Comparing regional variation in carbon sequestration for radiata pine and redwood throughout New Zealand

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Abstract

New Zealand has committed to a net zero carbon target by 2050 that will require significant afforestation of fast-growing exotic species. An understanding of where best to plant important plantation species in the landscape is critical for optimising carbon sequestration for both individual growers and the country as a whole. This paper presents and compares national spatial surfaces of carbon for the two fast-growing conifers radiata pine and coast redwood under a range of stand ages (30, 40, 50 years) and stand densities (400, 650, 900 stems ha^{-1}).

When averaged across New Zealand and all scenarios, redwood was 6% more productive than radiata pine in the North Island (1,900 vs 1,799 tonnes CO_2 ha^{-1}), but 51% less productive in the South Island (690 vs 1,405 tonnes CO_2 ha^{-1}). Increases in carbon with greater stand density and age were markedly higher for redwood than radiata pine, and consequently redwood is particularly well suited for clearwood and carbon regimes with longer rotation lengths.

Redwood generally outperformed radiata pine on warm, wet sites with moderate-to-high fertility, with gains highest in the West Coast, Taranaki, Waikato and Bay of Plenty. Radiata pine had higher carbon than redwood in cold and or dry areas and differences were most marked in Canterbury, Southland, Otago and Marlborough. Redwood should not be planted too close to the coast as it is salt intolerant and the species also requires shelter from strong prevailing winds. However, if redwood is correctly sited, and well managed during the establishment phase, it is capable of very high productivity on suitable sites. As predictions of carbon made here were derived from models based on fully stocked, well-managed permanent sample plots we recommend they are reduced by 15% before being applied to standard forestry sites.

Introduction

Plantation forests will play a critical role in achieving the net zero carbon aspirations of New Zealand. We need to plant up to 2.8 million ha of new forests between now and 2050 to achieve a low carbon economy under the carbon neutral target (New Zealand Productivity Commission, 2018). The centrepiece of New Zealand's response to climate change is radiata pine as the species has high growth rates over the short term (Watt et al., 2021c). However, the growth rate of radiata pine declines after 20–30 years (Watt et al., 2021b), which may limit our ability to build enduring carbon stocks if we establish large areas of this species as permanent carbon forests. This medium- to long-term issue could be best mitigated through increased planting of fast-growing climax species such as coast redwood. Redwood is a fast-growing exotic species that is able to maintain high growth rates over hundreds of years and has been found to sequester more carbon than forests dominated by any other species (Sillett et al., 2020).

Although redwood plantations are widely distributed throughout New Zealand the species constitutes only 1% of the total plantation area (Rapley, 2018), which is markedly lower than the 90% occupied by radiata pine (NZFOA, 2020). Recent research that has spatially compared the volume productivity of both species highlights the potential of redwood for further afforestation within New Zealand. Redwood volume productivity at age 30 for clearwood regimes, with low stand density, was found to be higher than that of radiata pine within most regions in the North Island and these gains increased with rotation length and stand density (Watt et al., 2021b).

As the carbon value of forests is becoming an important determinant of plantation value, species comparisons need to consider variation in carbon as well as timber volume. The Emissions Trading Scheme (ETS) is the primary tool used within New Zealand for reducing greenhouse gases and meeting domestic and international climate change commitments. Through placing a value on carbon, the ETS encourages carbon sequestration through activities such as afforestation. Within the ETS, forest growers receive a unit for each tonne of CO_2 sequestered, with the unit value varying according to supply and demand.

The precision with which carbon sequestration can be quantified over time for different species is an important element of the ETS that strongly influences the number of units allocated to a forest grower. The number of units allocated to afforested areas is currently based on inventory information for large plantings (≥100 ha) or Look-up Tables for smaller areas (Ministry for Primary Industries, 2017). Look-up Tables are pre-calculated and specify the quantity of carbon stock that will be produced by the species annually. These Look-up Tables give regional average values of carbon for radiata pine and national averages for Douglas-fir, but a generic look-up table is provided to cover all other exotic softwoods including redwood.

A fine-grained spatial characterisation of carbon for important plantation species, such as radiata pine and redwood, could be used to develop robust regional estimates of carbon stocks through time. This regional characterisation would incentivise growers to establish the most productive species within each region, benefiting both growers and the overall New Zealand carbon position. As described previously, there are many regions within New Zealand where redwood volume productivity exceeds that of radiata pine (Watt et al., 2021b) and the research reported here was undertaken to spatially compare carbon between these two species.

Predictions of radiata pine and redwood carbon

Predictions of carbon sequestration were made for both species using estimates of stem volume from growth models, allometric equations and functions describing basic density and carbon partitioning. Carbon predictions for both species were made across the New Zealand range of both 300 Index and Site Index, and the range in mean annual air temperature (*T*) for radiata pine.

