A spatial comparison of redwood and radiata pine productivity throughout New Zealand

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Abstract

Coast redwood (*Sequoia sempervirens*) is a very productive and long-lived conifer that constitutes less than 1% of New Zealand plantations. Despite the potential of redwood, little research has compared its productivity with radiata pine which comprises 90% of plantations. This paper describes a recently developed growth model for redwood and compares national maps of productivity for redwood and radiata pine that have been recently published. These productivity maps were used to generate regional comparisons of both species at ages 30, 40 and 50 years, under a clearwood regime, for areas that were suitable for redwood. On average, within the North Island, redwood was 8% more productive than radiata pine at age 30 (mean total volume of 972 vs 901 m^3/ha) and this gain increased to 45% by age 50 (total volume of 2,186 vs 1,505 m^3/ha). At a regional level, volume gains for redwood were largest for the Waikato, Taranaki and the Bay of Plenty, where increases over radiata pine averaged 60%, 57% and 56%, respectively, by age 50.

Redwood was more productive than radiata pine within many northern areas of the South Island with moderate-to-high rainfall. However, within most eastern and southern sites in the South Island radiata pine had higher productivity, reflecting the higher sensitivity of redwood to cold, dry conditions. Redwood produces a very stable appearance grade timber with low shrinkage that has a higher value per cubic metre than radiata pine. The wilding risk from redwood has been rated as very low and the species is an ideal choice for erosion control. Redwood has no major insect or disease problems and is resistant to damage by fire and wind. In combination with the high growth rates documented in this paper these factors demonstrate the considerable potential of redwood for further afforestation within New Zealand. Further research should collect more redwood growth data from Northland and areas that were projected to have high productivity in the South Island to improve confidence in model predictions.

Introduction

Coast redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) is a long-lived evergreen tree that is endemic to a narrow coastal strip from central California to southern Oregon in the US. Redwood has been planted for over 100 years throughout New Zealand and this alternative species has considerable potential for further afforestation. Compared to the

Figure 1: Stand near Taumarunui, age 84, volume 4,293 m^3/ha, mean top height 59.1 m

native distribution, New Zealand has a similar range in mean annual temperature, but rainfall is more evenly distributed throughout the year (Watt et al., 2021). As a result, impressive growth rates have been recorded in redwood stands growing within this country that include measured mean top heights of 66.4 m and volumes of 4,479 m^3/ha at 86 years (Kimberley & Watt, 2021). However, growth rates vary widely throughout New Zealand and the poor performance and survival of many stands has been related to siting, establishment and seed source (Knowles & Miller, 1993).

In contrast to redwood, which comprises less than 1% of the plantation area, radiata pine is the most widely planted species in this country, constituting 90% of plantations (NZFOA, 2020). Radiata pine has been widely planted as it grows rapidly within most New Zealand climates and the wood can be used for a variety of purposes (Mead, 2013). However, redwood does have a number of advantages over radiata pine. Redwood maintains high growth rates over a long period, is windfirm, resistant to pests and diseases, and produces a valuable appearance grade timber (Rapley, 2018). Quantitative information describing the growth rate of redwood throughout New Zealand and how this compares to radiata pine may provide growers with the confidence to establish redwood more widely.

300 Index models

Characterising site productivity is challenging as volume is not only affected by the environment, but also stocking, age and silvicultural regime. The 300 Index was developed to normalise these last three variables and is defined as the volume mean annual increment at age 30 for a stand growing at 300 stems/ha. An advantage of this metric is that once the 300 Index has been defined, volume can be predicted for a range of stockings, ages and silvicultural regimes.

A model of the 300 Index has been developed for radiata pine and is widely used throughout New Zealand for evaluation of site quality and predictions of growth and yield (Kimberley et al., 2005). Initially, a 400 Index model was developed for redwood in 2006 from a small set of plot data (n = 40 plots/stands) that used a normalisation stocking and age of, respectively, 400 stems/ha and 40 years. Recently this model was updated to a 300 Index using a far more comprehensive dataset obtained from 179 Permanent Sample Plots (PSPs). This update normalised the age and stocking to 30 and 300 stems/ha, respectively, which allows more direct productivity comparisons with radiata pine (for more details see Kimberley & Watt, 2021).

