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Executive summary

Juvenile height growth models are useful to get an indication and understanding of site-species matching and initial decision making. Furthermore, juvenile height yield models are rare especially from sparsely available datasets. However, such models could still be useful to get generate initial information. The aim of this study was to develop preliminary juvenile height yield models from very limited data sources by including site-specific variables for three durable *Eucalyptus* species, namely *E. argophloia*, *E. quadrangulata*, and *E. tricarpa*. The models were plausible and precise with minimal errors as Root Mean Square Error (RMSE) ranges from 0.454 to 1.175 metres. All the models showed a slight negative bias, which implies a minimal underprediction. Topographic wetness index (TWI) negatively influenced height growth of all three of these species, while maximum monthly temperature (MXT) positively influenced height growth of all three of these species. In addition, *E. argophloia* preferred to have more shelter from wind, higher rooting depth and precipitation to grow taller. All variables together indicated *E. agrophloia's* sensitivity to soil moisture availability. This study will provide a first-hand indication of how to handle the management and silviculture of these species, specifically with regard to planting them on appropriate sites.

Introduction

The New Zealand forestry industry is almost entirely based on *Pinus radiata* (D. Don) plantations (NZFOA, 2017) due to the species' rapid growth rate across a broad range of sites (Turner et al., 2008*)* and due to established processing infrastructure and markets. However, there are opportunities to introduce new species, which can produce more naturally durable wood and make a more diversified plantation forest ecosystem (Millen et al., 2018). New species can also ensure a resilient forest economy with healthy forests of all ages producing a range of different products and services.

Some species of *Eucalyptus* have been considered as alternatives to *P. radiata*, especially those that can grow well in dry conditions and produce high quality timber (Menzies, 1995). However, growing *Eucalyptus* in New Zealand has, over the years, been challenging (Berrill & Hay, 2005; Berrill & Hay, 2006) due to very limited information about site requirements (Bell & Williams, 1997; Williams & Woinarski, 1997), pests and diseases that affect their health and productivity (Lin, 2017), and markets for *Eucalyptus* wood products (Apiolaza et al., 2011). Recently the situation has started to change, in part, because of the New Zealand Dryland Forest Initiative (NZDFI) and a renewed consumer demand for *Eucalyptus* timber (Satchell & Turner, 2010). The NZDFI has facilitated research into several naturally durable *Eucalyptus* species, chosen for their desirable properties (Nicholas & Millen 2012), for deployment to ex-pasture lands in relatively dry parts of the country (NZDFI, 2013). Despite these advances, little is known about the growth dynamics of many of these *Eucalyptus* species in New Zealand.

Managed forests are dynamic biological systems that change in response to surrounding environment and silvicultural practices. Forest growth and yield models can help to understand that system and employ better strategies for secure future yield (Clutter et al., 1983). However, forest growth models are mostly developed for established trees (Spiecker et al., 1996) that have undergone canopy closure, when competition among trees is active (Zhang et al., 1996b). Juvenile growth models for the period prior to canopy closure and competition are rare (Avila, 1993; Mason et al., 1997) and they are often more complex and different from the commonly employed growth and yield models (Mason et al., 1997; Zhang et al., 1996a). However, juvenile growth models can provide information about the whole stand development process, and therefore assist in scheduling silvicultural treatments (Mason & Whyte, 1997; Zhang et al., 1996b).

The complexity of juvenile growth may be better explained by combining edaphic and biotic information with traditional growth and yield modelling systems. To do this, there are several approaches that have been successful. Among them, integrating growth factors into the mathematical environment is the most common procedure for both juvenile (Mason, 2001; Mason & Whyte, 1997) and mature stand models (Weiskittel et al., 2011; Woollons et al., 1997). This modelling approach is often based on large datasets, comprising long-term rigorous field measurements (Castedo-Dorado et al., 2007; Pienaar & Rheney, 1995) or remote sensing data (Battaglia et al., 2004; Landsberg et al., 2003).

However, in scenarios where comprehensive data are not available, it may still be desirable to develop preliminary growth and yield models to forecast forest growth (Vanclay, 2010), especially for new species (Berrill et al., 2007; Kitikidou et al., 2016; Palahí & Grau, 2003). Such models are often inaccurate, but can be useful (Box, 1976) to obtain an initial forecast and to make decisions about establishment and management planning. The development of preliminary juvenile yield models over a period of time not only characterises stand development, but also provides insight into the yield potential of the site – a crucial factor for sound management of any forest stand (Tewari & Gadow, 2003).

Tree height is the most widely modelled attribute to describe and indicate site quality and productivity, stand growth potential in terms of dominant height, or even simple height yield over time (Golser & Hasenauer, 1997; Salekin et al., 2019; Scolforo et al., 2016; Westfall et al., 2004). While juvenile height models are available for *Eucalyptus globoidea, and E. bosistoana* (Salekin et al., 2019) in New Zealand, no such models exist for the *Eucalyptus argophloia, E. tricarpa, and E. quadrangualta*, which are also included in the NZDFI programme. Development of species-specific, stand-level preliminary juvenile height models by explaining site factors will not only give forest managers more information but also guide them about species choice for planting and future management. Therefore, the main objective of this study was to develop stand-level preliminary juvenile height yield models for those three species.

