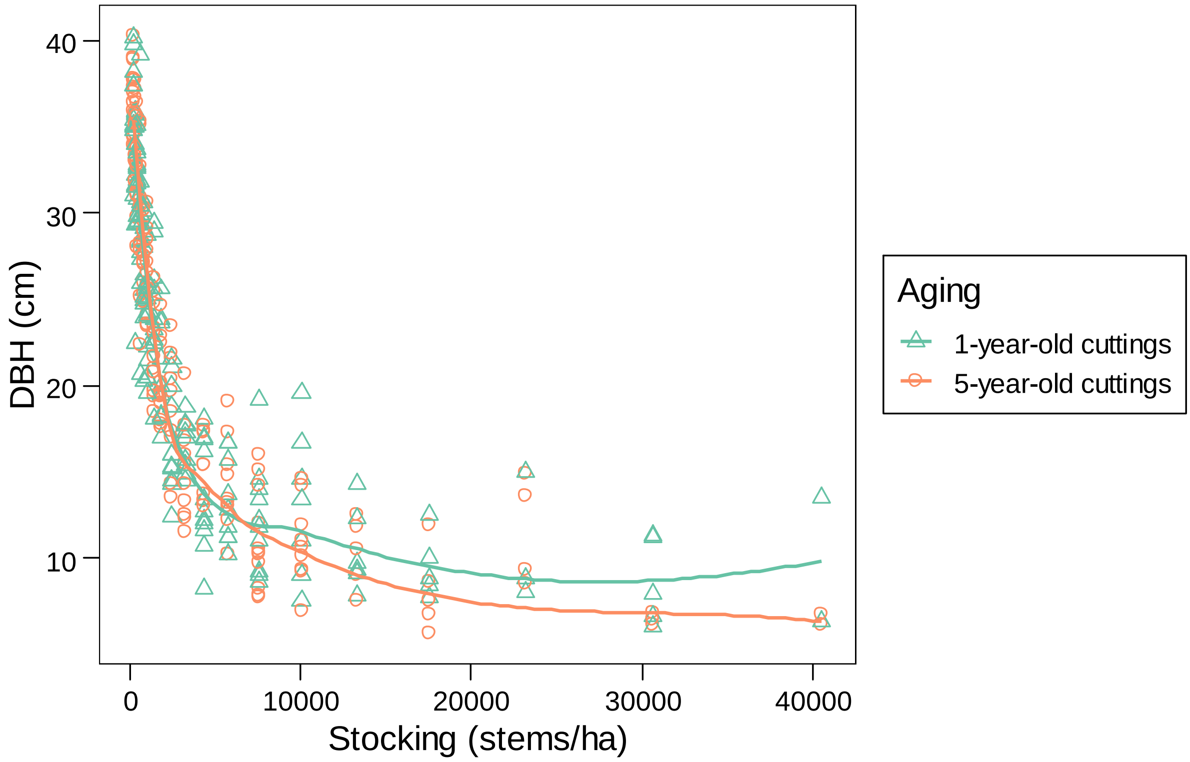

Figure 16. Stocking and aging effect on DBH for P. radiata.

Stocking (P < 0.001), aging (P = 0.0067) and their interaction (P = 0.0073) were significant predictors of DBH meaning the effect of aging depends on stocking. Both species decreased in stiffness in an exponential trend (Figure 16). Initially, it looked like there was little difference in DBH between the two seed stocks; however at stockings greater than 7,623 stems per hectare the 1-year-old cuttings were larger in DBH compared to the aged cuttings. The model had equal variance but some slight bias was present, where lower values were overpredicted (Figure 17). The residuals were normally distributed (Figure 18).