Using these 300 Index models, a grower can simulate stand dimensions (stocking, volume, mean top height, basal area, crown height) over time from either initial stocking and estimates of site productivity (site index and 300 Index) or measurements of stand dimensions obtained from plot data. These models are particularly well suited for regime evaluation as they can be used to assess how productivity is influenced by rotation length, stocking, and the intensity and timing of thinning. The most recent 300 Index model for redwood is available for use on the Forest Growers Research website (https://fgr.nz/programmes/calculators/redwood-growth-calculator/) and has been fully described in Kimberley and Watt (2021). The interface of this Excel-based model is shown in Figure 2.

Volume productivity surfaces

Estimates of 300 Index from these models can be used to develop surfaces that describe spatial variation in volume productivity for a species. Ideally, this is undertaken using plot data that covers a wide environmental range. Figure 3 shows the distribution of the PSPs that have been previously used to develop redwood (n = 130) and radiata pine surfaces (n = 3,676) (Watt et al., 2021). The 300 Index values are linked through their location with a comprehensive suite of environmental variables and a model is created to estimate 300 Index from these predictor variables. Once the model is finalised, a surface of 300 Index is then created using the environmental surfaces that were used in the final model.

These productivity surfaces provide growers with an understanding of how productivity is likely to vary within their estate and can be used to guide silvicultural decisions. These surfaces can also be used to quantify the potential productivity of unforested areas that growers may be interested in purchasing or planting. Although these surfaces provide useful decision support, growers should also consider other microsite factors that may limit growth when evaluating the potential of a particular species.

Species comparisons of volume productivity using surfaces

Comparisons of volume productivity between surfaces for different species can be used to match species to site, and below we compare productivity of redwood and radiata pine at a regional level. Estimates of 300 Index that are shown in Figure 4 are expressed as a total volume at age 30 assuming a final crop stocking of 300 stems/ha. This final crop stocking is fairly typical of radiata pine clearwood regimes, but is lower than the 400–700 stems/ha typically used for redwood. The comparison shown in Figure 4 therefore favours radiata pine. As a shade-tolerant, late succession species, redwood can typically carry a higher stand density at a comparable age than early succession species such as radiata pine.

The West Coast of the South Island was excluded from predictions as this very wet and often infertile environment was not adequately represented by PSPs for the redwood data. Areas with rainfall >3,000 mm have also been masked to ensure that predictions are not extrapolated beyond the environmental range used to create the model.

Although there were no plots within Nelson, Marlborough or Tasman, predictions were made for these three regions as plot data from areas with similar

Figure 2: Interface of the recently developed 300 Index growth model for redwood. The next iteration of this calculator (available through https://fgr.nz/programmes/calculators/redwood-growth-calculator/) will predict carbon