Materials and methods

Study sites

The models were developed with data collected from 13, 19 and 18 sites, mostly on retired pasture, planted with *E. argophloia, E. quadrangulata* and *E. tricarpa,* respectively, throughout New Zealand. The sites were situated between 38° 24' 41.94" S and 43° 11' 46.80" S, and 177° 41' 34.97" E and 172° 39' 08.15" E (Figure 1). Site elevations ranged from 34 - 613 metres above sea level (m asl). They experienced cool dry sub-humid to humid climates with total periodic precipitation of 423 – 11,708 mm (only for this study period), and mean annual temperatures of 3 – 24.5℃ (1 January, 2009 – 31 December 2017). However, both temperature and precipitation varied spatially across the planting sites due to their proximity to the coast and changes in topography (Mason et al., 2017). The growing season in New Zealand is typically from October to April, but the duration of the growing period varies due to climate and elevation gradients (Wardle, 1991). The sites covered most of the New Zealand soil classes (Hewitt, 2010), but were dominated by different types of pallic soils.
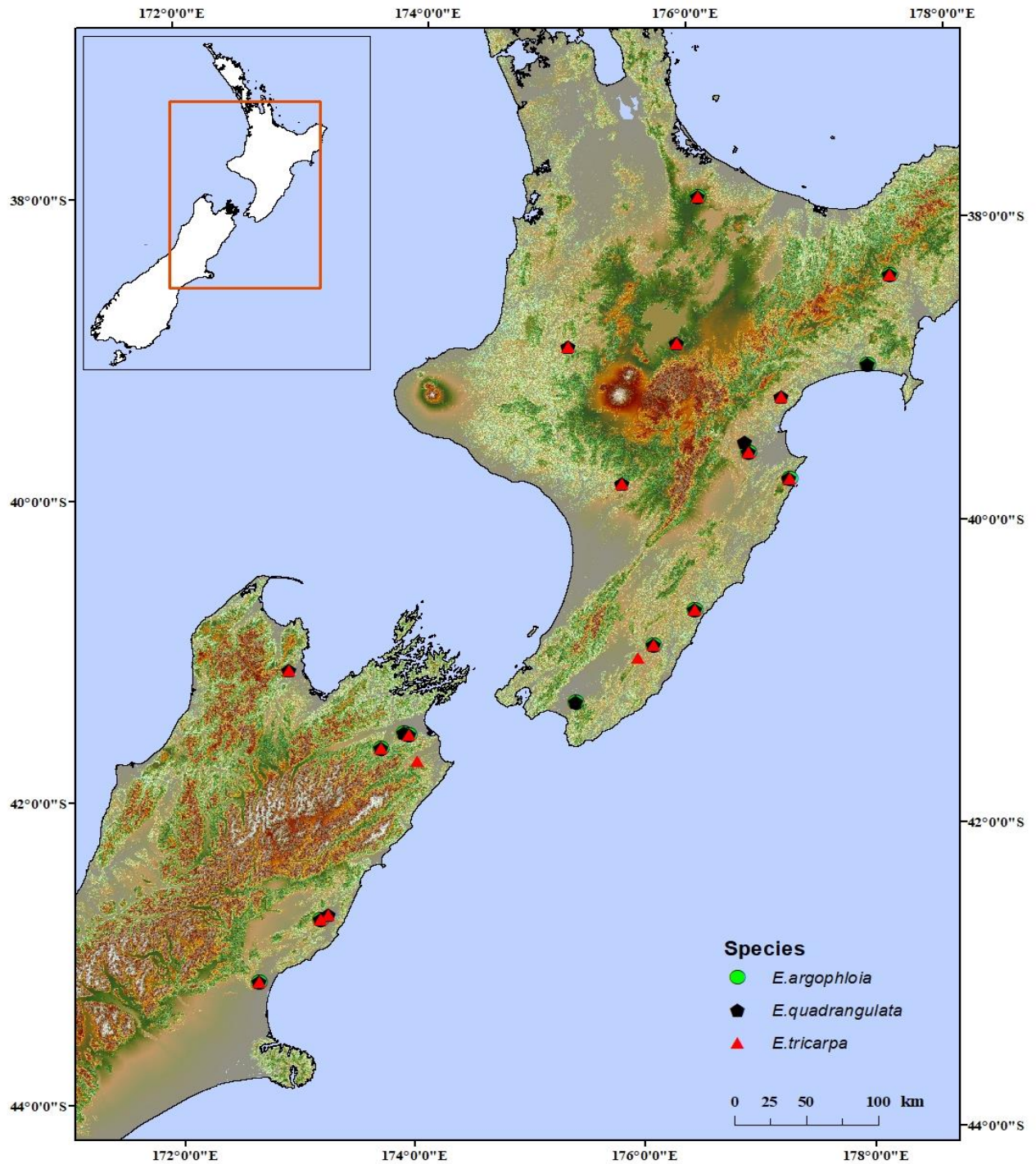
Figure 1. Locations of experimental sites.