Predictions were made at three initial stand densities (400, 650 and 900 stems ha^{-1}) grown to three ages (30, 40 and 50 years). The lower stand density (400 stems ha^{-1}) selected here is representative of final crop stockings used for pruned clearwood regimes for both species, while the highest stand density (900 stems ha^{-1}) is the scenario for high stocking regimes for both species. The intermediate stand density represents a carbon regime with lower stocking for both species. This stand density is also representative of a structural grade regime for radiata pine and a highly stocked pruned regime for redwood growing on sites with higher fertility.

The predictions described above for radiata pine were made using Forest Carbon Predictor (FCP) Version 5.1. The FCP is a stand level modelling system that integrates the radiata pine 300 Index growth model, a stem wood density model and the C_Change model (see Beets et al., 2011 for a detailed description). The 300 Index growth model was used to generate mean top height (MTH) and basal area from productivity indices, which were then used to predict under-bark stem volume using a national stand-level radiata pine volume function (Kimberley & Beets, 2007).

Annual variation in basic wood density was predicted using a wood density model from growth predictions and site mean annual air temperature (Kimberley et al., 2015). Stem volume and basic density were used by C_Change to estimate stemwood dry matter, which was then used to predict biomass in other components from growth partitioning functions (Beets et al., 1999). Biomass was converted into carbon using a range of conversion factors specific to each biomass component. Carbon flows to dead organic matter were estimated and decay functions were used to predict losses of carbon from these pools (Garrett et al., 2010).

Although FCP cannot be directly applied to redwood we adopted a similar approach for this species. The redwood 300 Index growth model (Kimberley & Watt, 2021) was used to predict MTH and basal area and these variables were used to estimate stem volume. Basic density was assumed to be 339 kg m^{-3}, which was the mean value from 16 North Island sites spanning an age range (Cown, 2008). Using functions from previous literature, bark volume adjusted for voids was assumed to be 18% of stemwood volume with a basic density of 437 kg m^{-3} (Miles & Smith, 2009), and allometric relations were used to predict biomass of branches and foliage from diameter at breast height (Kizha & Han, 2016).

Biomass of redwood roots was predicted using a root:shoot ratio of 0.23, the default for coniferous forests (IPCC, 2003). The volume of trees dying during each growth period was estimated by the redwood growth model and these estimates were partitioned to different components and decayed at the same rate as radiata pine. Biomass was converted into carbon using the fractions described in Van Pelt et al. (2016) and the IPCC default of 0.50 was used for deadwood.

For both species, total carbon was defined as carbon stored in the above ground biomass, below ground biomass and dead wood pools. For radiata pine, carbon in the litter pool was also included, but this pool was not estimated for redwood. Carbon sequestration for both radiata pine and redwood was converted into tonnes CO_2 ha^{-1} by multiplying by 3.667.

Spatial prediction of carbon using regression models

The carbon predictions, described above, provided data that were used to develop 18 regression models (2 species x 3 densities x 3 ages) using R (R Development Core Team, 2011). The regression models were built from 63 carbon estimates for radiata pine (seven 300 Indices x 3 Site Indices x 3 *T*) and 24 carbon estimates for redwood (eight 300 Indices x 3 Site Indices). For the radiata pine carbon predictions, the regression models were of the form:

$$C = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4S + a_5S^2 + a_6S^3 + a_7T + a_8T^2 + a_9VS + a_{10}VT + a_{11}ST + a_{12}V^2S + a_{13}V^2T + a_{14}S^2T + a_{15}VST + e \quad (1)$$

where, C is carbon (tonnes CO_2 ha^{-1}), V is the 300 Index (m^3 ha^{-1} yr^{-1}), S is Site Index (m), T is mean annual air temperature (°C), a_i are regression coefficients and e is the normally distributed random error term. Models were simplified by eliminating terms not statistically significant (at α=0.1). The same model form was used for redwood models, except that terms involving T were excluded. Predictions made using this model form fitted the data very well, with more than 99% of variance explained by all 18 models.

Projections of carbon were made across New Zealand for each of the 18 models using previously developed surfaces of 300 Index, Site Index (Watt et al., 2021a; Watt et al., 2021c) and mean annual air temperature (Wratt et al., 2006). All projections of carbon were made at a 25 m resolution using ArcGIS Pro version 2.5.1 (ESRI, Redlands, CA, US).

Projections from all surfaces were constrained to sites that were suitable for radiata pine as this species had broader spatial range than redwood (Watt et al., 2021a). This approach allowed fairer overall regional comparisons, but still gave visual comparisons of species productivity at sub-regional levels for site species matching. This constraint was implemented through creating a mask with 300 Index >7 for radiata pine and applying this mask across all 18 carbon surfaces. Additional surfaces were created describing the carbon difference between species (redwood carbon – radiata carbon) for all nine combinations of stand densities and ages. Using zonal statistics, mean values of carbon were determined by region and Island for the 18 surfaces of carbon and the nine surfaces describing the carbon difference.

