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Financial Comparison of Afforestation Using Redwood and Radiata Pine within New Zealand for Regimes That Derive Value from Timber and Carbon

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Abstract: Carbon sequestration has become an important source of supplementary revenue from forest plantations. Although there are many financial comparisons of species based on timber revenue, there have been few regional comparisons that integrate revenue from carbon. Within New Zealand, radiata pine is the most widely planted species, but there has been a recent upsurge in planting rates for coast redwood. Under New Zealand's Emissions Trading Scheme, areas that are newly afforested under clear-fell rotational forestry receive carbon payments up to a set age, intended to represent the long-term average under successive rotations. Using growth models for both species, the objectives of this research were to regionally quantify (i) how the rotation length and the carbon averaging age influenced the profitability of growing redwood and (ii) compare carbon, timber yields, and profitability between radiata pine and redwood. The results showed the legislated carbon averaging age of 22 years for redwood underestimated the actual mid-points of carbon accumulation, which averaged 26, 28, and 31 years across rotation lengths of 40, 45, and 50 years, respectively. The optimal rotation length for redwood varied markedly by region and carbon price but was most often 40 years, increasing to 50 years at higher carbon prices, particularly for southern regions. Under regimes where revenue was only derived from timber, the redwood internal rate of return (IRR) exceeded that of radiata pine for eight of the nine New Zealand regions. When revenue was received from carbon and timber, redwood had a higher IRR than radiata pine up to carbon prices ranging from 29 to 50 NZD/tonne CO_2 for the North Island and 23 to 34 NZD/tonne CO_2 in all South Island regions apart from Otago. The IRR of radiata pine exceeded that of redwood at carbon prices above these values for the eight regions and at all carbon prices within the cold, dry Otago region.

Keywords: 300 Index; *Pinus radiata*; *Sequoia sempervirens*; site index

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1. Introduction

Coast redwood (*Sequoia sempervirens* (Lamb. ex D. Don) Endl.) is a fast growing and long-lived coniferous species, native to a coastal strip on the western seaboard of the United States that is capable of accumulating very high amounts of carbon. The species is shade tolerant and in its native range can develop a mixed-aged distribution, with trees reaching ages greater than 2200 years and heights of 115 m [1–3]. Redwood forests have been found to store exceptionally high quantities of biomass and carbon within decay-resistant heartwood in primary (old growth) stands, but the rate of carbon sequestration is highest in secondary or plantation forests [3]. As redwood stands are typically very healthy [4,5] and resistant to damage from wind [6,7] and fire [8–10], the high quantities of carbon that accumulate are relatively safe from damage caused by pests, pathogens and abiotic factors. Redwood also produces high-quality timber that is mostly used for appearance grade purposes [7]. The timber is easily worked, stable, and odour free and has an attractive grain with a naturally durable heartwood [11].

Redwood can tolerate a considerable range in environmental conditions, but growth rates are optimal in temperate climates that are mild with rainfall that is moderate to high. Plantations have been successfully established in many countries with these climates, including France [12], Germany [13], and Chile [14]. Redwood is very well suited to New Zealand, where 8000 ha was established from 2000 to 2018 [7]. Afforestation rates increased rapidly after 2019 with ca. 2000 ha established in 2023 [15], and redwood is now the second most widely planted species in New Zealand, after radiata pine [15]. The majority of these plantings have been in North Island locations with a climate that suits the species [7] resulting in growth rates exceeding those of plantations within the native range [16]. Using measurements taken from a nationally distributed set of permanent sample plots (PSPs), models and spatial layers describing volume and carbon have been developed that clearly show the potential of redwood within New Zealand [16,17].

Within New Zealand, radiata pine (*Pinus radiata* D. Don) is the most widely planted species and constitutes 90% of the 1.7 M ha plantation area [18]. Radiata pine has been widely planted as it grows rapidly within most environments and can, for instance, tolerate salt winds, shallow soils with low fertility, and out of season frosts [19]. Measurements taken from an extensive PSP network have been used to characterise the variation in growth and carbon of radiata pine throughout New Zealand, and predictions show growth is greatest in North Island regions that are warm with moderately high rainfall [16,20]. Radiata pine timber can be used for a wide range of end uses, and a significant processing infrastructure and large number of export markets support the utilization of the species [19]. However, in contrast to redwood, radiata pine is susceptible to many damaging pathogens [21–24], wind [21,25], and fire [21]. Although mature radiata pine stands provide a high level of protection against erosion [26], there is a relatively high risk of erosion for a number of years following harvest [26] as roots decay very rapidly, reducing the soil stability [27,28]. Nonetheless, radiata pine is generally considered to be the most profitable and robust plantation species within New Zealand, and financial returns from radiata pine are the benchmark against which other species are evaluated [19].

Carbon is a valuable source of revenue from forests, and afforestation within New Zealand is the main means by which carbon can be removed from the atmosphere. The New Zealand Emissions Trading Scheme (ETS) incentivises carbon sequestration through afforestation [29] by giving carbon a value. Forest growers who are registered in the ETS receive a unit for each tonne of carbon dioxide sequestered, and supply and demand influences the unit value. Rapid rises in the carbon price over the last three years to 90 NZD/tonne CO_2 in late 2022 have stimulated an almost tripling of the afforestation rates from 25,000 ha in 2019 to 70,000 ha during 2022 [30]. These high carbon prices favour the establishment of fast-growing species such as redwood and radiata pine.

After recent changes to the ETS framework, areas that are newly afforested under clear-fell (or clear-cut) rotational forestry are allocated carbon under an averaging system for the first rotation. This system allows the payment of carbon to a set age, intended to represent the age when the carbon equals its long-term average under successive rotations. After these legislated mid-points, which are 16 and 22 years for radiata pine and redwood, respectively, the payments for carbon cease. The advantage of the averaging system is that carbon does not have to be repaid when harvesting occurs, provided the forest is replanted. Although the legislated mid-point for the averaging system does appear to be reasonably realistic for radiata pine [31], little research has investigated the accuracy of this value for redwood, under the normal range of rotation lengths.