Data collection and preparation

Within each trial sites, New Zealand Dryland Forest Initiative (NZDFI) established a single permanent sample plot (PSP) per species with either *E. argophloia, E. quadrangulata* or *E. tricarpa* between 2010 and 2014. PSPs were of different sizes (384 - 784 m^2) and shapes (e.g., circular, square and rectangular). Trees were planted in regular rows and columns within plots, with spacing equal to 2.4 m x 1.8 m. Neither the NZDFI plantations nor the PSPs therein

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were established in a single year. The PSPs were re-measured at different time intervals. Hence, the frequency of measurement was not equal for all PSPs. Tree height (h) was recorded from two to five times during the whole study period for all trees; however, the trees were not measured immediately after planting. In this study, the inventory data for the period 2010 - 2017 were used. Individual tree height (h) was averaged to the plot level at each measurement time (Table 1). Apart from tree measurements, soil, climatic and topographical data were also collected and described below.

A nationwide digital elevation model (DEM) with 15 m resolution (Columbus et al., 2011) was used to derive primary and secondary surface attributes (Table 1). The primary surface attributes included aspect and slope (Travis et al., 1975). From these, the following secondary surfaces were derived: total surface curvature (CURV) (Heerdegen & Beran, 1982; Zevenbergen & Thorne, 1987); topographic wetness index (TWI) (Beven & Kirkby, 1979; Moore et al., 1991); wind exposure index (WEI) (Gerlitz et al., 2015); and the Euclidian distance between the centre pixel of each plot and the nearest coast line (CD). Detailed descriptions of these indices are provided in (Salekin et al., 2019). All surfaces were interpolated or derived using ArcMap 10.4 (ESRI, 2012) or the System for Automated Geoscientific Analysis (SAGA) (Conrad et al., 2015).

Soil pits were excavated to a one metre depth at the centre of each PSP. Soil rooting depth and stoniness were measured according to Gradwell (1972) (Table 1). There were no visible signs for limited nutrition.

The National Institute of Water and Atmospheric (NIWA) Research operates meteorological stations throughout New Zealand. Those measurements are interpolated daily for the whole country on a regular (~ 5 km) grid (NIWA, 2015) called the Virtual Climate Station Network (VCSN). VCSN data, namely temperature, precipitation, and radiation were assigned to the nearest PSP. Temperature data included daily maxima (Tmax) and minima (Tmin), and were summarised by year and month, and averaged for each PSP. Radiation and precipitation data were summed for the whole period (i.e. 2010 – 2017) (Table 1).

Table 1. Study data description, including tree, topographic, soil and climatic data.

Attributes		Species		
Species		*E. argophloia*	*E. quadragunlata*	*E. tricarpa*
Number of PSPs		13	19	18
Tree data				
Tree age (year)	Minimum	1.4	1.4	1.5
	Maximum	6.7	6.7	5.7
Tree height (m)	Minimum	0.535	0.393	0.666
	Maximum	5.120	10.194	6.157
	Mean	2.609	4.253	2.325
	SD	1.183	1.912	1.329
Topographic attributes				
Distance from the coast (Km)	Minimum	5.525	5.545	5.507
	Maximum	43.561	96.590	96.506
	Mean	17.807	20.980	21.681
	SD	9.531	12.484	15.292
Aspect (°)	Minimum	25.539	25.336	15.561
	Maximum	334.875	326.511	326.582
	Mean	141.276	157.238	191.449
	SD	96.495	89.531	107.018
Slope (°)	Minimum	0.555	0.706	0.517
	Maximum	33.672	29.101	32.828
	Mean	16.040	14.831	13.691
	SD	9.088	8.706	8.039
Elevation (m asl)	Minimum	34.753	34.854	50.080
	Maximum	498.096	612.097	611.935
	Mean	143.153	165.439	216.792
	SD	116.489	121.459	127.599
Total curvature	Minimum	-1.679	-2.066	-1.300
	Maximum	2.495	3.385	3.219
	Mean	0.290	0.355	0.265

	SD	0.970	1.197	1.056
Wetness index	Minimum	-0.464	-0.140	-0.377
	Maximum	5.278	5.393	5.616
	Mean	1.361	1.457	1.183
	SD	1.155	1.232	1.075
Wind exposure index	Minimum	0.996	0.960	0.914
	Maximum	1.070	1.072	1.069
	Mean	1.026	1.029	1.016
	SD	0.015	0.024	0.025
Soil data				
Measured rooting depth (cm)	Minimum	40	30	40
	Maximum	100	100	100
	Mean	70.280	79.500	74.444
	SD	16.835	17.228	21.929
Stoniness	Minimum	4	4	2
	Maximum	140	90	130
	Mean	24.178	23.837	26.810
	SD	35.384	21.726	32.414
Climatic data				
Minimum monthly temperature (°C)	Minimum	1.693	0.832	0..32
	Maximum	5.131	5.131	4.733
	Mean	3.410	3.301	3.113
	SD	0.865	0.826	0.958
Maximum monthly temperature (°C)	Minimum	20.990	20.990	20.990
	Maximum	23.456	24.541	24.541
	Mean	22.469	22.702	22.453
	SD	0.588	0.642	0.823
Total periodic precipitation (mm)	Minimum	459.300	423.500	423.500
	Maximum	11,708.300	11,708.300	11,708.300
	Mean	3,481.243	3,197.575	3,002.593
	SD	2,082.786	1,874.396	2,225.063