Species comparisons of carbon using surfaces

Maps showing spatial variation in carbon for both species under all nine scenarios show that redwood productivity (Figure 1) was far more variable than that of radiata pine (Figure 2). Predictions of carbon for stands that were 40 years old growing at medium stand densities show that redwood reaches values of around 3,500–4,000 tonnes CO_2 ha^{-1} in suitable areas (Figure 1) which greatly exceeds the 2,000–2,200 tonnes CO_2 ha^{-1} reached by radiata pine under a comparable scenario (Figure 2). When averaged over all stand densities and ages (Table 1), redwood was 6% more productive than radiata pine in the North Island (1,900 vs 1,799 tonnes CO_2 ha^{-1}), but 51% less productive in the South Island (690 vs 1,405 tonnes CO_2 ha^{-1}).

These maps also show the strong positive relationship between carbon and both stand density and age for the two species (Figures 1 and 2). Redwood carbon increased on average 103% between 30 and 50 years (1,747 vs 862 tonnes CO_2 ha^{-1}), while carbon for radiata pine only increased by 51% (1,910 vs 1,268 tonnes CO_2 ha^{-1}) over this age range (Table 1). Increases in carbon with higher stand density were also more marked for redwood than radiata pine (Table 1). Redwood carbon increased by 36% across the stand density range (1,493 vs 1,096 tonnes CO_2 ha^{-1}), while carbon for radiata pine only increased 25% across this range (1,768 vs 1,414 tonnes CO_2 ha^{-1}).

Regional comparisons of productivity for low stand density regimes

Through using the same scale for carbon, Figure 3a–c directly compares spatial variation in productivity between species for a clearwood regime at age 40. Table 2 shows the regional means for both species under this regime from ages 30–50.

The most productive areas for redwood were located in the Waikato, Bay of Plenty, Taranaki and West Coast as these regions have moderate air temperatures, little seasonal water deficit and low vapour pressure deficit. Redwood productivity was lowest in dry and or cold regions within Otago, Canterbury, Southland and Marlborough and only exceeded 1,000 tonnes CO_2 ha^{-1} at age 40 in a few coastal areas in the eastern South Island (Figure 3a).

Table 1: Variation in mean carbon sequestration by species, age, stand density and region for areas that are suitable for radiata pine, as defined by radiata pine 300 Index >7 m^3 ha^{-1} yr^{-1}

Age (years)	Stand density	Region	Carbon (t CO_2 ha^{-1})	
			redwood	radiata
30	Low	Nth Island	1,007	1,239
30	Low	Sth Island	351	911
30	Medium	Nth Island	1,289	1,463
30	Medium	Sth Island	453	1,119
30	High	Nth Island	1,495	1,601
30	High	Sth Island	533	1,254
40	Low	Nth Island	1,606	1,628
40	Low	Sth Island	564	1,248
40	Medium	Nth Island	1,943	1,864
40	Medium	Sth Island	698	1,473
40	High	Nth Island	2,159	2,003
40	High	Sth Island	820	1,601
50	Low	Nth Island	2,211	1,937
50	Low	Sth Island	779	1,501
50	Medium	Nth Island	2,586	2,163
50	Medium	Sth Island	939	1,706
50	High	Nth Island	2,804	2,296
50	High	Sth Island	1,074	1,830
Mean values by category				
Region		Nth Island	1,900	1,799
		Sth Island	690	1,405
Age		30	862	1,268
		40	1,310	1,640
		50	1,747	1,910
Stand density		Low	1,096	1,414
		Medium	1,330	1,635
		High	1,493	1,768

Note: The mean values shown by age and stand density were determined as weighted averages across the North and South Islands

Spatial predictions of carbon for radiata pine show relatively consistent productivity throughout the North Island (Figure 3b). The regions with the highest productivity were Gisborne and Taranaki. In the South Island the highest carbon occurred on fertile sites in the very south and north while the lowest values occurred in Canterbury and Otago (Figure 3b).