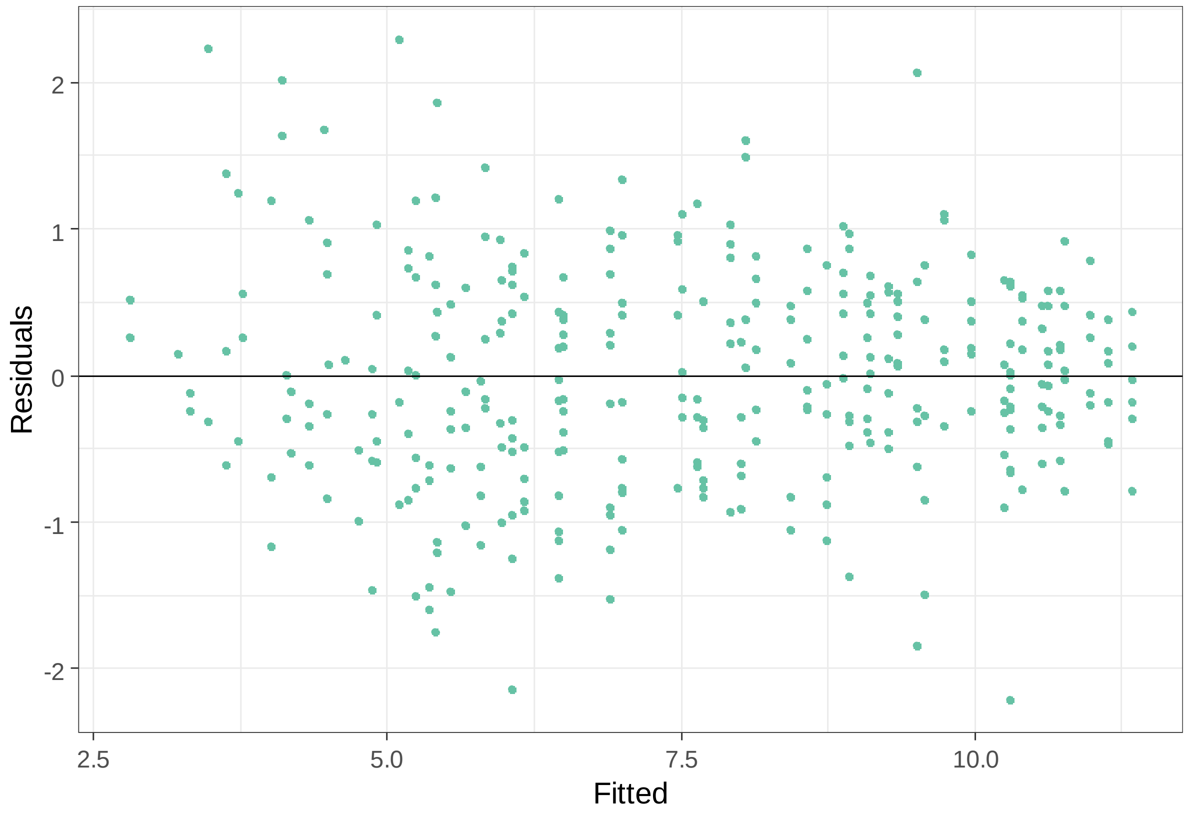

Figure 17. Residuals vs. fitted model for the stocking and aging effect on DBH model.

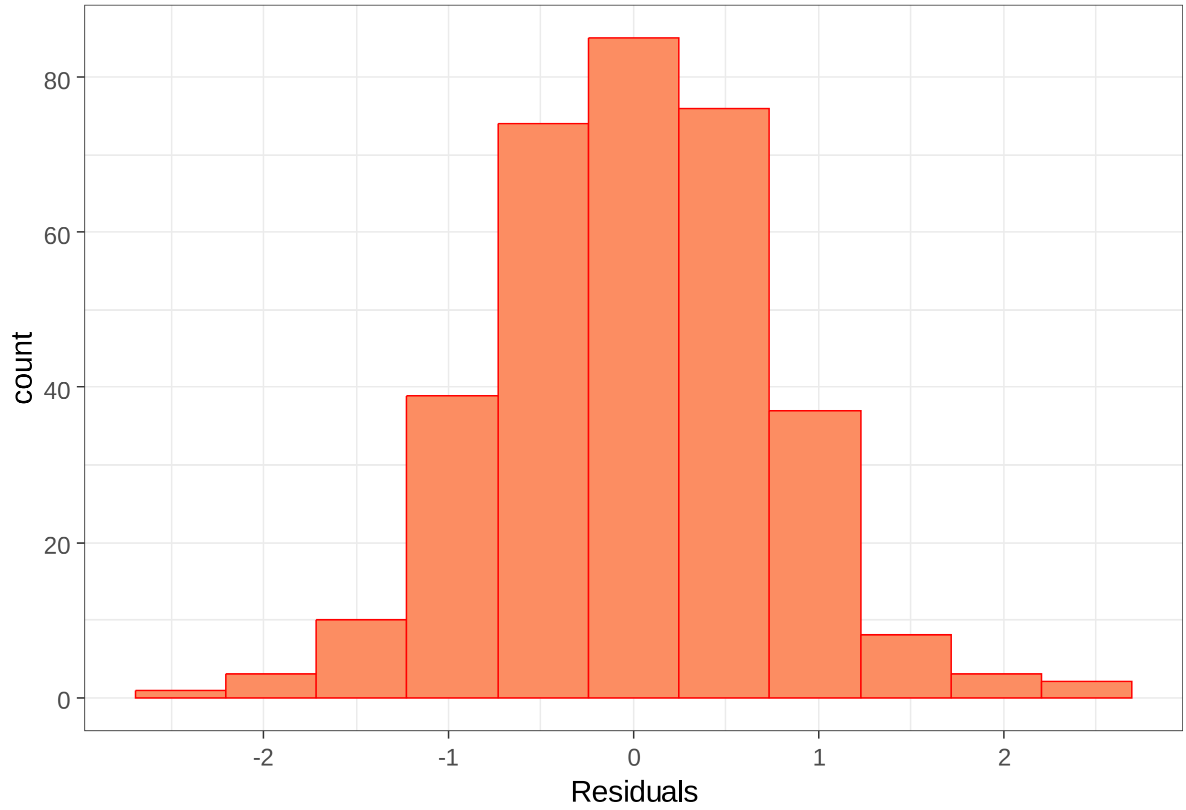

Figure 18. Histogram of residuals for the stocking and aging effect on DBH model.