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Building juvenile height model, testing and validation

In young plantations prior to canopy closure, one might expect that growth should be exponential, with larger trees having greater leaf and root surface areas than smaller trees. Mason and Whyte (1997) expressed this growth function as,

$$\frac{d\overline{h}}{dT} = \gamma \overline{h}^{-\delta} \tag{1}$$

by solving this,

$$\overline{h} = \overline{h}_0 + \alpha T^\beta \tag{2}$$

where,

$$\alpha = ((1-\delta)\gamma)^{\frac{1}{1-\delta}} \qquad \beta = \frac{1}{1-\delta} \tag{3}$$

And, $\overline{h}_0$ = mean height immediately after planting. Unfortunately, this was not measured, so a value of 0.25 m was used because it is the estimated height for *Pinus radiata* seedlings planted in plantations in New Zealand. Also, $\overline{h}_T$ = mean height at stand age T.

Equation 2 has been widely used for modelling juvenile crops (Belli & Ek, 1988; Mason & Whyte, 1997; Salekin et al., 2019). Furthermore, Mason and Whyte (1997) showed that the coefficients of Equation 2 can be extended as a linear function (Equations 4 and 5) to independent variables and their interactions by inserting them into linear functions.

$$\alpha = \alpha_0 + \alpha_1 V_1 + \cdots + \alpha_n V_n \tag{4}$$

$$\beta = \beta_0 + \beta_1 V_1 + \cdots + \beta_n V_n \tag{5}$$

Model validation is a procedure in which the model is tested for agreement with an independent dataset of those observations used to structure the model and estimate its parameters (Shugart, 1984). There are many types of model validation in use, where both quantitative and qualitative assessments are taken into consideration (Sargent, 2013). However, using statistical tests for validation has resulted in strong debate (Sale et al., 2002; Wright, 1972). This is because there are many criteria for assessing suitability of models (Mayer et al., 1994). As each model is unique, there is no single validation process or method, so Kozak and Kozak (2003) advised a combination of techniques. In consequence, the goals of model validation and testing are important, as they are not designed to prove that a model is accurate (Popper, 2014), but rather to see how well the model performs and agrees with the independent observations. Also, the model predictions should be sufficiently statistically

and biologically similar to independent observations that the model choices can be defensible (Yang et al., 2004). In this circumstance, a mixed approach was applied to evaluate the model, by performing a full set of residual analyses. Validation included a visual analysis of graphs of the residuals, the calculation of root mean square error (RMSE), mean absolute error (MAE), and bias.

For validation there was no independent dataset available for this study, nor was the dataset large enough to be subdivided into fit and validation datasets. Therefore, model validation was carried out by the 'leaving-one-out' method of cross-validations (LOOCV), a method which is also called "Jackknife" (Arlot & Celisse, 2010). Thus, the models were fitted n times, leaving out each sample plot once, so that the number of fittings was equal to the number of plots (Sánchez-González et al., 2005), and residuals of predictions for the plots left out were compared with those of the overall model fit.

For model evaluation, the metrics described above were considered. In this case, the overall estimation of these metrics was carried out by averaging as the prediction errors were calculated for each observation.

Statistical analysis

Neither the NZDFI sites nor the PSPs therein were established in a single year. The PSPs were re-measured at different time intervals. Hence, the frequency of measurement was not equal for all the PSPs. Also, a large number of explanatory variables were taken into account. Consequently, to avoid any kind of vague extrapolation by the final model, the most frequently measured points were separated and modelled by using base model Equation 2. Then by separating the coefficients, a hierarchical clustering through recursive partitioning analysis was carried out to identify the most important variables. Next, those important variables and their interactions were modelled against coefficients by using multilinear least square (MLS) regression. Finally, the significant variables and their interactions were included and modelled against height yield through nonlinear least square regression (NLS) (Equation 2).

All statistical analysis was performed in the R statistical environment (R Development Core Team, 2017). An assessment for potential multi-collinearity was performed for all the explanatory variables at the beginning by using variance inflation factor (VIF) with "vif.mer" function of car package in R (Fox & Weisberg, 2011). Elevation, slope, and total curvature were correlated with variables chosen for use in models, hence they were left out from the model building procedure. Then hierarchical clustering was executed through recursive partitioning, based on analysis of variance (ANOVA), by using packages "rpart" and

"rpart.plot" and their corresponding functions for this analysis (Therneau et al., 2010). Model coefficients were fitted and separated by running the "lm" function in the base package. Finally, the height and survival models were fitted using the "nls" function in the base package with the significant variables. The models were validated by following the previously explained procedure. R^2, "rmse", "mae", and "bias" functions were used from the "Metrics" package (Hamner & Frasco, 2018). In addition, residuals were visually inspected for their normality and variance homogeneity. All the graphical analyses and presentations were performed with the "ggplot2" (Wickham, 2016) package.