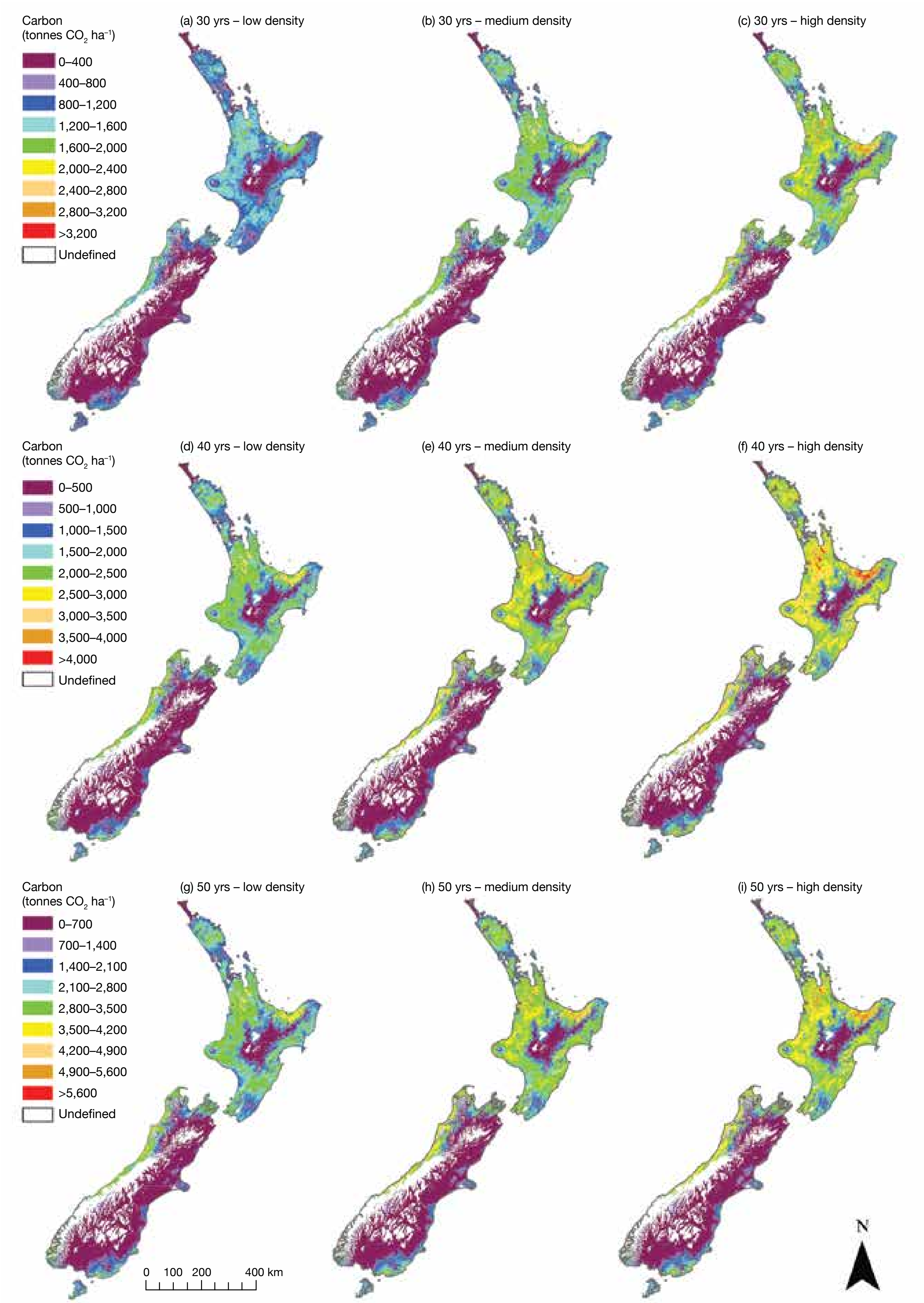

Figure 1: Spatial variation in redwood total carbon sequestration at age 30 (a–c), 40 (d–f) and 50 years (g–i) for stands grown under a low, medium and high stand density