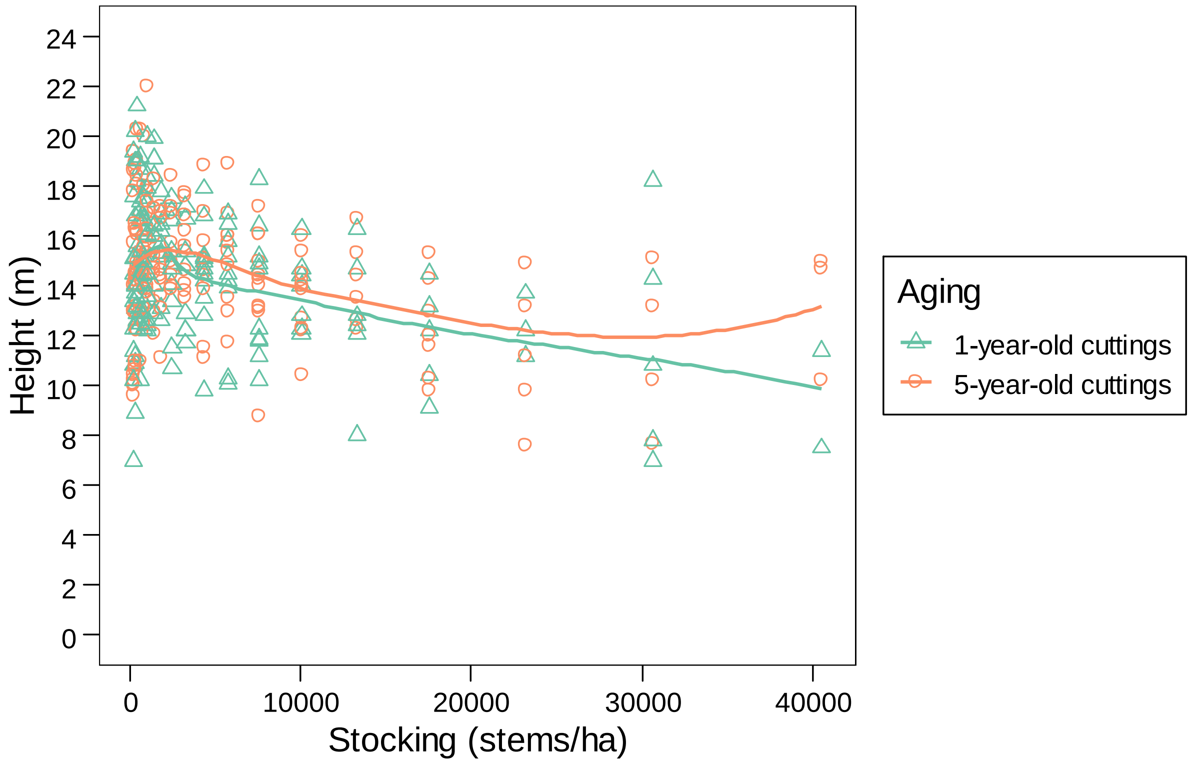

Figure 19. Stocking and aging effect on tree height for P. radiata.

In the mixed effects analysis, stocking was a significant predictor of height ($P < 0.001$). However aging was not significant ($P = 0.31$), and neither was the interaction between aging and stocking ($P = 0.74$). This insignificant trend can be visually identified by the tight arrangement of points around the trendlines (Figure 19). Both seed stocks decreased in height with increasing stocking until 23,198 stems per hectare in a parallel linear fashion. Thereafter the 5-year-old cuttings increased in height and the 1-year-old cuttings remained on that linear decreasing trend. This leads to the conclusion that aged trees had greater height growth. The model had equal variance with slight heteroscedasticity and the residuals were normally distributed (Figures 20 & 21).