Within the ETS there are two ways in which the quantity of carbon allocated to different species is measured. Participants who have registered 100 ha or more in the ETS must establish plots using the field measurement approach (FMA) to determine carbon values. On the other hand, growers with less than 100 ha registered must rely on pre-defined look-up table values, which describe annual changes in carbon for different species [32]. Previous research has spatially predicted carbon and volume productivity for both redwood and radiata pine at a fine resolution throughout New Zealand [16,17,33]. The estimates from these models can be averaged to a regional level and used as a means of predicting the carbon that growers would receive under the FMA system. These models and spatial surfaces can also be used to predict the volume, grade-outturn, and revenue from timber.

Carbon predictions from these models have been used to financially compare profitability for radiata pine and redwood that are permanently established and derive revenue only from carbon [34]. Model predictions showed that in eight of the nine New Zealand regions, the total carbon at 100 years was higher for redwood than radiata pine, and these differences averaged 74% in the North Island. Despite this higher carbon, both species had similar profitability within four of the five North Island regions as radiata pine grows more rapidly than redwood over the first 30 years, with this early period weighting heavily in discounted cash flow analysis [34]. The profitability of radiata pine exceeded that of redwood by quite a large margin in all South Island regions as the growth rates of radiata pine were greater that those of redwood within these colder climates over the first 50 years [34].

Although financial comparisons have been made for permanently established carbon regimes, we are unaware of any research that has compared the profitability of redwood and radiata pine, across regions, for regimes that produce both timber and carbon. Using growth models to predict carbon under the FMA system and timber yields, the objectives of this research were to (i) regionally quantify how the rotation length and carbon averaging age influenced the profitability of growing redwood and (ii) compare carbon, timber yields, and profitability between radiata pine and redwood. Sensitivity analyses were undertaken to determine how financial returns were affected across a wide range in carbon price.

2. Methods

2.1. Estimates of Carbon and Total Stem Volume

2.1.1. Overview

Regional estimates of volume and carbon were based on the 300 Index methodology, which is summarised below and has been described in detail previously for both radiata pine and redwood [33,35]. Growth models were used to estimate the volume for both species. Carbon was predicted using a combination of growth models, allometric equations, and functions describing carbon partitioning and basic density. Predictions of the 300 Index and site index were used to characterise the site productivity, at a regional level, from fine-grained estimates and subsequently scale the predictions of volume and timber across the nine regions within New Zealand.

The estimates of volume and carbon for radiata pine were for a regime designed to maximise the production of structural grade timber that had a moderate final crop stand density. This regime was selected as a previous regime comparison showed it to be more profitable across a range in carbon prices than a regime in which trees were pruned to maximise the production of clear-grade timber [36]. The selected regime had an initial planting density of 1000 stems/ha and was thinned at age 9 to a final crop stocking of 650 stems/ha. The redwood silvicultural regime was chosen to maximise the production of high-value clear heartwood as this grade attracts a large market premium over grades with sapwood content and unpruned “tight knot” grades, which in turn have higher value than timber with bark-encased knots [37]. The initial planting density of this regime was 625 stems/ha. A total of 450 stems/ha were pruned to 6.5 m over three stages at ages 6, 8, and 10, and a thinning was undertaken at age 11 to remove all unpruned trees.

2.1.2. Prediction of Productivity Indices

Productivity metrics form the foundation for timber and carbon prediction and the subsequent regional prediction of these metrics. The site index provides a measure of the mean top height (MTH, or the average height of the 100 largest diameter trees per hectare) using a benchmark age of 30 years for redwood and 20 years for radiata pine. The 300 Index was introduced as a volume productivity measure to address the shortcomings of the site index for estimating site quality. There are often significant variations in volume in stands of identical height that are not captured by the site index [33,35,38–44], with these variations sometimes reaching 30% [45]. While the stand volume provides a more robust assessment of the site quality compared with height, it is influenced by the stand density and silvicultural practices. The 300 Index was formulated to account for these two factors [33,35] and represents the mean annual stem volume increment at 30 years for a reference stand with 300 stems/ha. A significant benefit of the 300 Index, and the accompanying growth models, is that once the 300 Index and site index have been defined, the volume and carbon can be predicted over varying stand ages, densities, and silvicultural regimes.

National maps for both productivity metrics were generated for radiata pine [20] and redwood [17]. The modelling used 3676 permanent sample plots (PSPs) for radiata pine and 130 PSPs for redwood, covering the environmental range of New Zealand plantations of these species [46]. Using previously outlined techniques and equations for radiata pine [35] and redwood [33], the site index and 300 Index were derived from these PSP measurements (see also an R implementation of the 300 Index model for *Cypress* spp. [47]). An extensive array of environmental factors, including climate, soil characteristics, topography, and landforms that have been previously described in detail [17], were sourced for all PSPs from geospatial layers and paired with the site index and 300 Index estimates for each tree species.

Using these amalgamated data, models for the 300 Index and site index were constructed based on environmental factors. For radiata pine, regression kriging was used, which combined multiple regression with kriging of the residuals, while multiple regression models were used for redwood. The radiata pine models were fitted using data from 2572 PSPs and then tested on a dataset of 1104 PSPs. For redwood, a one-at-a-time validation was employed as this approach made more efficient use of test data than a train–test split for this smaller dataset.

The four models that were developed using the above methods were relatively accurate. For radiata pine, the coefficient of determination (R^2) and root mean square error (RMSE) were 0.68 and 3.45 $m^3\ ha^{-1}\ yr^{-1}$ for the 300 Index and 0.80 and 2.08 m for the site index, respectively. The final regression models for redwood also had high accuracy, with an R^2 of 0.66 and RMSE of 6.80 $m^3\ ha^{-1}\ yr^{-1}$ for the 300 Index and R^2 of 0.72 and RMSE of 3.44 m for the site index. Leveraging these models, predictions for site index and 300 Index were made across New Zealand at a 25 m resolution based on the environmental data included within each of the four models. Regions with an average annual air temperature below 8 °C were excluded as neither species are established at any scale in regions within these predominantly high-elevation climates. The spatial variation in the site index and 300 Index is shown in Figure 1, and these four surfaces can be accessed and freely downloaded from https://koordinates.com/, (accessed on 11 November 2023).