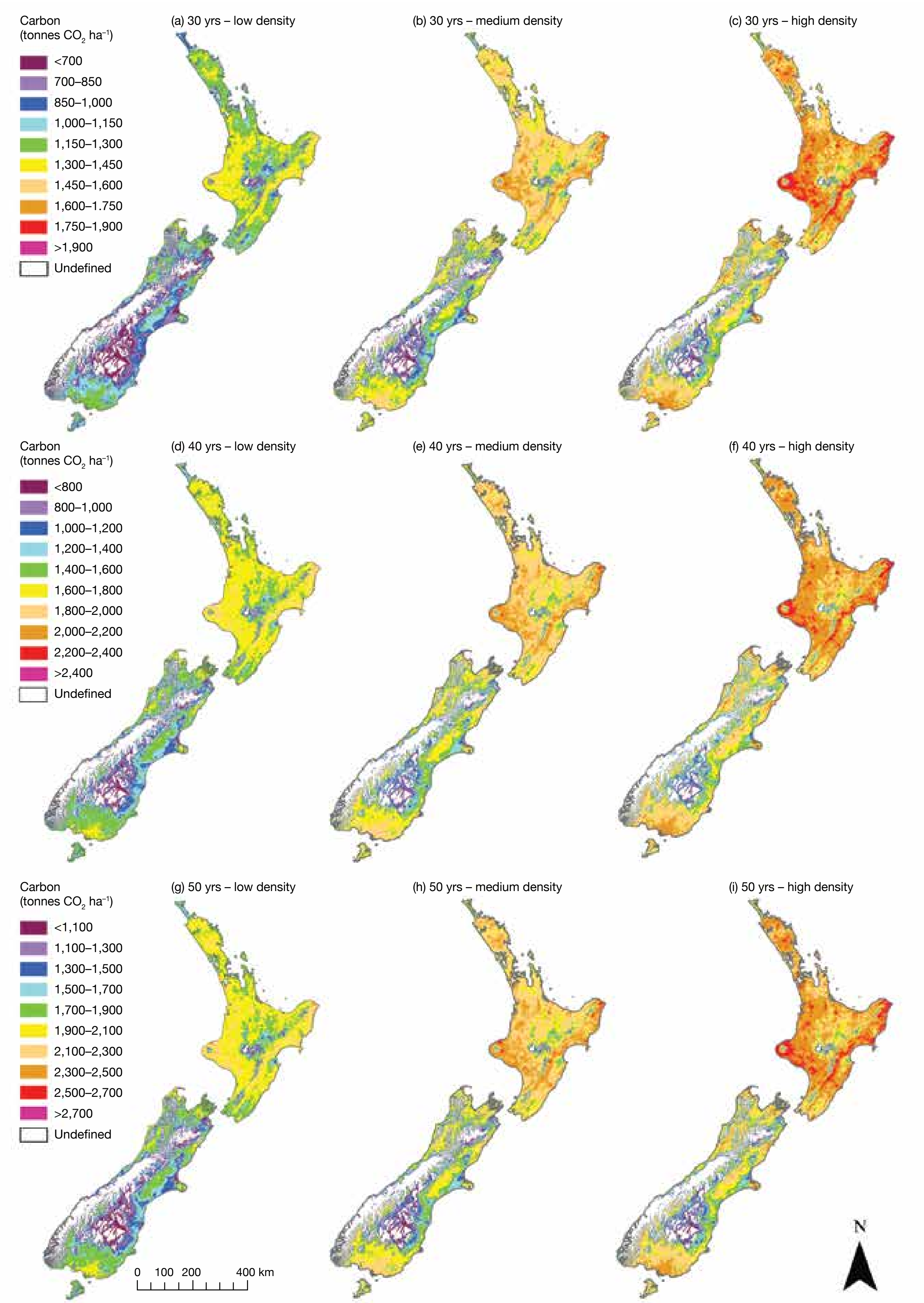

Figure 2: Spatial variation in radiata pine total carbon sequestration at age 30 (a–c), 40 (d–f) and 50 years (g–i) for stands grown under a low, medium and high stand density

At age 30 the West Coast of the South Island was the only region where mean carbon for redwood exceeded that of radiata pine (Table 2), although mean values were very similar between species for the Waikato and Taranaki (Table 2). By age 40 mean carbon for redwood was higher than that of radiata pine in three regions of the North Island and this expanded to all regions except Gisborne by age 50. Within the South Island redwood was only more productive than radiata pine on the West Coast and Nelson at ages 40 and 50 (Table 2).

The difference map (redwood – radiata pine carbon) clearly shows that redwood outperforms radiata pine at age 40 in most areas that experience warm air temperatures and moderate-to-high rainfall. These differences were most marked in the Waikato and Eastern Bay of Plenty where redwood carbon exceeded that of radiata pine by over 1,200 tonnes CO_2 ha^{-1} (Figure 3c). Carbon productivity of radiata pine was markedly higher than that of redwood in regions that were cold and/or dry. These areas were mostly located within the central North Island or east of the Southern Alps in the South Island (Figure 3c).

The percentage area with carbon sequestration higher for redwood than radiata pine (i.e. carbon difference >0) was also quantified, because in contrast to the mean this measure is not skewed by large species differences in carbon. Under the clearwood regime, the percentage area with higher carbon for redwood increased within the North Island from 29% to 57% and 69%, respectively, at ages 30, 40 and 50 (Table 3). At age 30, almost half of the Waikato had higher carbon for redwood than radiata pine and the species also outperformed radiata pine within large areas in both Taranaki (39%) and the Bay of Plenty (36%). By age 50, redwood had higher carbon than radiata pine across, respectively, 93% and 81% of the area within Taranaki and Waikato (Table 3).

Within the South Island the percentage area where redwood outperformed radiata increased slightly from 13–21% between ages 30 and 50. The low percentage of suitable area for redwood in the South Island was due to the large tracts of land east of the Southern Alps that had low predicted values of carbon for redwood. Within the West Coast and Nelson, and to a lesser extent Tasman, there were substantial areas where redwood sequestered more carbon than radiata pine, even at age 30 (Table 3).

Regional comparisons of productivity for regimes with higher stand densities

Predictions of productivity under the regime with higher stand density (900 stems ha^{-1}) favoured redwood. Figure 3 shows spatial variation in carbon at age 40 under this regime for both redwood (Figure 3d) and radiata pine (Figure 3e) and the species differences in carbon (Figure 3f). Predictions of carbon at age 40 for redwood were very high within the Bay of Plenty and Waikato where they exceeded 4,000 tonnes CO_2 ha^{-1} and were markedly greater than the 1,750–2,500 tonnes CO_2 ha^{-1} reached by radiata pine at these sites (Figure 3d, e). Redwood was on average more productive than radiata pine within three North Island regions by 30 years and this increased to seven regions by age 40 and all regions by age 50 (Table 2). Within the South Island, mean productivity of redwood exceeded that of radiata pine in the West Coast and Nelson at ages 40 and 50 (Table 2).