Results and discussion

Final height growth models (Equations 6, 7 and 8) demonstrated the site effect on juvenile tree height yield. Model residual plots (Figure 2, 3 and 4) and fitting statistics (Table 2) showed that for both species the models were reasonably precise. The residual plots were well distributed, with little or no heteroscedasticity. Models coefficients are provided in the Appendix.

Evaluation statistic values were reasonably reliable with a minor negative bias, except *E. argophloia* (Table 2), which indicated that the models slightly underpredicted tree heights. A minimal increase of RMSE, MAE and SE in the validation statistics can be seen for *E. argophloia* and *E. quadrangualta*, which decreased slightly for *E. tricarpa*.

$$h_{EAG} = h_0 + (\alpha_0 + \alpha_1 * TWI + \alpha_2 * MXT + \alpha_3 * ERD)T^{(\beta_0 + \beta_1 * WEI + \beta_2 * TPRE)}$$
(6)

$$h_{EQ} = h_0 + (\alpha_0 + \alpha_1 * TWI + \alpha_2 * MXT)T^{(\beta_0)}$$
(7)

$$h_{ET} = h_0 + (\alpha_0 + \alpha_1 * MXT)T^{(\beta_0 + \beta_1 * TWI)}$$
(8)

In these equations, h_{EAG}, h_{EQ} and h_{ET} are the height of *E. argophloia*, *E. quadrangualta* and *E. tricarpa* at time T, h_0 is the initial height immediately after planting, MXT is the average daily-monthly maximum temperature, WEI is the wind exposure index, TWI is the topographic wetness index, ERD is the measured rooting depth, TPRE is the accumulation of precipitation over the total period, and α and β are the model coefficients.

The minimal error and minor heteroscedasticity may also have arisen from a non-orthogonal structure and sparsely organised dataset (Salekin et al., 2019). Furthermore, none of the NZDFI plantations were assessed immediately after planting, so use of 0.25 m as an initial

height measurement for all seedlings may also increase the erroneous nature of these models, at least for the first period, where measurements were not available.