2.1.3. Predictions of Volume and Carbon

The prediction of volume and carbon sequestration for radiata pine was undertaken using the Forest Carbon Predictor 5.1 (FCP), a stand-level modelling system that is fully described in [48]. The FCP predicted the MTH, basal area, and stand density from silvicultural information, the site index, and the 300 Index, using a stand-level radiata pine growth model [35]. The stem volume was estimated from these using a nationally applicable volume function [49]. These predictions, when combined with estimates of basic wood density, formed the input for C_Change [50], which was used by the FCP to predict annual carbon stocks on a per hectare basis. C_Change includes growth partitioning factors and decay functions to allocate carbon to the live biomass components and to predict losses of carbon in dead wood arising from mortality and thinned and felled trees, respectively [16,51]. The generated biomass predictions were then transformed into carbon, through an age-related function for bark and carbon fractions, ranging from 0.50 to 0.51, for other tree components that included stem wood, branches, foliage, roots, deadwood, and litter.

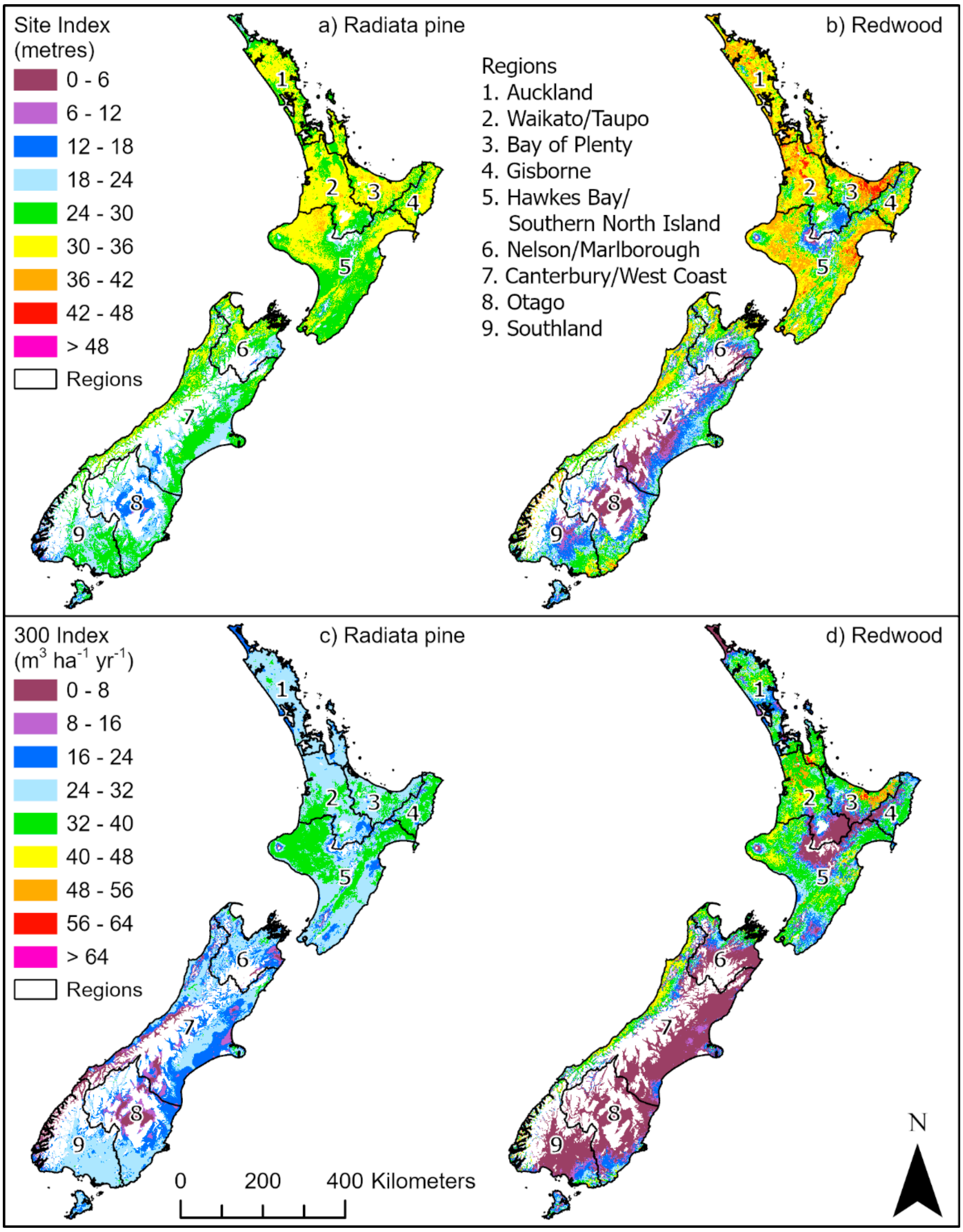

Figure 1. Spatial variation in site index for (**a**) radiata pine at age 20 and (**b**) redwood at age 30 and 300 Index for (**c**) radiata pine and (**d**) redwood. The boundaries and names of the nine regions used within this study are shown.

Carbon estimations for redwood were made using an analogous methodology [16]. Utilising the 300 Index and site index estimates, the redwood 300 Index growth model [33] predicted annual changes in the MTH and basal area, which were used to predict the stem volume. Data from previously studied New Zealand stands were used to estimate the basic density (for details see [16]), and the stem wood biomass was derived as the product of basic density and volume. The bark, branch, and foliage were estimated using allometric relationships. The biomass of redwood roots was predicted using the IPCC default root:shoot ratio for a coniferous forest of 0.23 [52]. The carbon losses from the decay of dead wood from mortality and thinned and felled trees were modelled using an exponential decay function, with a decay half-life of 15 years. Documented carbon fractions, ranging from 0.495 to 0.53, sourced from the literature, were used to convert the biomass estimations for all components into carbon. Predictions of carbon integrating all the previously described functions were made through an Excel model implementation, which can be freely supplied to all interested parties.