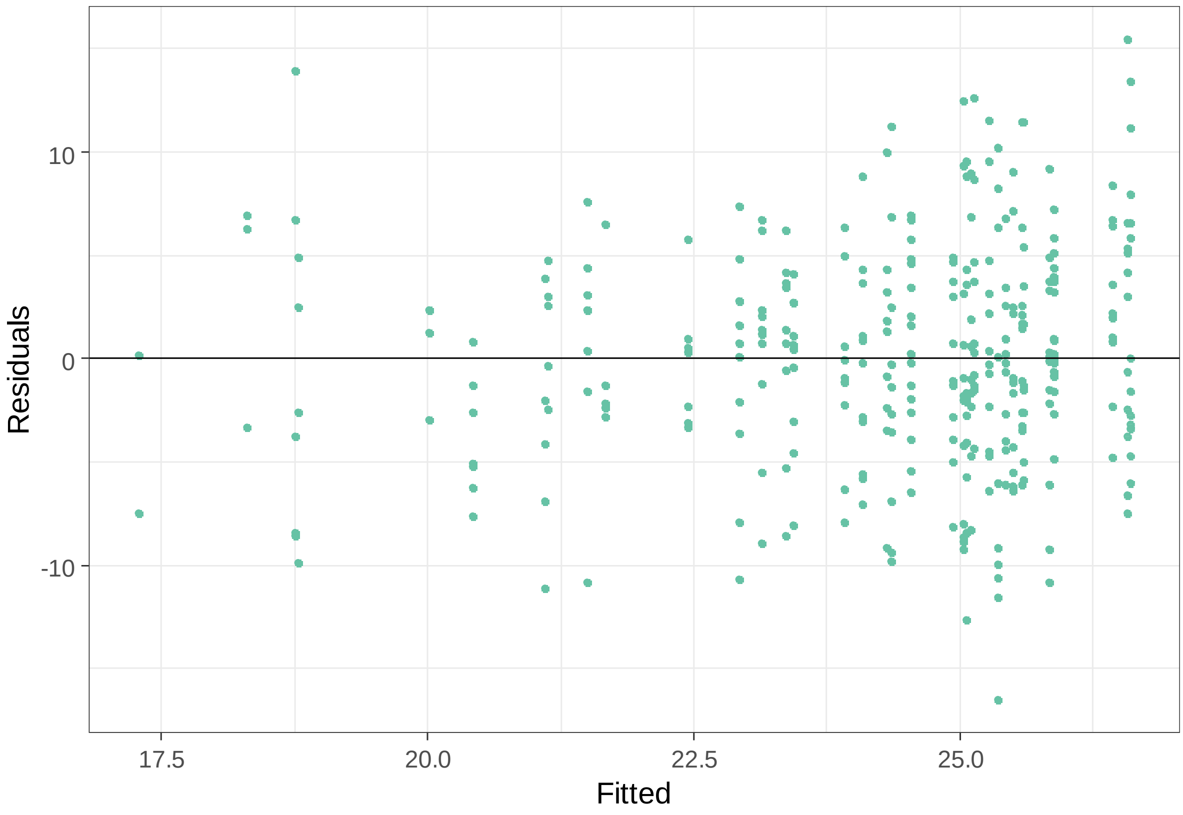

Figure 20. Residuals vs. fitted plot for the stocking and aging effect on tree height model.

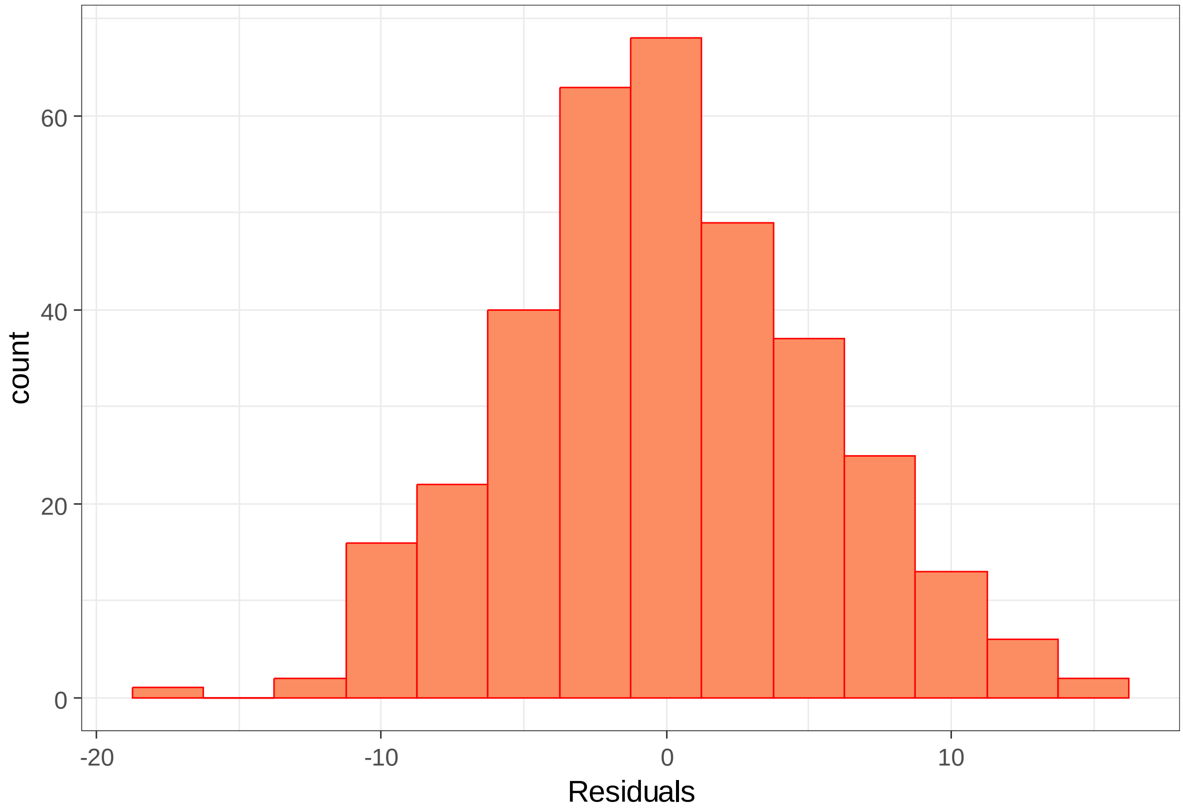

Figure 21. Histogram of residuals for the stocking and aging effect on tree height model.