All three species were negatively influenced by the wetness index (TWI) and positively influenced by maximum monthly temperature (MXT) (Figures 2, 3 and 4). The wetness index is a modelled estimate of soil wetness based on topography, which is useful when measurements of soil moisture over large spatial scales are not available, as in this study. Taken together, this result implies that all three species experienced greater height growth with dryer soil conditions and hotter air temperatures. Salekin et al. (2019) and Salekin (2019) reported effect of wetness index at both micro and macro site levels for *E. globoidea* and *E. bosistoana* in New Zealand. However, results were reversed in this case, which means these studied species may have lower optimum moisture threshold to grow taller. Water availability is one of the most important factors in tree growth (Beedlow et al., 2013) and trees adapt to different strategies based on moisture conditions (McDowell et al., 2008). Mason (2001) reported that water supply is a critical factor for newly established plantations, and Watt et al. (2004) tested the effects of weeds on the juvenile growth of *Pinus radiata*, based on competition for available water. In comparison with *E. quadrangualta* and *E. tricarpa*, *E. argophloia* showed the greatest height growth with lower TWI. It indicates that *E. argophloia* can sustain with lower available moisture and grow taller.
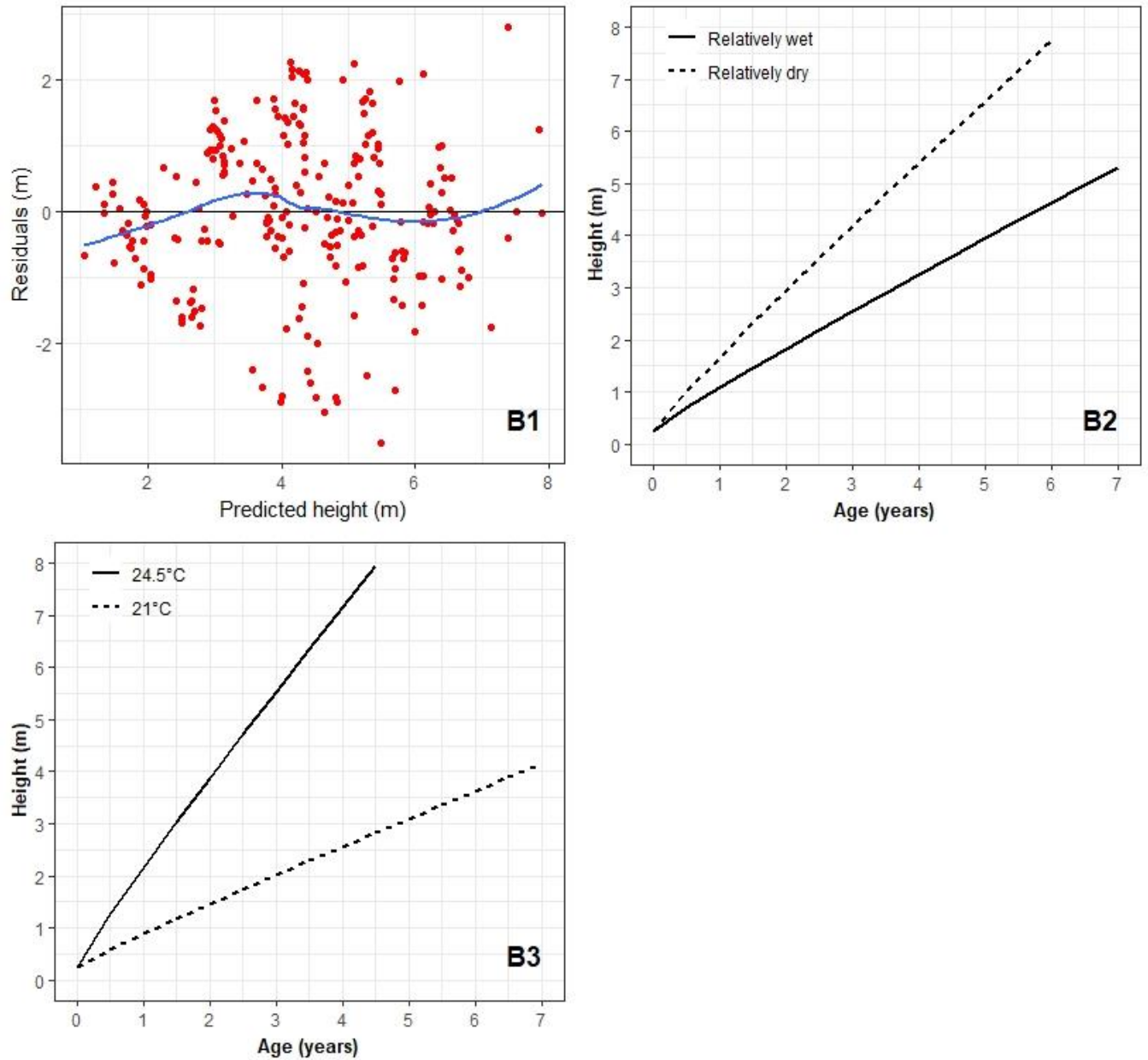
Figure 2. (B1) Residuals plot and influence of site factors on *E. quadrangulata* height growth; (B2) Wetness index; and (B3) Maximum monthly temperature.
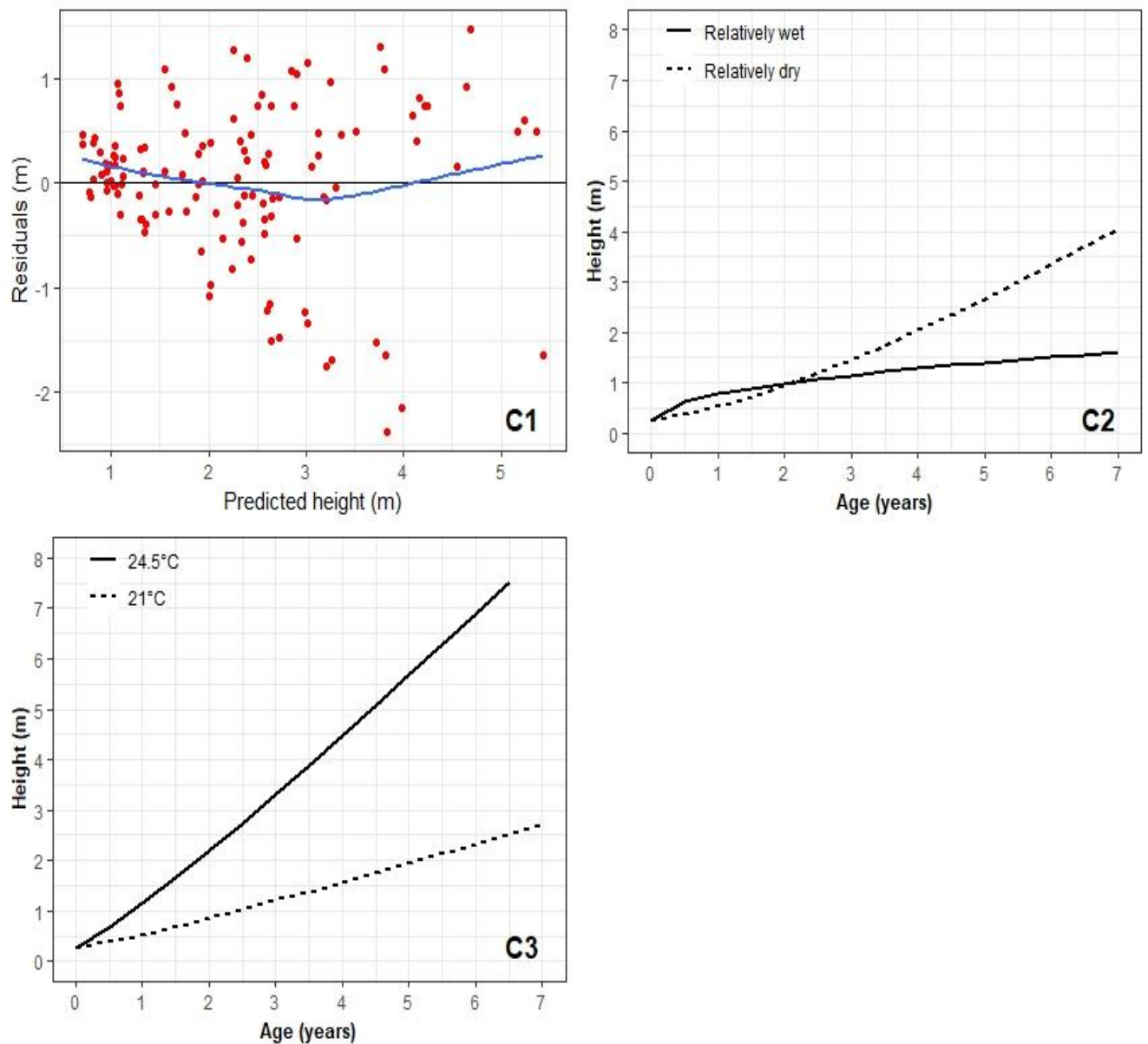
Figure 3. (C1) Residuals plot and influence of site factors on *E. quadrangulata* height growth, (C2) Wetness index; and (C3) Maximum monthly temperature