2.1.4. Regional Estimates of Volume and Carbon by Age

The values of the site index and 300 Index were averaged across each of the nine regions displayed in Figure 1. These regional estimates were used as inputs to the models, described in Section 2.1.3, to annually predict the volume and carbon over the length of the rotation for both species within the nine regions. As timber and carbon predictions use estimates of 300 Index derived from fully stocked PSP data, and most forests include gaps, the values were reduced by 15% to ensure the predictions were conservative (Figure 2).

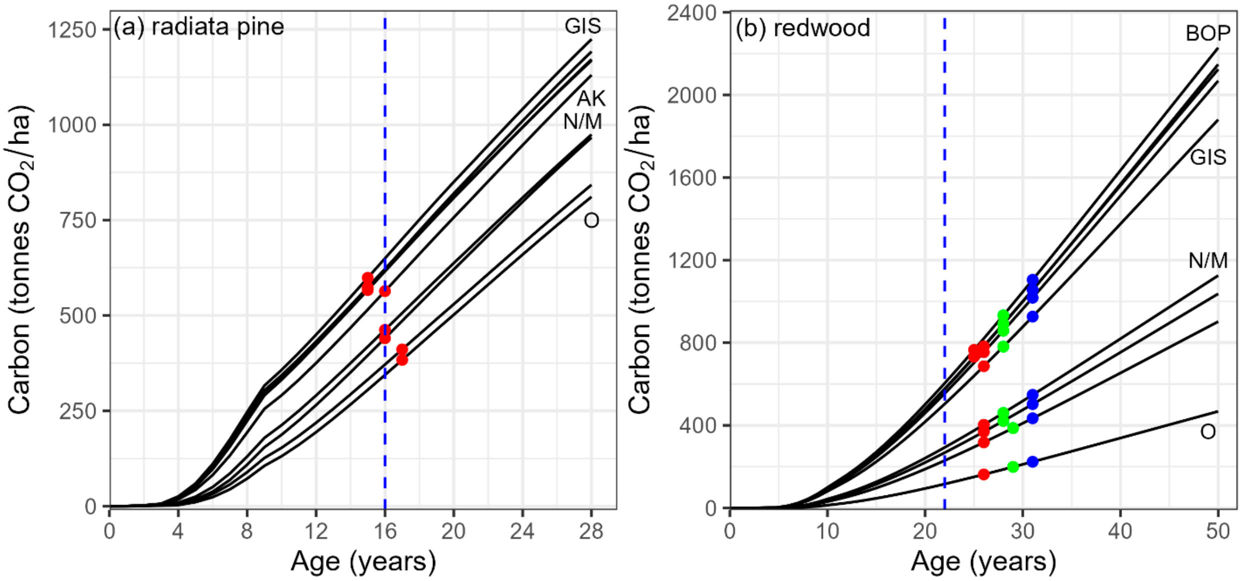

Figure 2. Relationship between age and carbon by region for (**a**) radiata pine and (**b**) redwood. The legislated age of carbon averaging is shown as a blue dashed line, and the circles show the actual mid-points of carbon accumulation for radiata pine (red circles) and redwood grown to rotation lengths of 40 (red circles), 45 (green circles), and 50 years (blue circles). The regions with the highest and lowest carbon at the end of the rotation for both species are displayed and abbreviated as follows: AK, Auckland; BOP, Bay of Plenty; GIS, Gisborne; N/M, Nelson/Marlborough; O, Otago.

Comparisons were made between redwood rotation lengths of 40, 45, and 50 years to determine the impact of the rotation length on profitability. The shortest rotation length of 40 years represents the age at which a significant proportion of durable heartwood is expected to develop. Following standard practice, a rotation length of 28 years was assumed for radiata pine. The simulations included four sequential rotations for radiata pine and three sequential rotations for redwood to ensure that the financial metrics were robust. Carbon was estimated over the entire first rotation for both species (Figure 2) to quantify how accurately the legislated averaging ages for radiata pine (16 years) and redwood (22 years) represented the mid-point of carbon accumulation over the first rotation. Following this comparison, carbon was predicted to these legislated averaging ages. Additional simulations were undertaken for redwood that accumulated carbon to the actual carbon mid-point for the three different rotation lengths (Figure 2).

Thus, in total, estimates of volume and carbon were made for seven base scenarios. These included, for redwood, the factorial combination of three rotation lengths (40, 45, and 50 years) × two averaging ages (the legislated 22 years and the actual mid-point) and a single rotation length (28 years) and averaging age (16 years) for radiata pine. Predictions of volume and carbon for these seven scenarios were generated across all nine regions (7 scenarios × 9 regions = 63 predictions).

2.1.5. Predictions of Log Grades

The radiata pine log grade output for all regional simulations was determined using Forecaster, a versatile forest stand growth and yield simulation system that predicts the growth and potential log yield of a forest stand [53]. Forecaster integrates various component models, such as growth models, branch size prediction models, and log bucking algorithms. Forecaster uses a stem list as a model of a crop of trees growing on a site. These stems are grown until a designated felling age and are subsequently cut into logs. Every stem in the list possesses certain attributes, such as diameter and height. These attributes facilitate predictions of key variables used for log grading, such as the maximum branch diameter and underbark volume, for logs derived from all locations within the stem. For this study, the same stand-level radiata pine growth model used by FCP to predict carbon was used to predict the log volumes using the mean regional values of the site index and 300 Index described above to account for variation in the site productivity between regions. The grading of logs into specific products, within Forecaster, was based on the export log specifications given in Table 1. The unpruned logs were optimally cut into A, K, KS, KI, and KIS grades by Forecaster, with the criteria for allocating logs to these five grades based on the small end diameter (SED) and knot size (Table 1).

Table 1. Log grade specifications for the export log grading strategy used for radiata pine. The area that is shaded in yellow denotes the SED range of each log grade.