At age 30, in almost half of the North Island (48%) redwood had higher sequestration than radiata pine, and this percentage increased to 64% and 73%, respectively, by ages 40 and 50 (Table 3). At age 30, carbon for redwood was higher than that of radiata within almost two-thirds of the Waikato and Taranaki, and 55% of the Bay of Plenty (Table 3). At age 50, redwood carbon exceeded that of radiata pine by between 72–93% of the area in six of the nine North Island regions (Table 3).

Although the overall percentages of suitable area for redwood within the South Island did not vary substantially from the regime with lower stocking, increases were noted within warm, wet regions. Over half the area within Nelson and the West Coast was more suited to redwood than radiata pine at age 30, which increased to 71–75% by age 50 (Table 3).

Discussion

Redwood is sensitive to environmental conditions and the previously documented poor performance and survival of many early plantings has been related to siting, establishment and seed source (Knowles & Miller, 1993). Establishment practices and genetic material have improved markedly during the last two decades. Over this time there have been some examples of establishment failures due to poor siting and management decisions. However, these have been exceptions in the vast majority of the 10,000 ha of redwood plantations successfully established by forestry companies during the last two decades (Rob Webster, pers. comm).

There have also been significant improvements in planting stock deployed since 2000, and most stands established over the last two decades have been clones selected for superior growth, form, basic density and durability (Rapley, 2018). Recent research clearly defines optimum site conditions for redwood and shows that the species grows most rapidly on sites with warm air temperatures, few out-of-season frosts, little seasonal water deficit and moderate-to-high soil fertility (Watt et al., 2021b). However, it is worth noting that the species can withstand hard frosts, snow and very dry summers, but will not thrive in places where these are common (Rapley, 2018).

This study reinforces previous research (Watt et al., 2021b) showing that if redwood is correctly sited the species is capable of very high productivity. When grown at a high stand density, predicted carbon for redwood at age 40 reached 4,000 tonnes CO_2 ha^{-1} on the best sites, which greatly exceeded the maximum of 2,500 tonnes CO_2 ha^{-1} for radiata pine. Redwood is more suited to the warm, wet regions in the North Island, while radiata pine has higher productivity than redwood in cold and/or dry regions. Increases in carbon with greater stand density and age were markedly higher for redwood than radiata pine, and consequently redwood is particularly well suited for clearwood and carbon regimes with longer rotation lengths.

Table 2: Regional variation in mean carbon sequestration for redwood and radiata pine and the difference between redwood and radiata pine carbon

Region	Redwood (t CO_2 ha^{-1})			Radiata pine (t CO_2 ha^{-1})			Redwood – radiata (t CO_2 ha^{-1})		
	30 yr	40 yr	50 yr	30 yr	40 yr	50 yr	30 yr	40 yr	50 yr
Low stand density regime (400 stems ha^{-1})									
Northland	930	1,484	2,041	1,209	1,620	1,947	−279	−136	94
Auckland	912	1,454	1,999	1,199	1,609	1,935	−287	−155	64
Waikato	1,151	1,836	2,526	1,249	1,637	1,945	−98	199	581
Bay of Plenty	1,040	1,654	2,268	1,226	1,602	1,900	−186	52	368
Gisborne	898	1,435	1,979	1,299	1,692	2,006	−401	−257	−27
Hawke's Bay	876	1,396	1,920	1,219	1,602	1,904	−343	−206	16
Taranaki	1,283	2,048	2,820	1,362	1,759	2,079	−79	289	741
Manawatu	958	1,532	2,111	1,249	1,632	1,936	−291	−100	175
Wellington	928	1,486	2,051	1,130	1,515	1,817	−202	−29	234
Nelson	926	1,477	2,034	1,102	1,468	1,754	−176	9	280
Tasman	562	901	1,243	999	1,344	1,612	−437	−443	−369
Marlborough	400	641	883	915	1,252	1,512	−515	−611	−629
West Coast	1,041	1,666	2,300	927	1,270	1,543	114	396	757
Canterbury	105	170	236	864	1,197	1,448	−759	−1,027	−1,212
Otago	217	350	484	830	1,147	1,377	−613	−797	−893
Southland	355	573	794	1,019	1,375	1,638	−664	−802	−844
North Island	1,007	1,606	2,211	1,239	1,628	1,937	−232	−22	274
South Island	351	564	799	911	1,248	1,501	−560	−684	−702
High stand density regime (900 stems ha^{-1})									
Northland	1,448	2,100	2,718	1,566	1,986	2,288	−118	114	430
Auckland	1,443	2,088	2,692	1,556	1,975	2,276	−113	113	416
Waikato	1,669	2,407	3,134	1,599	1,999	2,291	70	408	843
Bay of Plenty	1,585	2,272	2,928	1,569	1,957	2,239	16	315	689
Gisborne	1,337	1,932	2,510	1,670	2,078	2,378	−333	−146	132
Hawke's Bay	1,337	1,928	2,495	1,588	1,985	2,271	−251	−57	224
Taranaki	1,829	2,637	3,443	1,741	2,156	2,466	88	481	977
Manawatu	1,398	2,027	2,643	1,625	2,024	2,313	−227	3	330
Wellington	1,351	1,955	2,549	1,494	1,890	2,169	−143	65	380
Nelson	1,371	1,977	2,564	1,446	1,823	2,089	−75	154	475
Tasman	849	1,253	1,638	1,331	1,688	1,934	−482	−435	−296
Marlborough	611	942	1,225	1,242	1,590	1,825	−631	−648	−600
West Coast	1,443	2,110	2,786	1,234	1,587	1,839	209	523	947
Canterbury	193	345	444	1,199	1,541	1,764	−1,006	−1,196	−1,320
Otago	362	580	754	1,168	1,494	1,699	−806	−914	−945
Southland	537	812	1,078	1,413	1,779	2,020	−876	−967	−942
North Island	1,495	2,159	2,804	1,601	2,003	2,296	−106	156	508
South Island	533	820	1,074	1,254	1,601	1,830	−721	−781	−756