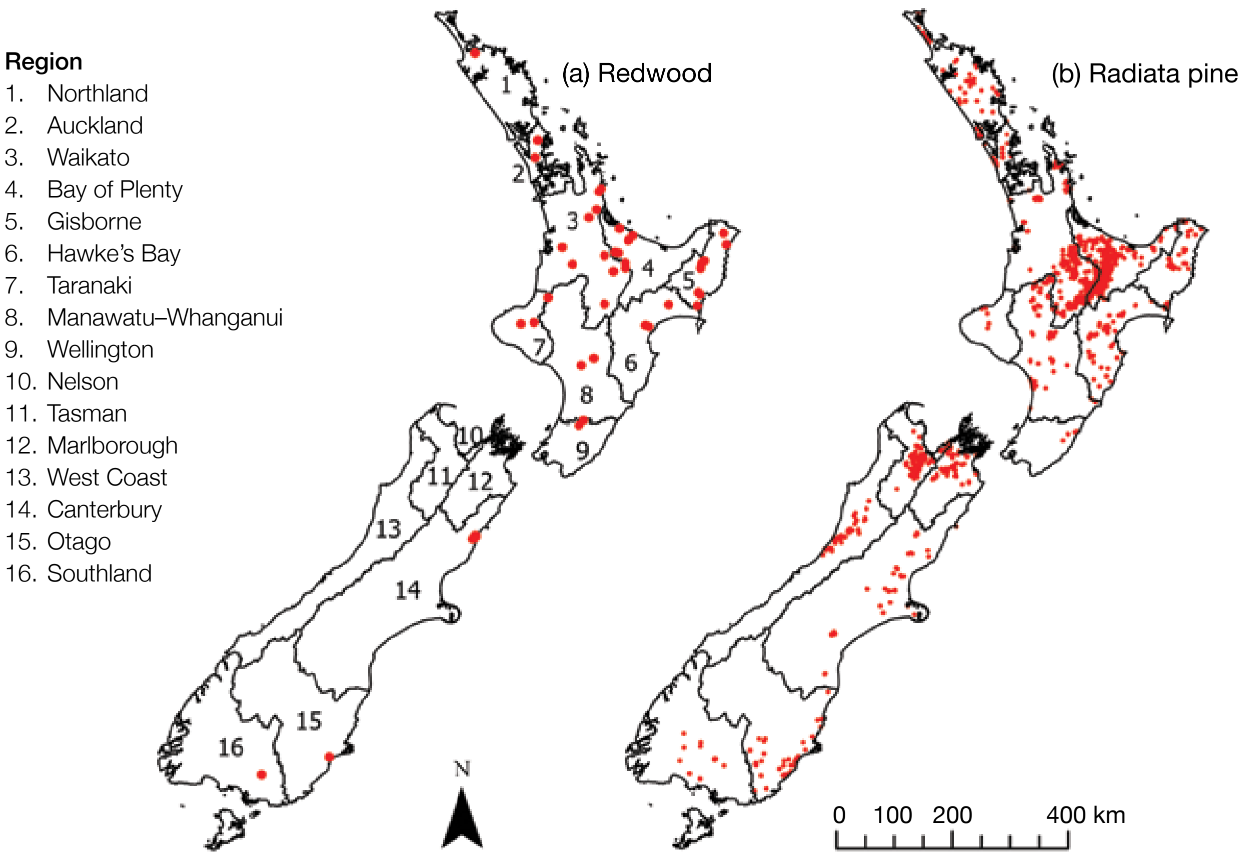

Figure 3: Distribution of (a) redwood (n = 130) and (b) radiata pine (n = 3,676) plots (red-filled circles) used to create spatial surfaces shown in Figure 4 (the regional boundaries shown on the maps were used for all analyses)

climates were used for developing the model (see Watt et al., 2021 for climatic ranges). In the case of eastern Marlborough, plot data was available from dry, warm locations on the east coast of the North Island, while for north-western Marlborough, Nelson and Tasman, plot data was available from areas with low-to-moderate air temperatures and moderate-to-high rainfall. None of these three regions have nutrient limitations that are as severe as the West Coast of the South Island. This environmental matching is common practice for extending the range over which model projections can be made. However, further research should collect data from these potentially high productivity regions in the South Island and elsewhere with sparse data (e.g. Northland) to verify model predictions.

The displayed surface in Figure 4a conservatively assumes an establishment date of 2000 (see Watt et al., 2021 for more details). However, redwood stands established after this time are likely to be more productive, as most plantings over the last two decades have used high productivity clones and there is a greater awareness of the importance of weed control in young redwood stands (Rapley, 2018).

Figure 4a can be used to identify areas suitable for growing redwood and those that are unsuitable. Areas where the redwood 300 Index is greater than 7 can be considered suitable for redwood (i.e. where the volume age 30 is more than 210 m^3/ha). Similarly, Figure 4b can be used to identify areas where the radiata pine 300 Index is greater than 7, which can be considered suitable

Table 1: Areas of land suitable for redwood and radiata pine, by region and island (includes percentage of total area considered suitable for each species)

	Suitable area (km^2)		Percent land area (%)	
	Redwood	Radiata pine	Redwood	Radiata pine
North Island				
Northland	11,100	12,360	89	99
Auckland	4,552	4,794	92	97
Waikato	21,637	23,900	91	100
Bay of Plenty	10,082	12,070	84	100
Gisborne	7,357	8,183	88	98
Hawke's Bay	11,085	14,083	78	100
Taranaki	6,794	6,782	94	93
Manawatu	18,148	21,618	82	97
Wellington	7,315	7,611	91	95
South Island				
Nelson	350	415	82	98
Tasman	3,687	6,921	38	72
Marlborough	2,757	7,695	26	74
Canterbury	4,073	34,500	9	78
Otago	5,666	22,265	18	71
Southland	6,434	19,680	21	63
By Island				
North Island	98,070	111,402	86	98
South Island	22,966	91,477	18	72

