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Modelling the influence of environment on juvenile modulus of elasticity in *Pinus radiata* grown in Chile

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ABSTRACT

Measurements of modulus of elasticity (E) were taken from *Pinus radiata* D. Don growing at 88 sites that encompass the range of environmental conditions over which forest plantations have been established in Chile. Using this dataset the objectives of this research were to (i) identify the key determinants of E across sites and (ii) develop a robust tree level model to predict E across the environmental range over which *P. radiata* is grown in Chile.

Variance components analysis showed variation between sites to account for almost twofold more variation in E than variation within sites. Across the studied region, mean site values of E varied widely ranging fourfold from 3.41 to 14.1 GPa, with a mean of 8.52 GPa. The mean within site variation at each site was 4.50 GPa, ranging from 1.50 to 14.6 GPa.

Of the climatic and stand level variables used in analyses stem slenderness, S, (tree height/diameter at breast height) exhibited the strongest correlation with E accounting for 43% of the variance in the property. The final model of E at the site level included S and minimum air temperature during May, both of which were positively related to E. This model was extended to the tree level through inclusion of a term that accounted for the random intercept between S and E. This model accounted for 75% of the variation in the data and exhibited little apparent bias.

1. Introduction

The last few decades have seen considerable advances in tree breeding and silvicultural practices that have led to greatly improved growth rates in plantation conifers. As a result of these improved growth rates the proportion of juvenile wood has increased (Downes et al., 2000). Juvenile wood is generally characterised by low density, thin cell walls, short tracheids with large lumens, high grain angle, high microfibril angle and large directional ring-to-ring variation. Given these poor qualities juvenile wood has low strength and stiffness, and poor dimensional stability compared to mature wood and is non-homogeneous (Macdonald and Hubert, 2002).

Within plantation forestry there is often an emphasis on maximising the volume of wood products. However, under many circumstances it is advantageous to optimise both growth rate and wood properties. Management strategies often use genetic stock and silvicultural practices that maintain growth rates yet produce wood properties that are within acceptable limits, particularly within stands grown for structural grade timber (Evans, 1997; Downes et al., 2000) Often, the silvicultural practices required to optimise these two objectives are well synchronised. For example, in structural grade regimes, maintaining greater final crop stand density within the limits required to meet minimum diameter restrictions for valuable log grades, results in both improved wood properties and greater volume of valuable framing timber with small branches (Watt et al., 2017).

Modulus of elasticity is a useful determinant of juvenile wood quality in the widely grown plantation softwood *Pinus radiata* D. Don. This property, which measures the resistance of wood to deformation under an applied load, is an important threshold criterion in machine stress grading of structural lumber (Walker and Nakada, 1999) and a key property for determining quality of laminated veneer lumber. In comparison to other internationally traded structural lumber species, plantation-grown *P. radiata* has relatively poor E and dimensional stability which often limits the utility and value of the species. Given the relatively low E of this species there is considerable interest in determining the environmental and stand level factors that regulate this wood property and how they can best be manipulated to produce log grades that meet required threshold criteria.

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Considerable research has investigated the influence of environment and silviculture on *E* for *P. radiata* within New Zealand. National studies using trial series of the same age have demonstrated three–fold variation in juvenile *E* for *P. radiata* (Watt et al., 2009). Increases in *E* that occur across this environmental range have been largely attributable to concurrent increases in stem slenderness, *S*, (tree height/diameter at breast height) and mean minimum air temperature during autumn. Studies within sites have demonstrated *E* to be positively related to both stand density (Lasserre et al., 2005; Waghorn et al., 2007b; Zoric, 2009) and the degree of weed competition (Watt et al., 2005, 2009). Both of these effects have been found to be mediated through the reductions in light availability and increases in *S* that result from greater competition (Lasserre et al., 2005; Waghorn et al., 2007b; Watt et al., 2009).

The applicability of these findings to *P. radiata* growing outside of New Zealand is unknown as little research has been undertaken around environmental determinants of *E* in other countries. Although much is known about how *P. radiata E* varies between sites little research has developed combined models that can be used to predict *E* at the tree level across broad environmental gradients. Further research is therefore needed to develop robust tree level models of *E* for *P. radiata* that examine the generality of previous findings from New Zealand.

Measurements of *E* and stand characteristics were taken from *P. radiata* stands of a similar age (aged 10–14 years) growing at 88 sites in Chile that covered the environmental range over which the species is found in this country. Using this dataset the objectives of this research were to (i) identify the key determinants of *E* across sites and (ii) develop a robust tree level model to predict *E* across the environmental range over which *P. radiata* is grown in Chile.