Export Grades		**Small End Diameter (SED) Range**					
Group	**Knot Size (cm)**	**40 cm+**	**35 cm+**	**30 cm+**	**25 cm+**	**20 cm+**	**10 cm+**
Structural	<10	A (4.1 m+)					
Utility	<15	K (4.1–12.1 m)/KS (3.6–4.0 m)					
Industrial	<25	KI (4.0 m+)					
Pulp	No limit	KIS (3.7 m)					

Log grades for all redwood simulations were estimated using the Excel implementation of the redwood growth model described above. In addition to providing rotation length estimates of volume and carbon, this implementation provided a list of harvested logs with each log including information specifying the height, the SED and volume. These data were extracted and processed using R [54] into the total underbark volume for pruned and unpruned log grades by 10 cm SED classes ranging from 10 cm to 100 cm.

2.2. Financial Analysis

2.2.1. Internal Rate of Return

The financial returns from the two species were compared using the internal rate of return (IRR). The IRR was determined as the rate of return at which the sum of all discounted costs and revenues over the duration of the forest investment were equal to 0, i.e., such that

$$\sum_{i=0}^{n} \frac{R_i - C_i}{(1 + IRR)^i} = 0 \tag{1}$$

where R_i represents the revenues from timber sales and carbon sequestration in the ith year from establishment; C_i is the costs in the ith year associated with land purchase, stand establishment, management, harvest, and participation in the ETS; and n is the number of years the investment provides a return. The IRR was determined using R (Version 4.2.3) [54]. All simulations were run over multiple rotations to a point beyond which the impacts of discounted costs and revenues on the IRR were negligible, as previously documented [34].

2.2.2. Land Purchase, Establishment, Silviculture, and Management Costs

The costs used for both species were in New Zealand dollars and quantified through a literature review and consultation with industry and the Sequoia Action Group (Table 2). Following [34], farm land sold for afforestation within New Zealand was costed at

10,000 NZD/ha. Although redwood was established at a lower stand density, the planting costs were higher than those of radiata pine as it was assumed high-value clones were used. Redwood was pruned to 6.5 m over three stages during years 6, 8, and 10 for a total cost of $2329/ha. The thinning to waste cost was higher for radiata pine as a larger number of trees were removed during this operation for radiata pine (1000 reduced to 650 stems/ha) than redwood (625 reduced to 450 stems/ha). As redwood coppices following harvest, there were no costs for planting or release spraying from the second rotation onward, but a cost was included for thinning the coppicing redwood sprouts.

Table 2. Summary of costs and the year in which they occurred, by species. All costs are given in New Zealand dollars.

Item	**Radiata Pine**		**Redwood**	
	Cost (NZD/ha)	**Year**	**Cost (NZD/ha)**	**Year**
Land purchase, silvicultural costs				
Land purchase	10,000	0	10,000	0
Tracking, land preparation	100	0	100	0
Pre-plant spray	184	0	184	0
Seedlings, planting	1311	0	2425	0
Release spraying	400	0	400	1
Mapping	50	0	50	0
Total pruning cost	-	-	2329	6, 8, 10
Thinning to waste	1200	9	900	11
Thinning coppiced sprouts	-	-	2000	Second rotation onward year 11
Harvesting costs				
Harvest planning	150	26	150	2 yrs before harv.
Road construction (first rotation)	5000	27	5000	1 yr before harv.
Road rehabilitation (2nd + rotations)	1500	27	1500	1 yr before harv.
Periodic costs				
Carbon administration for field measurement approach	71	Every 5 yrs to averaging age	71	Every 5 yrs to averaging age
Maintenance roads, tracks, fences	50	Every 5 yrs	50	Every 5 yrs
Animal control	100	0, 1, 2, 3, 4, 5, then every 5 yrs	100	0, 1, 2, 3, 4, 5, then every 5 yrs
Annual costs				
Forest management	40		40	
Rates, insurance, administration	42		42	
	Costs (NZD/m^3)	**Year**	**Costs (NZD/m^3)**	**Year**
Harvesting costs				
Log harvesting	48	28	48	Yr of harvest
Cartage	19	28	19	Yr of harvest
Road maintenance	3	28	3	Yr of harvest
Post-harvest ancillary costs	1.5	28	1.5	Yr of harvest
Harvest management fee	4.5	28	4.5	Yr of harvest
Forest growers levy	0.33	28	0.33	Yr of harvest

All periodic and annual costs were the same between species. As the established area increases, the density of the required plots and cost of participation in the ETS declines on a per hectare basis. A typical establishment area of 200 ha and an associated cost of 71 NZD/ha was used with a claim frequency of five years, which is the minimum frequency under current legislation.

2.2.3. Timber Value and Harvesting Costs

Log values at mill gate (AMG) for the radiata pine export log grades shown in Table 1 were extracted from AgriHQ (https://www.agrihq.co.nz/, accessed on 11 November 2023), which is a professional log price database service that provides monthly log grade values. The log values were inflation adjusted to 2023 using the consumer price index (CPI), and the average over the last twelve years (2011–2023) was determined from this adjusted series for each log grade. Following previous analyses [55], we assumed equivalence between tonnes and cubic metres, measured using standard methods and according to the Japanese Agricultural Standard (JAS). The resulting AMG values for A, K, KS, KI, and KIS grades were 140, 131, 129, 123, and 107 NZD/JAS m^3, respectively.

The redwood AMG log values were estimated using two complementary approaches that included a comparative price analysis and lumber recovery, or "millback", analysis. This analysis was based on a commissioned study by the New Zealand Redwood Company. The comparative price approach used time series redwood and pine values within the California market that were sourced from the New Zealand Redwood Company. The average long-term price for redwood logs was found to be more than double that of pine logs, and this ratio over a 10-year period to 2021 was 226%. As this multiplier was assumed to apply across all grades and dimensions, a lumber recovery analysis was used to differentiate the variation in log value by type (pruned and unpruned) and log SED.