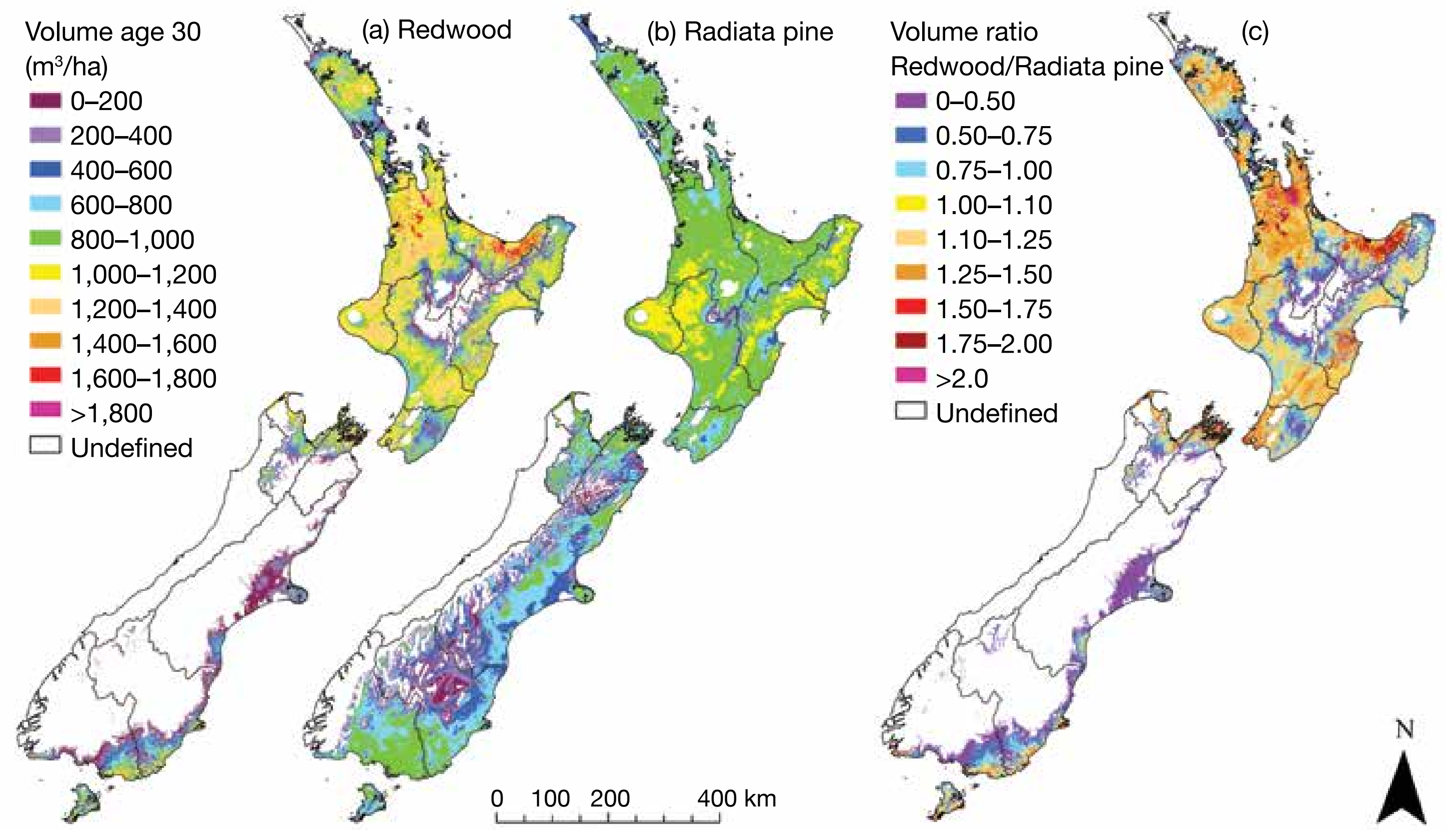

Figure 4: Spatial variation in volume at age 30 for stands with a final crop stocking of 300 stems/ha for (a) redwood and (b) radiata pine and (c) the ratio of redwood/radiata pine volume

for radiata pine. These are fairly broad definitions and simply indicate that the species can be established and grown; higher thresholds would generally be required for either species to be considered commercially viable. Areas suitable for growing redwood and radiata pine are summarised by region in Table 1.

Across the entire North Island 86% of the land area was suitable for redwood (Figure 4a), which was not markedly less than the 98% of area that was suitable for radiata pine (Table 1). With the exception of Nelson, all regions within the South Island had substantially less land suitable for growing redwood than radiata pine, and most areas east of the Southern Alps in Canterbury and Otago were unsuitable or displayed low growth rates (Table 1; Figure 4a). Throughout most of the east coast of the South Island growth rates of radiata pine were predicted to be higher than those of redwood (Figure 4) and a far larger proportion of the land area was suitable for radiata pine within this area (Table 1).