Only *E. argophloia* was influenced by the rooting depth (ERD), wind exposure index (WEI) and total periodic accumulation of precipitation (TPRE). The ERD indicated how far trees can reach to collect growth resources, e.g. moisture, nutrients. A deeper ERD indicates a positive relationship for *E. argophloia* (Figure 2). Similar reasoning and results were shown by Mason (2004) for *P. radiata* in the central North Island, New Zealand. The effects of WEI on juvenile growth and tree architecture were reported by Brüchert and Gardiner (2006) and they also enhanced surface evapotranspiration (Berg et al., 2017; Fremme & Sodemann, 2018), which may reduce the availability of moisture to juvenile trees as they normally have a very shallow spread of root architecture. Therefore, a decrease in height growth is presumably expected

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with an increase of WEI. The height growth of *E. argophloia* increased with a higher accumulation of total periodic precipitation; however in this case the effect was marginal and this may not have a significant effect – which needs further research. Similar results to the above were found by Salekin et al. (2019) for other *Eucalyptus* species in New Zealand at microsite level and site specific level (Salekin, 2019).

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Table 2. Height growth model fitting and validation statistics.

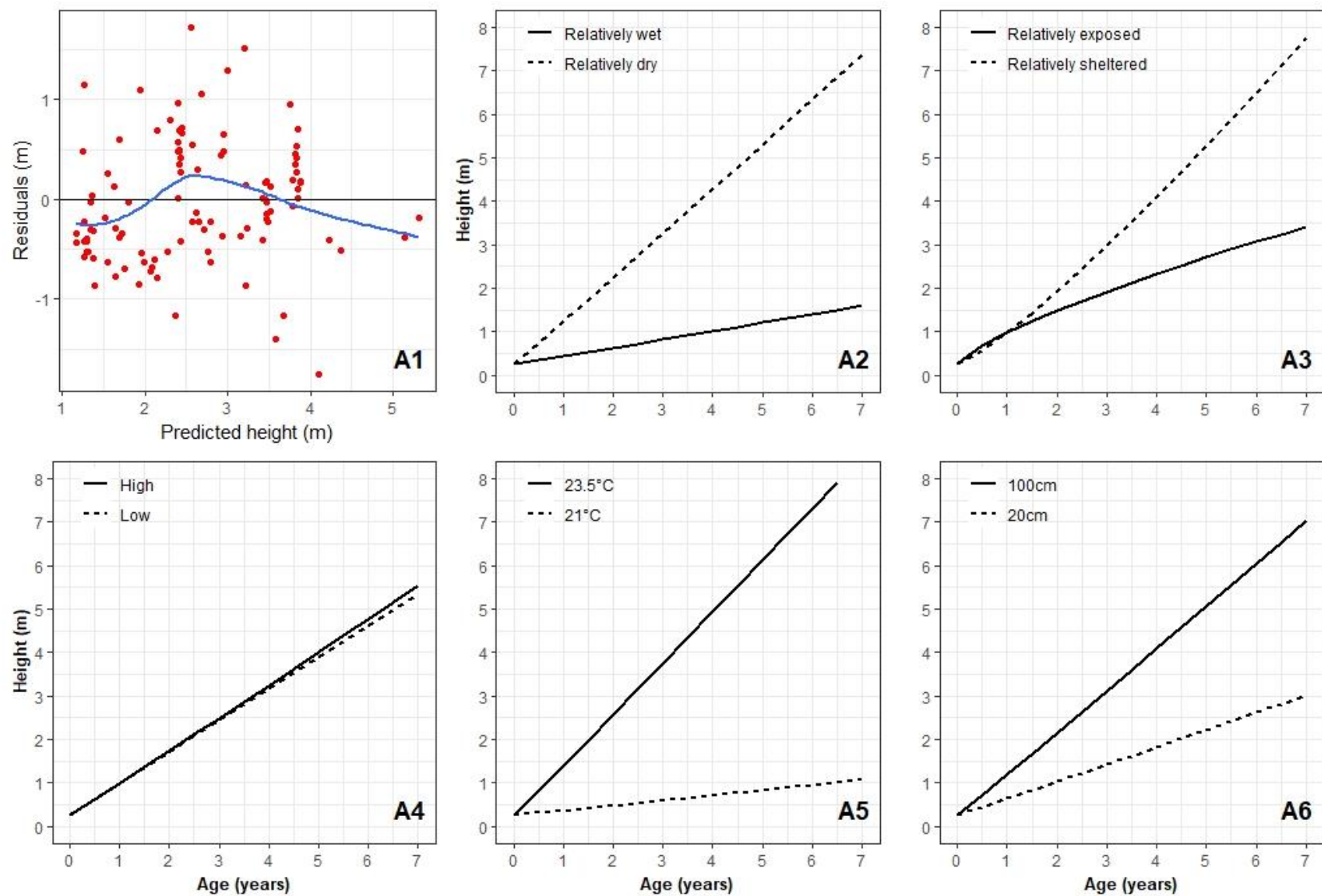| Species	Action	RMSE (m)	MAE (m)	BIAS	SE (m)
E. argophloia	Fitting	0.454	0.368	-0.001	0.470
	Validation	0.457	0.367	0.001	0.477
E. quadrangulata	Fitting	1.175	0.914	-0.006	1.185
	Validation	1.190	0.927	-0.002	1.156
E. tricarpa	Fitting	0.739	0.549	0.024	0.751
	Validation	0.574	0.444	-0.011	0.5859