3.6 Influence of wind on wood stiffness

Table 4. Results of wind direction effect on P. radiata MOE.

	Chi-square	Df	Pr>(Chisq)
Aging	10.81	1	< 0.001
Stocking	2.84	1	0.092
Wind Direction	7.65	1	0.0057
Wind Direction:Stocking	9.62	1	0.0019

Note: Formula: moe ~ I((moe^0.89-1)/0.89) ~ Aging + WindDirection * I(log(stocking)) + (1|Block/Age/TreeID)

Table 4 shows the results of a mixed-effects model predicting MOE where wind direction (the leeward or windward side of the tree) ($P = 0.0057$) and aging ($P < 0.001$) were significant. The interaction between wind direction and stocking was also significant ($P = 0.0019$). Figures 22 and 23 show that the model had some bias where smaller values were underestimated, and larger values were overestimated.

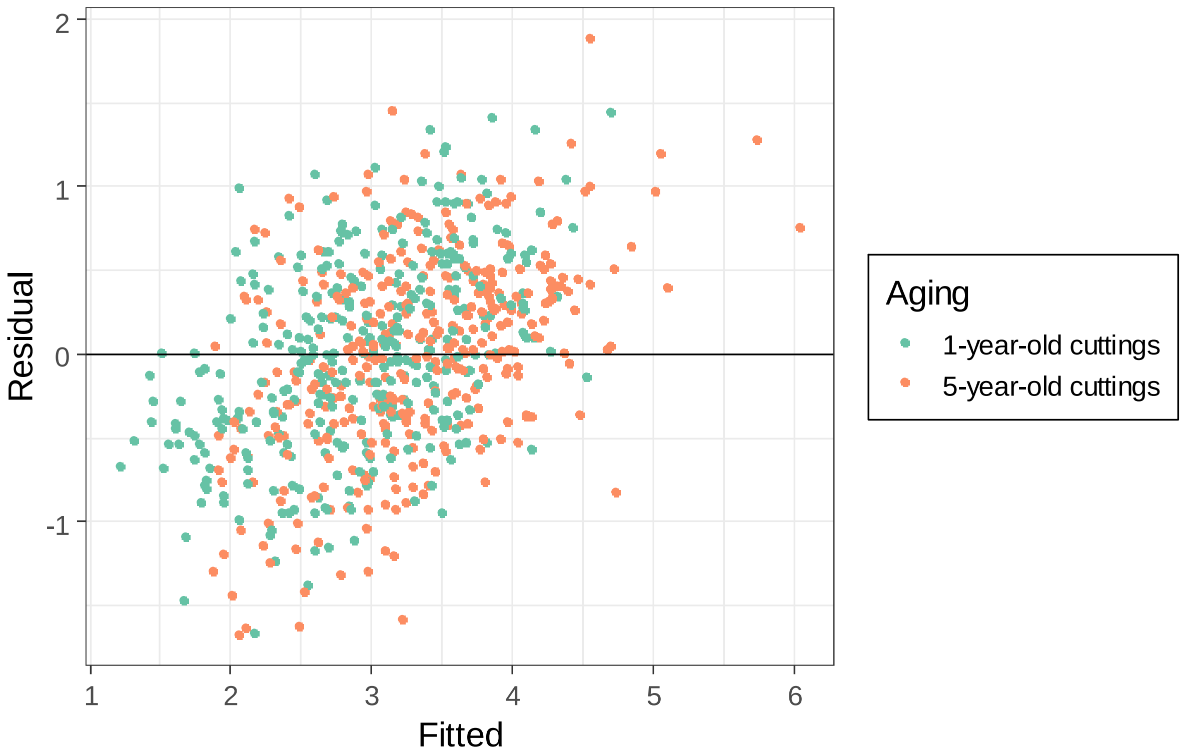

Figure 22. Residuals of the wind direction effect on MOE model sorted by aging.