Redwood volume at age 30 years exceeded 1,000 m^3/ha in most western and north-eastern parts of the North Island with moderate air temperatures and both low seasonal water deficit and vapour pressure deficit (Figure 4a). In this region volume reached up to 1,800 m^3/ha within the Waikato and north-eastern Bay of Plenty. Redwood productivity was markedly lower in the South Island, apart from the very northern and southern regions, which have low seasonal water deficits and vapour pressure deficits (Figure 4a). Most areas along the east coast were unsuitable for the species as they were too dry and/or cold and there was only a narrow coastal strip of land suitable for redwood in which stand volumes were of low-to-moderate productivity (Figure 4a).

Spatial predictions of volume for radiata pine show relatively consistent productivity throughout most of the North Island (Figure 4b). Volumes most commonly ranged from 800–1,000 m^3/ha, but higher values of 1,000–1,200 m^3/ha were also predicted in many locations within Taranaki, Manawatu–Whanganui, the Hawke's Bay and Gisborne (Figure 4b). Within the South Island the highest volumes occurred on fertile sites in the very south (on warmer, low elevation sites) and north, while the lowest volumes occurred in dry, cold eastern regions (Figure 4b).

The redwood/radiata pine volume ratio ranged widely throughout New Zealand (Figure 4c). Redwood was markedly more productive than radiata pine within the Waikato, Bay of Plenty and Taranaki. Elsewhere within the North Island the volume ratio mostly exceeded 1 demonstrating that redwood outperforms radiata pine on most sites. Within the North Island radiata pine was more productive than redwood (i.e. ratio <1) on cold sites with severe seasonal water deficits that were mainly located in the south-east, Central North Island or the far north (Figure 4c). Within the South Island redwood was more productive than radiata pine in the very north and in isolated areas in the very south. However, in most regions the ratio was far less than 1, indicating the greater productivity of radiata pine on cold, dry sites (Figure 4c).

Species comparisons across an age and stocking range for different regions

Figure 5 shows the relationship between age and volume simulated by the 300 Index growth models of both species for low-, medium- and high-quality sites (as defined by 300 Index). These trajectories are shown for stand densities of 300 stems/ha (Figure 5a) and 600 stems/ha (Figure 5b) which, respectively, represent final stockings of typical clearwood (pruned) regimes and regimes utilising higher stockings, including carbon regimes. By definition, the volume for both species is identical at age 30 for all three common site qualities (300 Index values) at 300 stems/ha (Figure 5a). However, redwood greatly outperforms radiata pine after age 30 for each site type, with gains over time most marked for high productivity sites (Figure 5a).