North Island **South Island** **Weighted mean**

Note: Values are shown for three ages under low and high stand density regimes

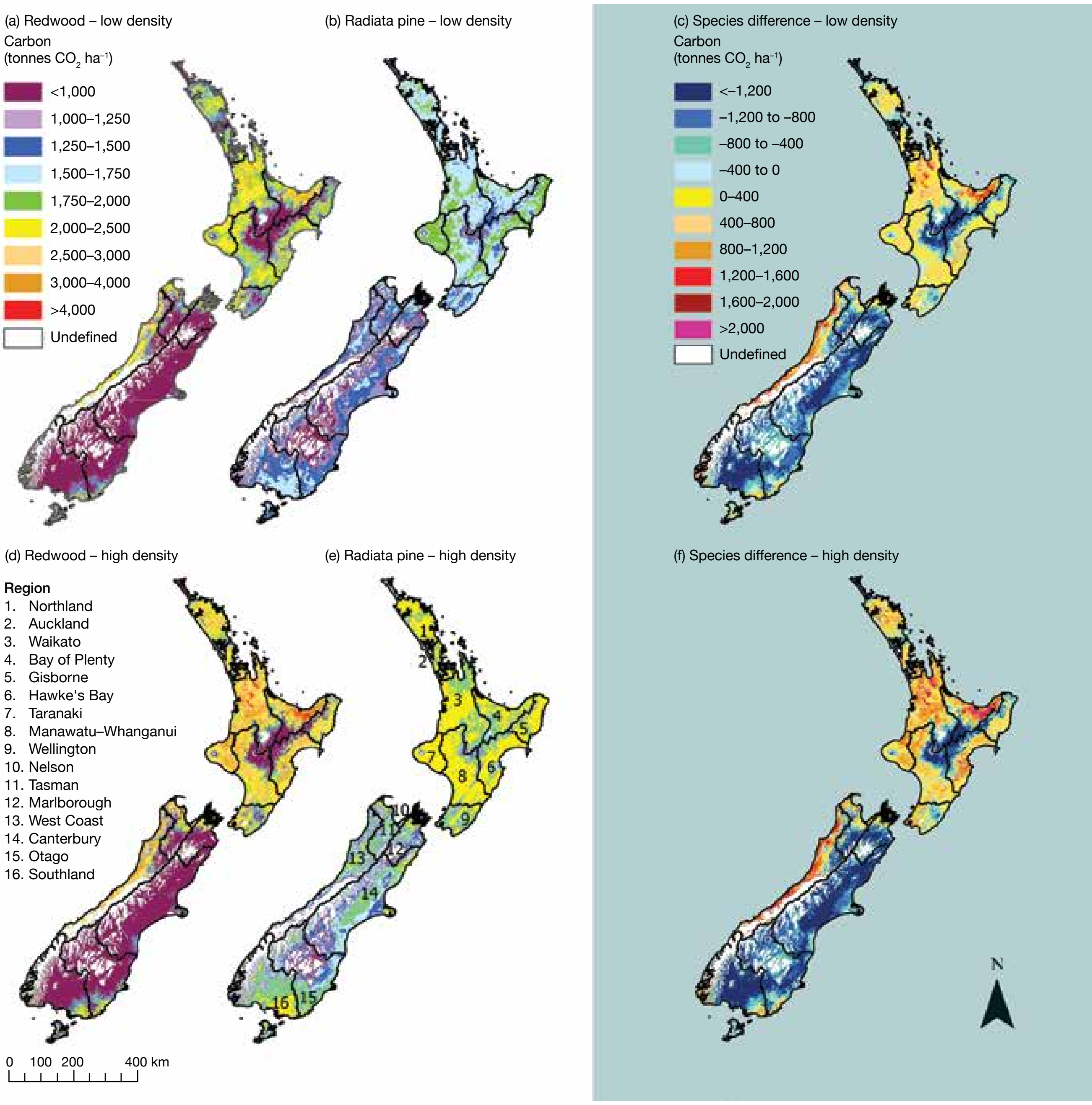

Figure 3: Spatial variation in carbon sequestration for redwood and radiata pine for 40-year-old stands under (a, b) low and (d, e) high stand density with carbon expressed on the same scale. Also shown are (c, f) species differences in carbon (redwood – radiata pine carbon)