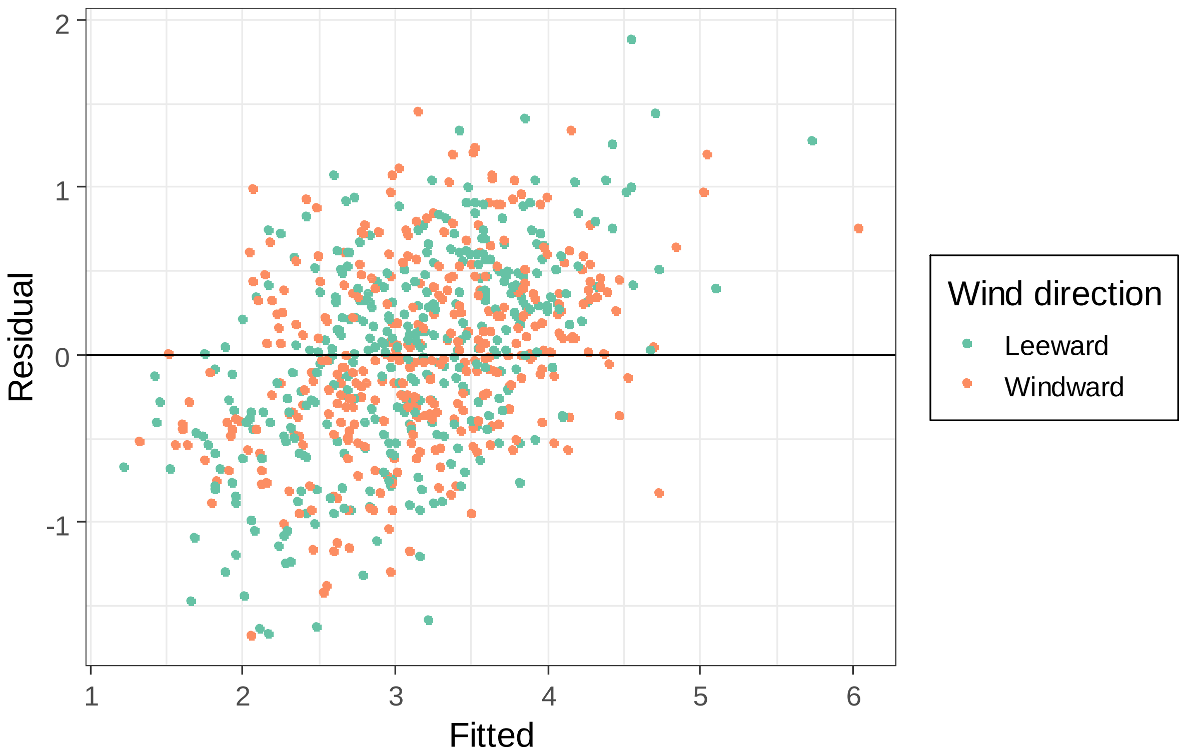

Figure 23. Residuals of the wind direction effect on MOE model sorted by wind direction.

4.0 Discussion

4.1 Stocking and species effects

By planting at a higher initial stocking, the benefits of greater wood stiffness were significant in both *P. radiata* and *E. nitens* trees. The effects of higher stocking diminished for *E. nitens* trees after 1,087 stems per ha, indicating that there is little value in planting at a higher stocking than this. While stiffness was high for *E. nitens* at this planting density (41% greater than *P. radiata*), it is widely considered a very difficult species in wood processing. Washusen et al. (2009) reported a poor 30% conversion rate for 22-year-old *E. nitens* logs due to log and board-end splitting, bow, thickness variation, cups and checking. Furthermore, *E. nitens* had poorer machinability in comparison to *P. radiata* (Kotlarewski et al., 2019). Due to the poor sawing and machinability of the species, it would be an unsuitable structural timber species to replace *P. radiata*. However, that is not to say that all *Eucalyptus spp.* have poor processing capability. *E. globoidea* has been shown to meet stiffness grades of above MSG10 (Nicholas & Millen, 2012), has just as good machinability as *P. radiata* and has a conversion rate of 55% which was much stronger than reported for *E. nitens* with just 3% of boards affected by internal checking and some distortion, bow and crook attributed to sawing techniques (Jones et al., 2010; Scown et al., 2023). Determining whether the same trend of diminishing increases in stiffness above 1,087 stems per ha occurs in *E. globoidea* or other *Eucalyptus spp.* with good processing performance would be an interesting course of future study.

For *P. radiata*, the benefits of higher stocking diminished after 17,564 stems per ha indicating that foresters may have great control over outerwood stiffness through the manipulation of initial crop stocking. The economic viability of establishing a tree crop at 17,564 stems per ha is poor, nor will there be good survival. In the future, structural *P. radiata* regimes will need to be designed to maximise stocking throughout the rotation while not causing mortality (Mason, 2023). However, regime choices for improved stiffness will need to be balanced with the economics of establishing at a higher stocking.

For *P. radiata* from 835 stems per hectare to 2,500 stems per hectare, Lasserre et al. (2004) measured a gain in MOE of 44% in 11-year-old trees. Waghorn et al. (2007) measured a gain of 4% with 17-year-old trees. In this study of 16-year-old trees, there was a gain of 14%. The fact that stiffness gain was significantly lower in older trees compared to younger trees supports the suggestion that stiffness gains may converge with age. This was attributed to competition effects being higher at younger tree ages (Waghorn et al., 2007).

While the species effect was statistically significant, the difference in wood stiffness was expected to be greater between species. In a previous dissertation study at the same site by Watson (2013), the stiffness of *E. nitens* was double that of *P. radiata* whereas this was not the case in this study. In the present study, the stiffness values for *E. nitens* were only a maximum of 1.6 times greater than the stiffness of *P. radiata*. This may be attributed to different ToF tools used, stand age effects on wood stiffness, or a combination of both.