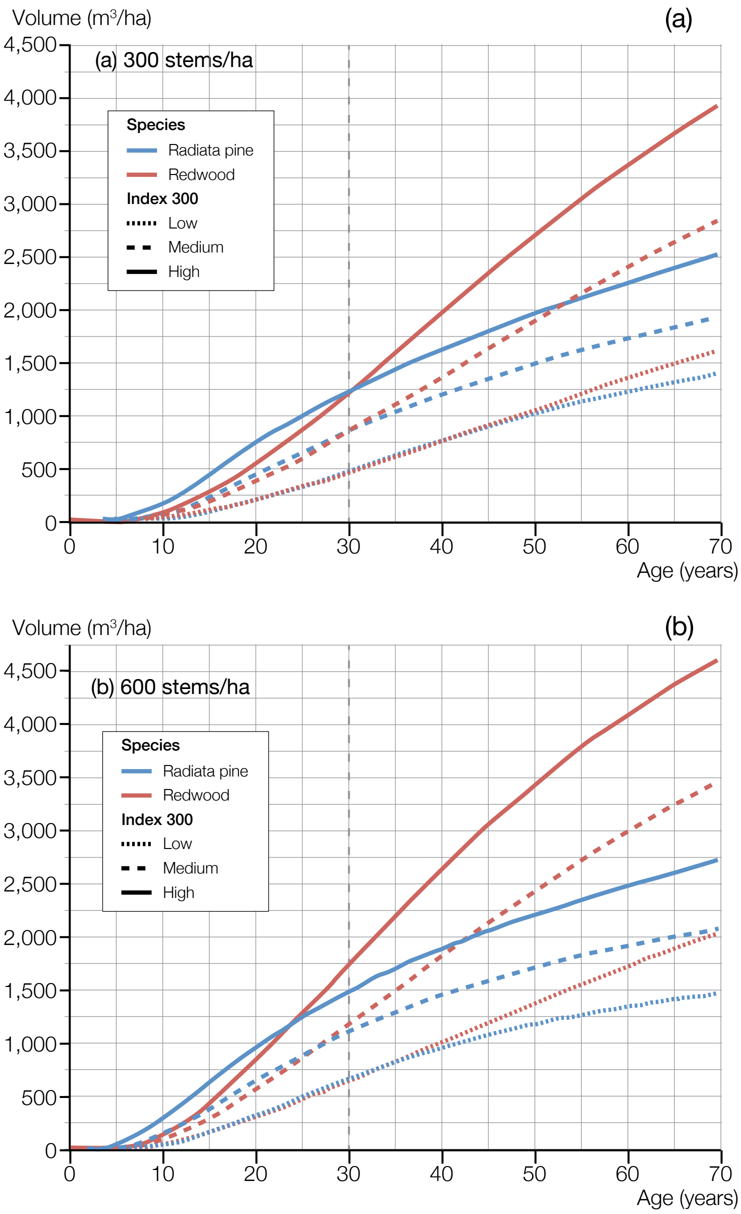

Figure 5: Relationship between age and volume, by species and 300 Index values, with the latter category representing sites with low (15 m^3/ha/yr), medium (27.5 m^3/ha/yr) and high (40 m^3/ha/yr) productivity

At the higher stocking redwood outperforms radiata pine on all three site types, and species divergence in volume for a common site type is greater than at the lower stocking (Figure 5b). The extent of this divergence is such that by age 70 redwood volume productivity on medium-quality sites exceeds that of radiata pine growing on high-quality sites at both stockings (Figure 5). These results illustrate the potential of redwood for rapid growth after age 30 and highlight the conservative nature of the presented map of redwood productivity (Figure 4a) that is indexed to 30 years and a stocking of 300 stems/ha.

This methodology has also been used to predict average regional productivity for both species across an age range using a final crop stocking of 300 stems/ha. As the area suitable for redwood is more restricted, the comparisons use average regional productivity values for radiata pine constrained to areas considered suitable for redwood (defined as 300 Index >7 or volume, age 30 >210 m^3/ha). This approach was adopted as it provides growers with guidance around species selection for sites that are suitable for both species. Predictions of volume made at age 30 (Figure 4) were averaged by region and the distribution of these productivity values within each region were then grown on to ages 40 and 50, with the composite average extracted for these older ages. An area weighted average of volume predictions was then determined for the North and South Island for all three ages.

Within the North Island these predictions show that redwood volume was on average 8%, 28% and 45% higher than that of radiata pine at, respectively, 30, 40 and 50 years after planting (Table 2). On average, across suitable areas in the North Island redwood reached volumes of 972, 1,581 and 2,186 m^3/ha, respectively, by ages 30, 40 and 50, with radiata pine reaching a lower predicted volume at all ages and 1,505 m^3/ha by age 50 (Table 2). At a regional level, volume gains for redwood were largest for the Waikato, Taranaki and Bay of Plenty where volume increases over radiata pine averaged 60%, 57% and 56%, respectively, by age 50. With the sole exception of Gisborne at age 30, predicted redwood volume was on average higher than that of radiata pine in all regions, at all ages within the North Island.

Within the South Island, there was a species interchange in the productivity ranking over the three examined ages (Table 2). At age 30, redwood was 14% less productive on average than radiata pine, but by age 40 redwood productivity exceeded that of radiata pine by 1%, with this gain increasing to 14% by age 50. Nelson was most suitable for redwood of all the examined regions, with gains in productivity over radiata pine, increasing from 15% at age 30 to 50% by age 50 (Table 2). Compared to radiata pine only a small proportion of Marlborough was suitable for redwood (26 vs 74%, Table 1), but within this suitable region in the north-west of the province, redwood

Table 2: Regional variation in predicted mean volume for redwood and radiata pine and the ratio of redwood volume to radiata pine volume