Redwood has a number of other advantages over radiata pine as a carbon species. The thick bark of mature redwood confers fire resistance and the species is resistant to damage from strong winds. Redwood has no significant insect or disease issues and has a reputation as a healthy species (see Watt et al., 2021b for more details). In contrast, there are a number of diseases that can detrimentally impact the growth of radiata pine and the species is prone to windthrow, particularly at older ages and the high stand densities that are typical of carbon regimes (Watt et al., 2019). Radiata pine is also susceptible to damage from fire and the risk of fire is likely to increase under climate change (Watt et al., 2019).

Recent species comparisons of volume favoured redwood more strongly within the North Island (Watt et al., 2021b) than results reported here that compared carbon between the two species. This primarily occurred as redwood has a lower wood density than radiata pine in the North Island and these lower values of wood density reduce carbon but not volume. As redwood produces a valuable appearance grade timber, many growers will want to consider both carbon and timber volume when selecting a species. However, even if redwood is only grown for carbon, results presented here suggest it can out-compete radiata pine at age 30 on many warm, wet sites in the North Island and these gains increase over longer rotations.

Table 3: Regional variation in the percentage area where carbon sequestration is higher for redwood than radiata pine (i.e. carbon differences >0)

Region	400 stems ha⁻¹ (%)				900 stems ha⁻¹ (%)		
	30 yr	40 yr	50 yr		30 yr	40 yr	50 yr
North Island							
Northland	21	46	61		45	62	73
Auckland	20	43	56		44	62	72
Waikato	48	74	80		65	77	81
Bay of Plenty	36	57	68		55	65	72
Gisborne	5	38	58		29	48	62
Hawke's Bay	22	47	59		41	55	63
Taranaki	39	83	93		64	85	93
Manawatu	22	56	69		41	61	72
Wellington	24	47	64		36	54	69
South Island							
Nelson	39	62	69		55	65	71
Tasman	18	31	38		25	35	41
Marlborough	16	24	27		22	26	28
West Coast	64	70	74		66	71	75
Canterbury	0.1	1	2		0.2	1	2
Otago	3	6	9		4	7	10
Southland	10	17	21		9	13	20
By Island							
North Island	29	57	69		48	64	73
South Island	13	18	21		14	18	21

Note: Values are shown for three ages under low and high stand density regimes

Further research should be undertaken to refine the redwood model which was based on conservative assumptions for many components. Previous research suggests that values may be higher for the carbon fraction (Jones & O'Hara, 2012) than the Van Pelt et al. (2016) fractions used in this study, and the decay rate of woody biomass may be slower than assumed in this study (Busing & Fujimori, 2005). Changes to these attributes will increase the presented carbon values for redwood by between 6–8%. Furthermore, roots remain alive following harvest (Bond & Midgley, 2001), which supports generally prolific and rapid recoppice (O'Hara & Berrill, 2010). The refinement of the decay rate for roots and woody biomass is likely to reduce post-harvest carbon liabilities.

Further research should undertake a comprehensive survey of redwood basic density across environments as carbon estimates are sensitive to this attribute. The establishment of permanent sample plots (PSPs) in many South Island locations that are under-represented in the data, such as the West Coast, would improve confidence in estimates of both the 300 Index and carbon. Although high carbon was predicted on the West Coast these predictions should be treated with caution, particularly within infertile areas, and further research is required to verify them.

The presented surfaces are intended only as a guide for afforestation and growers should take into account the impact of microsite when choosing an appropriate species. These surfaces were derived from PSP data, which typically comprise plots of well-managed trees which do not have any unstocked areas and are sited away from exposed ridges (Ellis & Hayes, 1997). We therefore recommend that presented carbon values are reduced by 15% when applied to standard forestry sites.

Conclusion

The maps and regional estimates of carbon presented here are useful both as decision support for growers and for the development of government policy. These estimates were underpinned by well-validated models that have been widely applied, such as the 300 Index growth models, productivity surfaces and the Forest Carbon Predictor. Comparisons show that radiata pine had higher carbon within cold and or dry areas and often had higher productivity under regimes with low stand density at younger ages.

Redwood often outperformed radiata pine on warm, wet sites, even at a young age in some regions (e.g. Waikato), and species differences on this site type favoured redwood with increasing age and stand density. Further research is required to refine the carbon model for redwood and check on the validity of predictions in areas with sparse underpinning PSP data, such as the West Coast.

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