The lumber recovery analysis estimated the AMG log values using Californian market prices that were applied to sawn timber. A sawing simulator was developed to cut pruned and unpruned logs with different dimensions (SED classes of 10 cm to 100 cm, in 10 cm steps) into boards with grades of varying quality, based on the heartwood content and level of defect. The outturn from this sawing simulator was checked and adjusted using detailed measurements of outturn from sawn redwood trees from a 38-year-old stand (for details, see [56]). The values for each board grade were estimated from wholesale redwood lumber prices in the Californian market, reduced to account for local processing, shipping, and port costs, using appropriate conversions for currency (USD to NZD) and log measurement (thousand board feet to m^3). Log values for all combinations of log type (pruned and unpruned logs) and SED class were then determined through the summation of values for simulated boards within each log. These log-level values were re-expressed on a cubic metre basis through dividing the log value by the log volume.

Although the lumber recovery analysis did provide absolute values, there were a number of potential sources of error within the value chain. The prevalence of these uncertainties suggested that it would be most appropriate to use relative changes in value across the log type and SED classes, estimated from the lumber recovery analysis, to create a gradient of log grade values that scaled the base-level comparative price estimations. The resulting log values for pruned and unpruned redwood logs, updated to 2023 using the CPI, are given in Table 3.

Applying these values to the log output from the redwood growth model, the average regional AMG values for pruned and unpruned redwood were 441 NZD/m^3 (range 318–509 NZD/m^3) and 204 NZD/m^3 (range 131–255 NZD/m^3), respectively, while the mean value across all log types was 307 NZD/m^3 (range 221–349 NZD/m^3). This mean value across all logs was within 2% of the CPI adjusted AMG value previously documented by Maclaren [19].

The harvesting and transport costs to a mill were deducted from the AMG estimates, described above for both species, which were combined with the log grade volume (see Section 2.1.5), to estimate the net harvest returns. Following Manley [57], the mean cart distance across all regions was determined as ca. 100 km, and a cartage cost of 19 NZD/m^3 was assumed. Log harvesting was estimated at 48 NZD/m^3, while other more minor costs included road maintenance, post-harvest ancillary costs, harvest management fees, and the forest growers levy (Table 2). The total harvesting and transport costs of ca. 76 NZD/m^3 were consistent with a previous survey of small forest growers, where CPI adjusted costs averaged 76 NZD/m^3 [58], and a previous analysis for radiata pine that used CPI adjusted total costs of ca. 75 NZD/m^3 for a mid-range scenario [31]. Following the mid-range estimate in Manley [31], road and landing constructions were costed at 5000 NZD/ha for the first rotation. Road rehabilitation in all subsequent rotations was included in the analyses as 30% of the initial construction costs (Table 2).

Table 3. Variation in at mill gate redwood log values by log type (pruned and unpruned) and small end diameter (SED) class.

SED	Log Values (NZD/m^3)	
Class (cm)	Pruned	Unpruned
10	-	51
20	-	153
30	295	167
40	428	242
50	460	274
60	515	330
70	609	423
80	611	425
90	614	428
100	614	428

After deducting the harvesting and transport costs, the mean net values for redwood pruned and unpruned logs were 365 NZD/m^3 (range 241–433 NZD/m^3 across regions) and 127 NZD/m^3 (range 55–179 NZD/m^3), respectively, with an overall mean return across all logs of 231 NZD/m^3 (range 145–272 NZD/m^3). Compared with previous sale data, these values were conservative. For instance, a shipment of sawn redwood from a 73-year-old unpruned stand to California yielded a CPI adjusted net value of 284 NZD/m^3 of log volume after the deduction of all costs (pers. comm. Mark Dean).

2.2.4. Carbon Price Range

Over recent years, there has been a rapid increase in the carbon price from 25 NZD/tonne CO_2 in 2019 to nearly 90 NZD/tonne CO_2 by November 2022. In this study we assumed a base real value of 80 NZD/tonne CO_2, which reflects the average carbon price throughout the latter half of 2022. Sensitivity analyses investigated the impact on IRR of changes in real carbon prices using values ranging from 0 to 160 NZD/tonne CO_2 that were equally spaced at a resolution of 1 NZD/tonne CO_2. The lowest value in this series (0 NZD/tonne CO_2) represented a regime where revenue was only derived from timber. Although values between 0 and 35 NZD/tonne CO_2 were likely to be very conservative as the New Zealand Government has recently set a floor price (minimum value below which units will not be sold) of 35 NZD/tonne CO_2 [59], they were included in the analyses for completeness and to ensure that the results could accommodate any future changes in legislation. The maximum value (160 NZD/tonne CO_2) was the assumed value of carbon in 2035 by the Climate Change Commission [60].

3. Results

3.1. Regional Variation in Volume and Carbon

The regional variation in the total stem volume (TSV) was far more pronounced for redwood than radiata pine (Table 4). Within the North Island, the values of TSV for radiata pine ranged from 850 m^3/ha in Auckland to 972 m^3/ha in the Gisborne region. The mean regional values of TSV in the North Island exceeded those of the South Island by

26%, with values in the South Island ranging from 664 m^3/ha in Otago to 794 m^3/ha in Southland. In contrast, the mean regional values of TSV for redwood growing in the North Island exceeded the values in the South Island by between 142 and 146% across the three rotation lengths (Table 4). For all rotation lengths, the values in the North Island were greatest in the Bay of Plenty (range 40–50 years of 1501–2049 m^3/ha) and lowest in the Gisborne region (range of 1257–1725 m^3/ha). The redwood TSV in the South Island was highest in Nelson/Marlborough (range of 736–1020 m^3/ha) and lowest in Otago (range of 293–411 m^3/ha). The total recoverable volumes for radiata pine and redwood were, on average, 84% and 83%, respectively, of the stated TSV values.

Table 4. Regional variation in total stem volume for radiata pine grown to 28 years and redwood grown over rotation lengths of 40, 45, and 50 years.