Region	Vol. redwood (m^3/ha)			Vol. radiata pine (m^3/ha)			Ratio – redwood/radiata vol.		
	30 yrs	40 yrs	50 yrs	30 yrs	40 yrs	50 yrs	30 yrs	40 yrs	50 yrs
North Island									
Northland	874	1,432	1,991	831	1,164	1,435	1.05	1.23	1.39
Auckland	812	1,335	1,862	805	1,136	1,408	1.01	1.18	1.32
Waikato	1,077	1,741	2,393	896	1,229	1,500	1.20	1.42	1.60
Bay of Plenty	1,058	1,709	2,348	905	1,239	1,509	1.17	1.38	1.56
Gisborne	849	1,395	1,943	950	1,284	1,554	0.89	1.09	1.25
Hawke's Bay	936	1,527	2,115	920	1,253	1,524	1.02	1.22	1.39
Taranaki	1,140	1,839	2,525	1,001	1,335	1,606	1.14	1.38	1.57
Manawatu	971	1,581	2,187	942	1,276	1,546	1.03	1.24	1.41
Wellington	817	1,345	1,876	799	1,130	1,401	1.02	1.19	1.34
South Island									
Nelson	948	1,545	2,139	822	1,155	1,426	1.15	1.34	1.50
Tasman	798	1,312	1,830	829	1,161	1,432	0.96	1.13	1.28
Marlborough	918	1,498	2,076	803	1,133	1,405	1.14	1.32	1.48
Canterbury	434	741	1,060	670	992	1,262	0.65	0.75	0.84
Otago	614	1,025	1,445	781	1,112	1,383	0.79	0.92	1.04
Southland	712	1,179	1,652	839	1,171	1,441	0.85	1.01	1.15
Weighted mean									
North Island	972	1,581	2,186	901	1,234	1,505	1.08	1.28	1.45
South Island	680	1,128	1,582	789	1,118	1,389	0.86	1.01	1.14

Note: Values are shown for three different rotation lengths using a stocking of 300 stems/ha at age 30 years productivity was on average 14% higher at age 30, with this gain increasing to 48% by age 50 (Table 2). Similarly, in north-eastern Tasman (which contained considerable land suitable for redwood) both species had similar average productivity at age 30, but redwood outperformed radiata pine at ages 40 and 50 (Table 2). Redwood was generally less productive than radiata pine within Otago and Canterbury, although there was convergence between the species with increases in stand age. Similarly, redwood was only substantially more productive on average than radiata within Southland at age 50 years (Table 2).

Regional comparisons are not shown for the West Coast of the South Island due to an absence of growth data from this region. However, the region was predicted to have the highest productivity for redwood of any region within the South Island. Its wet, warm climate is likely to suit redwood, although there are also many nutrient deficient areas where growth rates may be low. Further research should establish growth plots within this region to verify and calibrate model predictions and identify fertile areas likely to be suitable for redwood.

Additional considerations

Despite the conservative nature of these spatial projections, model results clearly show that redwood is more productive than radiata pine throughout most of the North Island when grown on a similar rotation length for clearwood. As redwood timber is used for decorative purposes its value per cubic metre is markedly higher than that of industrial softwoods such as radiata pine (Rapley, 2018). Comparative log price data is available from the California log market where redwood, Douglas-fir, sugar pine and ponderosa pine logs are sold in the same market. Long-term trends within this market show log prices for redwood exceed prices for equivalent quality pine and Douglas-fir log grades by, respectively, 100% and 60%. Recent economic analyses show that the internal rate of return for redwood regimes increases with increased rotation length (Rapley, pers. comm.) due to the rapid increase in volume after age 30, during which time there is also increased recovery of more valuable heartwood and clear grades from pruned stands.

Species comparisons over longer rotation lengths with higher final crop stockings strongly favour redwood. Redwood gains in growth over radiata pine at older ages are more marked for regimes utilising higher stockings, including carbon regimes (e.g. Figure 5a vs 5b). This finding is consistent with previous international literature. Exceptional old-growth redwood forests have been found to sequester more carbon in decay resistant heartwood than forests dominated by any other species (Sillett et al., 2020). Redwood individuals growing within the native range constitute the oldest and tallest living trees on earth that have reached ages exceeding 2,200 years (Brown, 1982; Earle, 2018; Sillett et al., 2020) and heights of 115 m (Watson, 1993).