Figure 4. (A1) Residuals plot and influence of site factors on *E. argophloia* height growth, (A2) Wetness index; (A3) Wind exposure index; (A4) Total accumulation of precipitation; (A5) Maximum monthly temperature and (A6) Measured rooting depth

The findings of other researchers were all in line with this study. For example, Olesen and Grevsen (1997) reported that the vegetative growth of plants under such conditions was highly modulated by the temperature and intercepted radiation, which was consistent with these results. Prior and Bowman (2014) found that *Eucalyptus* are sensitive to temperature and that they grow best within the temperature ranges 15°C - 24°C. Temperature effects are prominent at the mature stage though they can gain up to 20% total growth at the juvenile stage within the mentioned temperature range. Also, Way and Oren (2010) noticed that increasing temperature influenced tree growth positively, except in the tropical biome, which means that others biomes are maintained under their optimum temperature (Ryan, 2010). Also, Yang et al. (2006) found a growth increase with increasing temperature. Comparing with the three studied species, *E. tricarpa* showed the lowest sensitivity to maximum temperature: it grew slowly with increasing temperature.

Limitations

All the models developed and discussed in this study were developed from sparsely available and non-orthogonal datasets. There were no available data from the stage immediately after planting, which was a primary need of this study and this may affect results at the initial stage. Therefore, these models should be used cautiously.

Most of the plantation sites were in the dry regions of New Zealand, and it is expected that the trees were limited by edaphic resources, for example soil water and nutrients, though it was not explicitly proved in this study. The soil data were collected manually based on expert knowledge at each site, which is limited. Many PSPs are located at different sites, hence any direct comparison of these species should also be made cautiously. This is because different sites have different characteristics, which may affect the height growth of these species differently. For example, the maximum monthly temperature was 24.5°C for *E. quadranguala* and *E. tricarpa*, whereas *E. argophloia* sites only reached 23.5°. On the other hand, climatic data from VCSN were found to be reliable and useful, except for precipitation data as this is more localised (Mason et al., 2017). For this reason, it may be useful to have local climatic station data to test the effect of precipitation, which was not available at all.

Summary and conclusion

The principal aim of this study was to develop height growth models for three durable *Eucalyptus* species by identifying and including the most influential site-specific factors in the framework. This study explicitly tested a comprehensive set of site-specific edaphic and biotic variables for two juvenile dryland *Eucalyptus* species.

This study found that topographic and climatic features were the most important factors for juvenile plantation height growth of these species. The findings show that *E. quadrangulata*, *E. tricarpa*, and *E. argophloia* grew taller in relatively less moist soils and sites with higher maximum monthly temperatures. Moreover*, E. argophloia* also needed wind shelter and deeper potential rooting depth to grow taller at the juvenile stage. The models and results here for the three *Eucalyptus* species are useful for forest managers to get an indication about site-species matching as well as silvicultural regimes.

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Appendix

Table I. Final height models summary with parameters

Species	Statistics	α_0	α_1	α_2	α_3	β_0	β_1	β_2
E. argophloia	Est	-8.966e+00	-1.394e-01	4.184e-01	6.926e-03	7.173e+00	-6.00e+00	-4.311e-05
	SE	1.230e+00	1.994e-02	5.714e-02	1.184e-03	1.155e+00	1.105e+00	9.736e-06
	p	7.48e-11	3.13e-10	6.30e-11	6.24e-08	1.21e-08	3.95e-07	2.43e-05
E. quadrangulata	Est	-6.65766	-0.10637	0.35481	-	0.93218	-	-
	SE	0.97762	0.01865	0.04495	-	0.05657	-	-
	p	8.02e-11	3.50e-08	1.10e-13	-	<2e-16	-	-
E. tricarpa	Est	-3.36245	0.17342	-	-	1.29096	-0.14438	-
	SE	0.55371	0.02676	-	-	0.09253	0.02382	-
	p	1.47e-08	2.02e-09	-	-	<2e-16	1.54e-08	-