4.2 The age effect

The advantages of establishing *P. radiata* crops with parents of a greater physiological age were found to be significant in this study. These trees were greater in maturity and thus had improved wood stiffness. This result is not what was found in a previous study on the site by Watson (2013) where the benefits were negligible. Although, Watson (2013) was correct in saying the age effect may become apparent in future years. Menzies et al. (2004) and Waghorn et al. (2007) found that trees with greater physiological age yielded higher wood stiffness, consistent with the findings of this study.

Physiological aging was found to have a lesser effect on tree dimensions compared to wood stiffness. Trees with physiological aging had an insignificant effect on tree height which supports the findings from Menzies et al. (2004). Physiological aging had a significant effect on DBH, consistent with research from Menzies et al. (2004). The use of physiologically aged cuttings was found to decrease DBH in the Menzies et al. (2004) study. The same result was seen in this study but only at a stocking greater than 7,623 stems per ha.

Whether physiologically aged tree stock is appropriate for use in structural regimes will be dependent on the economics of growing these trees in the nursery and the purchase price of the tree stock at establishment. Planting physiologically aged seedlings can increase stiffness by up to 1.2 GPa which could help increase the stiffness grades achieved by plantation-grown *P. radiata*.

4.3 The wind effect

The fact that the side of the tree the MOE measurement was taken on had a significant influence on the prediction of MOE suggests that one side of the tree experiences different MOE than the other. This is consistent with the findings from Doyle (2011), where there was the least correlation (0.75) between the north-west and south-west sides of the tree when using an Ultra Sonic Velocity scanner. The inherent differences in stiffness on each side of the tree are attributed to reaction wood (a growth stress), which occurs under the windward side of the stem. Compression wood in conifers and tension wood in angiosperms have a lower microfibril angle and are generally regarded as lower stiffness timber (Butterfield, 2006; Jacobs, 1936; Nicholls, 1982). Bascuñán (2004) determined across four stands on the Canterbury plains that stiffness values on the windward side of the stem were 10 to 18% lower than those on the leeward side of the stem. This is a similar finding to the Grabianowski et al. (2004) study where they observed lower stiffness values on a windward-facing strip of trees compared to the leeward strip. From the significant results of this study compounding on previous research, it is conclusive to say that measuring the windward and leeward sides of the tree should be of priority when using ToF tools to measure MOE. This conclusion is furthermore supported by the Toulmin and Raymond (2007) study.

4.4 Limitations and potential for future study

Randomisation in a forestry experiment is the process of randomly assigning trees to different treatment groups or conditions. There was no source of randomisation in the Nelder, every tree was meticulously planted in a systematically chosen spot to accurately represent a particular stocking level. Randomisation is typically used to ensure that an experiment's results are unbiased and applicable to other forests or other forest conditions. Therefore, some could argue that this experiment may have some bias and is site-specific.

Competition-related mortality is a widely known issue in Nelder experiments (Mason, 2023; Parrott et al., 2012). Blanking (planting trees in place of dead ones) was undertaken for some *E. nitens* trees; however, especially at high stockings, significant mortality occurred for both species. This means the nominal planted stocking of the Nelder rings may no longer accurately represent the real stocking. To overcome this problem, many researchers suggest analyses should be run using only trees with a full set of neighbours (Mark, 1983; Mason, 2023; Stape & Binkley, 2010). This would heavily reduce the sample size, which was not appropriate for this study as the sample size was already quite low for high stockings.

The results of the wind effect models could either be a type I or II error because the replication rate was so low. An option for future study could be to set up a blocked experiment where the leeward and windward sides of trees are measured with multiple replications to increase the statistical power of the experiment.

The stiffness values measured were much lower than expected. Watson (2013) measured the same trees at age 6 and 7 with the TreeTap ToF tool and recorded stiffness values of above 10 GPa for *E. nitens*, whereas the measurements with the IML Micro Hammer were only around 6 to 8 GPa. This was an odd observation because the expectation was as trees get older they increase in stiffness (Moore et al., 2018; Toulmin & Raymond, 2007; Waghorn et al., 2007; Watt et al., 2011). This limitation was likely attributed to the use of different ToF tools.

Assuming a constant green density of 1,000 kg/m^3 for both species may not be an accurate way to calculate MOE on a tree level. Assuming a constant green density value for all trees has been shown to result in a 3 to 10% error (Watt & Trincado, 2014; Wielinga et al., 2009). Furthermore, green density is known to differ between species. A more accurate way to calculate MOE would be to measure some green density samples and use an average value for assumed green density.

When collecting data, the precision of repeated height measurements of the same tree was very poor. The measurements sometimes varied by up to 2 m each measurement and because of this variability, it was hard to determine the Vertex's accuracy. The Nelder is densely stocked near the centre, which made it difficult to locate the tops of the trees. This could have been a reason why the measurements were affected. However, the analysis was still valid on a comparative basis.