The slow decay rate of redwood reduces carbon liabilities. Redwood is noted as very decay resistant and

Figure 6: Clonal stand age 7.5 near Hunterville, comprised of clones selected for superior growth, form, basic density and durability

post-harvest litter remains on the ground surface long after harvesting (Madej, 2010), which suggests that redwood roots also decay at a slow rate (Garrett et al., 2012). The ability of redwood to re-coppice after harvesting keeps a proportion of the root system alive and functioning. The decay rate of roots could be best estimated from the decay rate of above-ground material (Garrett et al., 2012), and previous research shows that redwood coarse woody debris has a lower decay rate than radiata pine (Busing & Fujimori, 2005; Garrett et al., 2010).

Several studies have advocated the suitability of redwood for erosion control (Burdon, 1975; Marden, 1993;

Phillips et al., 2013). Redwood has wide-spreading lateral roots (Olson et al., 1990) that increase the interlinkage of roots between neighbouring trees, which together with root grafting further increases root cohesion. Observations show that young redwood have many fine lateral roots, which suggests that the species has the potential to bind and hold the soil together strongly (Phillips et al., 2013). The ability of redwood to coppice following clearfell reduces the post-harvest window of erosion vulnerability through extending the life of the root system (Garrett & Clinton, 2013). As has been described in detail by Garrett and Clinton (2013), redwood has many characteristics that are ideal for erosion control.

A lack of crown-shyness, high growth rates, shade tolerance and the ability to coppice following harvesting make redwood an excellent choice for management under selectively harvested, continuous cover regimes. Such regimes are capable of producing both high-value wood products and high levels of sequestered carbon managed to limit liabilities.

New Zealand grown redwood is a very stable timber with low shrinkage (Cown, 2008). However, both basic density and heartwood durability have been found to be highly variable (Cown, 2013). Wood density has been found to average 330 kg/m^3, with high variation between individual trees (Cown, 2013). Importantly, there appears to be large genetic variability in wood density, which demonstrates that clones can be selected for this trait (Cown, 2013). The heartwood of redwood is a naturally durable alternative to preservative treated pine at H1.1, H1.2 and H3.1 treatment levels (NZS 3602, 2003). Heartwood is produced from an early age (Vincent, 2001) and is rated as moderately durable when in contact with the ground (Hughes, 1982; Page & Singh, 2014) and durable in above-ground situations, but shows considerable variation in natural durability (Clark & Scheffer, 1983).

Redwood forests present a very low risk of wilding spread. Redwoods rely on vegetative, as well as seedling, reproduction (O'Hara et al., 2017) and produce small cones inconsistently that contain seeds with very low viability (Jepson, 1910). Wilding spread is a significant problem around New Zealand plantation forests and the National Environmental Standard for Plantation Forestry requires mitigation of wilding spread risk. A tool developed by the New Zealand Forest Research Institute gives redwood a zero rating for wilding spread risk.

An important consideration when selecting a species is vulnerability to disease, wind and fire as these have a large influence on long-term crop stability and health. Redwood has a justified reputation as a healthy species with no major insect or disease problems (Bain & Nicholas, 2008). The species is resistant to toppling and breakage under strong storm winds (Brown et al., 2008) and the thick bark and lack of flammable resin of older trees protects the species against fire (Jacobs et al., 1985; Stuart, 1987; Olson et al., 1990).

In contrast to redwood, radiata pine is susceptible to a number of damaging needle cast diseases within New Zealand, including Dothistroma needle blight, cyclaneusma needle cast and red needle cast (Watt et al., 2019). Importantly, radiata pine is very prone to windthrow at older ages, when grown at the high stockings typical of carbon regimes, and this vulnerability will increase under climate change (Watt et al., 2019). Radiata pine is also prone to fire damage and research clearly shows that this risk will increase in the future within New Zealand (Watt et al., 2019).

Conclusion

This study clearly shows the potential of redwood as a plantation species within New Zealand. Comparisons of spatial surfaces, within areas suitable for redwood, show that mean redwood volume is on average 8% higher than that of radiata pine within the North Island at age 30 and that this gain increases to 45% by age 50. Although this research clearly demonstrates the potential of redwood and how productivity varies, these surfaces and predictions are only intended to be a guide and growers should take into account any impacts of microsite on productivity when evaluating the potential of redwood. Further research should collect data from a broader range of sites in the South Island, with a focus on potentially high productivity sites that currently do not have plots (i.e. the northern and western regions). The integration of these data will improve confidence in the model and provide a more robust understanding of the extent of potential productivity gains.

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