Region	Total Stem Volume at Harvest (m^3/ha)			
	Radiata Pine	Redwood		
		40 Years	45 Years	50 Years
Auckland	850	1436	1700	1959
Waikato/Taranaki	928	1432	1700	1964
Bay of Plenty	933	1501	1777	2049
Gisborne	972	1257	1492	1725
Hawkes Bay/Southern North Island	953	1381	1639	1894
Nelson/Marlborough	789	736	878	1020
Canterbury/Westland	689	577	692	806
Otago	664	293	352	411
Southland	794	673	804	936
Mean by Island				
North Island	927	1401	1662	1918
South Island	734	570	682	793

The regional variation in radiata pine carbon followed a similar pattern to that of volume (Figure 2). Radiata pine carbon in the North Island was highest in Gisborne and lowest in Auckland, while carbon within the South Island was highest in Nelson/Marlborough and lowest in Otago. The legislated carbon averaging age (16 years) was relatively similar to the actual mid-point of the rotation length carbon accumulation, which ranged from 15 to 16 years within the North Island and 16 to 17 years within the South Island, averaging 15.8 years over all regions (Figure 2a).

In contrast, the legislated averaging age (22 years) for redwood underestimated the actual mid-point of carbon accumulation for all rotation lengths. These mid-points for 40-, 45-, and 50-year rotations, averaged across regions, were 25.8 years (range 25–26 years), 28.2 years (range 28–29 years), and 31 years (no range), respectively, with mid-points generally occurring at slightly higher ages in South Island regions (Figure 2b). The additional carbon gain that would accrue using the correct mid-point year compared with a fixed age of 22 years was determined. The averages and ranges in these gains across regions, for the 40-, 45-, and 50-year rotations, were 139 tonnes CO_2/ha (range 46–207 tonnes CO_2/ha), 233 tonnes CO_2/ha (range 83–329 tonnes CO_2/ha), and 350 tonnes CO_2/ha (range 108–501 tonnes CO_2/ha), respectively. The growth rates during the 23- to 31-year period were very high and averaged 93% (regional range of 91%–94%) of the maximum current annual carbon increment, which was reached at age 41–46 years within the nine regions.

3.2. Redwood IRR in Relation to Rotation Age and Averaging Period

3.2.1. Scenario with Revenue from Timber

Under a scenario where revenue was only derived from redwood timber (i.e., carbon price = 0 NZD/tonne CO_2), the 40-year rotation length was most profitable in all regions apart from Canterbury/West Coast, Otago, and Southland (Figure 3, Appendix A). The

IRR for this regime markedly differed between the North and South Islands. The values of IRR in the North Island ranged from 6.53% to 7.14% (mean = 6.91%) for the 40-year rotation and 6.00% to 6.46% (mean = 6.29%) for the 50-year rotation. Within the South Island, the IRR values were markedly lower and ranged from 1.36% to 4.78% (mean = 3.70%) for the 40-year rotation and 2.11% to 4.62% for the 50-year rotation (mean = 3.82%).

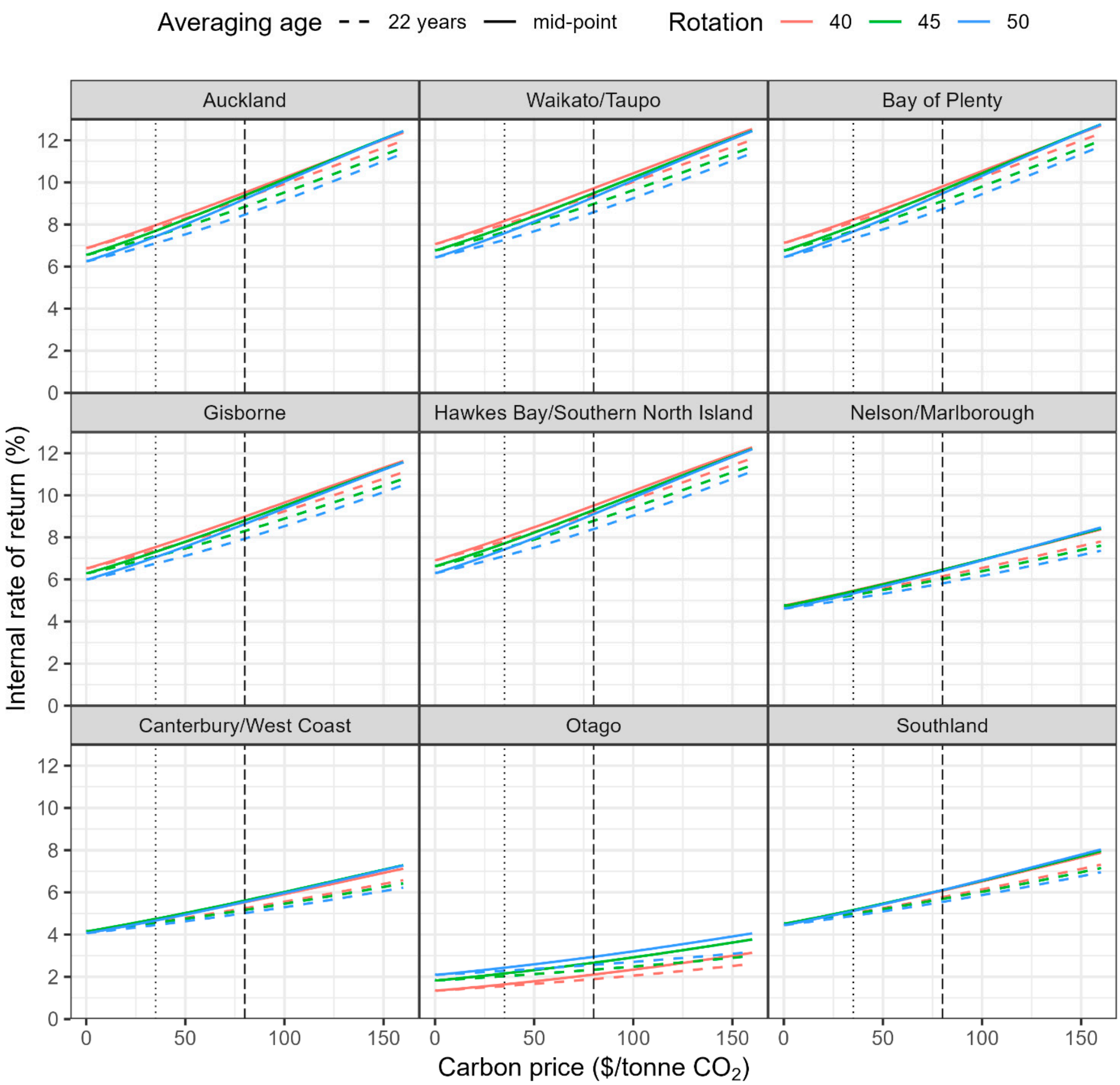

Figure 3. Relationship between internal rate of return and carbon price for three different rotation lengths and two averaging methods (22-year—dashed line and mid-point averaging—solid line) for redwood, by the nine regions in New Zealand (see Figure 1 for names and boundaries), which have been sorted from north to south. The left dotted and right dashed vertical lines are drawn at carbon prices of 35 and 80 NZD/tonne CO_2, respectively.