Since this Nelder experiment was established in 2007/8, the NZDFI has proposed a selection of *Eucalyptus spp.* which have potential to become large-scale durable plantation timber species (Millen et al., 2018). Analysing how stocking influences MOE, DBH and tree height of those *Eucalyptus spp.* would provide very valuable information for the New Zealand forestry industry. Foresters could use those models to determine the optimum initial crop stocking to plant at and what standing MOE estimates to expect. This would further the research in proving that *Eucalyptus spp.* is a valuable structural timber that could be widely planted throughout New Zealand.

5.0 Conclusions

i. Stocking significantly ($P < 0.001$) increased the stiffness of *P. radiata* outerwood by a maximum of up to 3.34 GPa (a 94% increase from 3.56 GPa at 271 stems per hectare to 6.9 GPa at 17,564 stems per hectare).

ii. *E. nitens* outerwood stiffness was significantly greater than *P. radiata* outerwood stiffness by 2 GPa (41% increase) at 1,087 stems per hectare.

iii. Stiffness was significantly ($P < 0.001$) greater for cuttings taken from physiologically aged parents and can increase stiffness by up to 1.2 GPa.

iv. Stocking significantly decreased DBH and tree height for both species ($P < 0.001$).

v. Physiological aging significantly influenced DBH ($P = 0.0067$) but was not significant for tree height ($P = 0.31$).

vi. The side of the tree the MOE measurement was taken on (leeward or windward) was a significant predictor of MOE ($P = 0.0057$).

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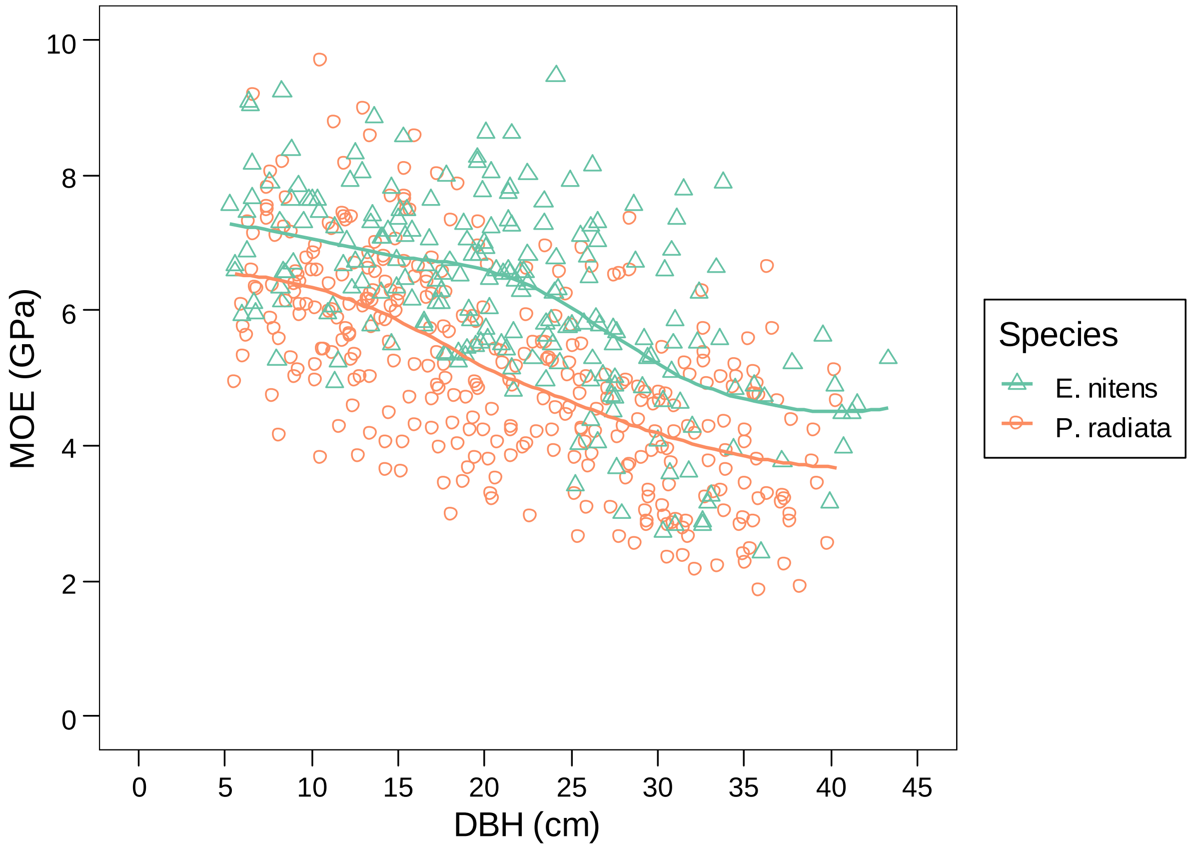
Appendices

Appendix A. DBH and species effect on MOE.



Appendix B. Height and species effect on MOE.