2. Methods

2.1. Sample sites

Data for this research were obtained from an extensive survey that included 88 forest stands that spanned the geographical distribution of intensively-managed *P. radiata* plantations in Chile (Fig. 1). The selected sites represent a range of climatic conditions and were located from the Maule region (35.1°S) to Los Lagos region (40.4°S) at altitudes ranging from 30 to 895 m above sea level and distances to the coast ranging from 2.7 to 147 km (Table 1). The sites encompassed a diversity of soil types that included metamorphic, granitic, sandy, volcanic ashes, and red clay. In order to isolate the effect of environment on *E*, from that of stand age, only stands aged between 10 to 14 years-old were selected (mean = 11.6 years). The rotation length of plantation grown *P. radiata* generally ranges from 25 to 30 years and the age range selected here represents the age at which wood transitions from corewood to outerwood (Burdon et al., 2004). All stands except for one were pruned to a height of at least 2 m and 60

Table 1
Site level variation in modulus of elasticity (*E*), tree dimensions and climatic variables. Values shown include the mean followed by the range in brackets for the 88 sites.

Variable	Mean and range
E and tree dimensions	
E	8.52 (3.41–14.1)
Stand density (stems ha^{-1})	706 (360–1560)
Basal area ($\text{m}^2\ \text{ha}^{-1}$)	28.9 (15.7–45.9)
Volume ($\text{m}^3\ \text{ha}^{-1}$)	64.6 (73.4–422)
Mean height (m)	20.6 (12.4–28.6)
DBH (mm)	252 (174–399)
Slenderness ($\text{m}\ \text{m}^{-1}$)	83.4 (60.2–103)
Climatic variables	
Mean annual air temp. (°C)	11.7 (9.0–13.7)
Mean min. air temp (°C)	6.54 (4.53–8.15)
Mean max. air temp. (°C)	18.0 (14.8–20.9)
Total annual rainfall (mm)	1566 (794–2502)
Stand location	
Latitude (deg. S)	37.8 (35.1–40.4)
Longitude (deg. W)	72.5 (71.2–73.4)
Elevation (m)	318 (30–895)
Distance to coast (km)	58.1 (2.73–147)

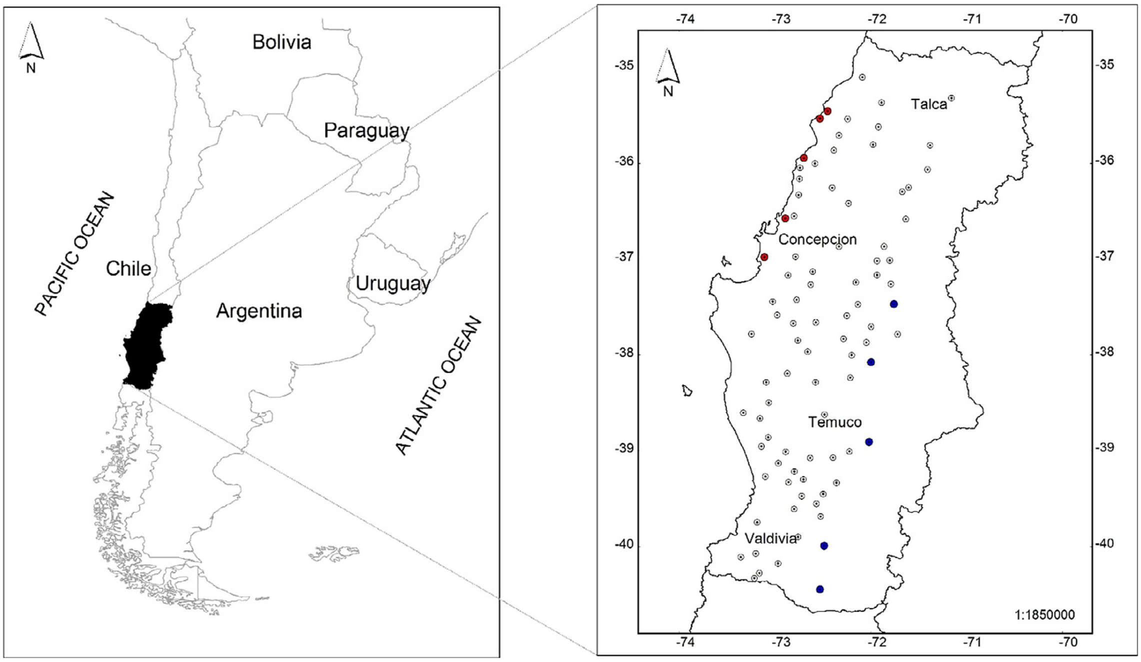

Fig. 1. Map showing (left) the region of the sampled area within Chile and (right) the location of the sample plots which spanned the geographical distribution of *Pinus radiata* plantations in Chile. The five warmest sites are shown as red filled circles while the five coldest sites are shown as blue filled circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)