In the North Island, the IRR of the 40-year rotation exceeded those of the 45- and 50-year rotations by, on average, 0.31% (6.91% vs. 6.60%) and 0.62% (6.91% vs. 6.29%), respectively. In the South Island, the IRR values of the 40-year rotation exceeded those of the 45- and 50-year rotations, within the most northern region. The 45-year rotation was most profitable within Canterbury/West Coast and Southland, but rotation length differences in IRR were not marked, while the 50 year rotation was most profitable within Otago.

3.2.2. Scenarios with Revenue from Carbon and Timber

The inclusion of a revenue stream from carbon under the base carbon price scenario (carbon price = 80 NZD/tonne CO_2) using the legislated averaging age of 22 years resulted in a marked increase in IRR (Figure 3; Appendix A). Within the North Island the 40-year rotation was most profitable among the three ages examined in all regions. The average IRR under the 40-year rotation was 9.20% (range 8.64%–9.55%) which exceeded that of the timber-only regime by 2.29% (9.20% vs. 6.91%). Similar trends between regions were noted for the 45- and 50-year rotations, which had mean IRRs within the North Island of 8.80% and 8.42%, respectively.

Within the North Island, the accumulation of revenue to the mid-point carbon age increased the regime profitability for the baseline carbon price of 80 NZD/tonne CO_2 (Figure 3; Appendix A). Compared with 22-year averaging, the accumulation of carbon to the mid-point increased the IRR for the 40-, 45-, and 50-year rotation lengths by, on average, 0.31% (9.51% vs. 9.20%), 0.52% (9.32% vs. 8.80%), and 0.72% (9.14% vs. 8.42%), respectively. The 40-year rotation length was most profitable under mid-point carbon averaging, with mean regional differences in IRR between the three rotation lengths at a carbon value of 80 NZD/tonne CO_2, ranging by 0.37% between the 40- and 50-year rotations (9.51% vs. 9.14%).

In the South Island, similar patterns were evident. At an averaging age of 22 years, the values of IRR ranged from 1.89% for Otago to 6.15% for Nelson/Marlborough for a 40-year rotation. The 40-year rotation was the most profitable rotation length in all regions, apart from Otago, where the 50-year rotation had the highest IRR (IRR = 2.57% vs. 1.89%). Compared with averaging at 22 years, the use of mid-point averaging resulted in marked increases in IRR, which increased the mean values across regions, for 40-, 45-, and 50-year rotations, by 0.27% (5.04% vs. 4.77%), 0.41% (5.21% vs. 4.80%), and 0.51% (5.25% vs. 4.74%), respectively. Under mid-point averaging, a mixture of 40-, 45-, and 50-year rotation lengths was most profitable within the four South Island regions (Figure 3; Appendix A).

Using the lower carbon value of 35 NZD/tonne CO_2, IRR values were highest under the 40-year rotation within all North Island regions under both carbon averaging scenarios. Even at this lower carbon value, the IRR values considerably exceeded those of the timber-only scenario within the North Island, for the 40-year rotation, by 0.92% (7.83% vs. 6.91%) for 22-year averaging and by 1.06% (7.97% vs. 6.91%) for mid-point carbon averaging. Within the South Island the 40-year rotation length was optimal for all regions apart from Otago under 22-year averaging, while the optimal rotation lengths ranged from 40 to 50 years across the four regions using mid-point averaging (Appendix A). Under the optimal rotation length, gains in IRR over the timber-only regime averaged 0.41% for 22-year averaging (4.31% vs. 3.90%) and 0.55% (4.45% vs. 3.90%) for mid-point averaging.

At the 160 NZD/tonne CO_2 carbon price within the North Island, the IRR was highest under 40-year rotations for 22-year averaging and 40- to 45-year rotations for mid-point averaging (Figure 3). Comparing the most profitable rotation lengths, the IRR values exceeded those of the timber-only scenario by 4.93% (11.84% vs. 6.91%) for 22-year averaging and 5.42% (12.33% vs. 6.91%) for mid-point carbon averaging. Within the South Island, under 22-year averaging, the 40-year rotation length was most profitable in all regions, except Otago, where the 50-year rotation had the highest IRR (Figure 3). Under mid-point averaging, the most profitable rotation length was 50 years for all regions except for Canterbury/West Coast, where the IRR was highest for the 45-year rotation length. Under the optimal rotation lengths, within each region, gains in IRR over the timber-only regime averaged 2.32% (6.22% vs. 3.90%) for 22-year averaging and 3.06% (6.96% vs. 3.90%) for mid-point averaging (Figure 3).

3.3. Comparison of Redwood and Radiata Pine IRR

Under the scenario in which revenue was derived only from timber (carbon price = 0 NZD/tonne CO_2) the IRR for radiata pine within the North Island averaged 4.35% (IRR range: 4.06%–4.56%) but was considerably lower within the South Island, averaging 3.38% (IRR range: 3.01%–3.75%) (Figure 4; Appendix A). The values of redwood IRR in the North Island for the timber-only regime were markedly higher than those of radiata pine with mean regional differences averaging, for the 40-, 45-, and 50-year rotations, 2.56% (6.91% vs. 4.35%), 2.25% (6.60% vs. 4.35%), and 1.94% (6.29% vs. 4.35%), respectively (Figure 4; Appendix A).

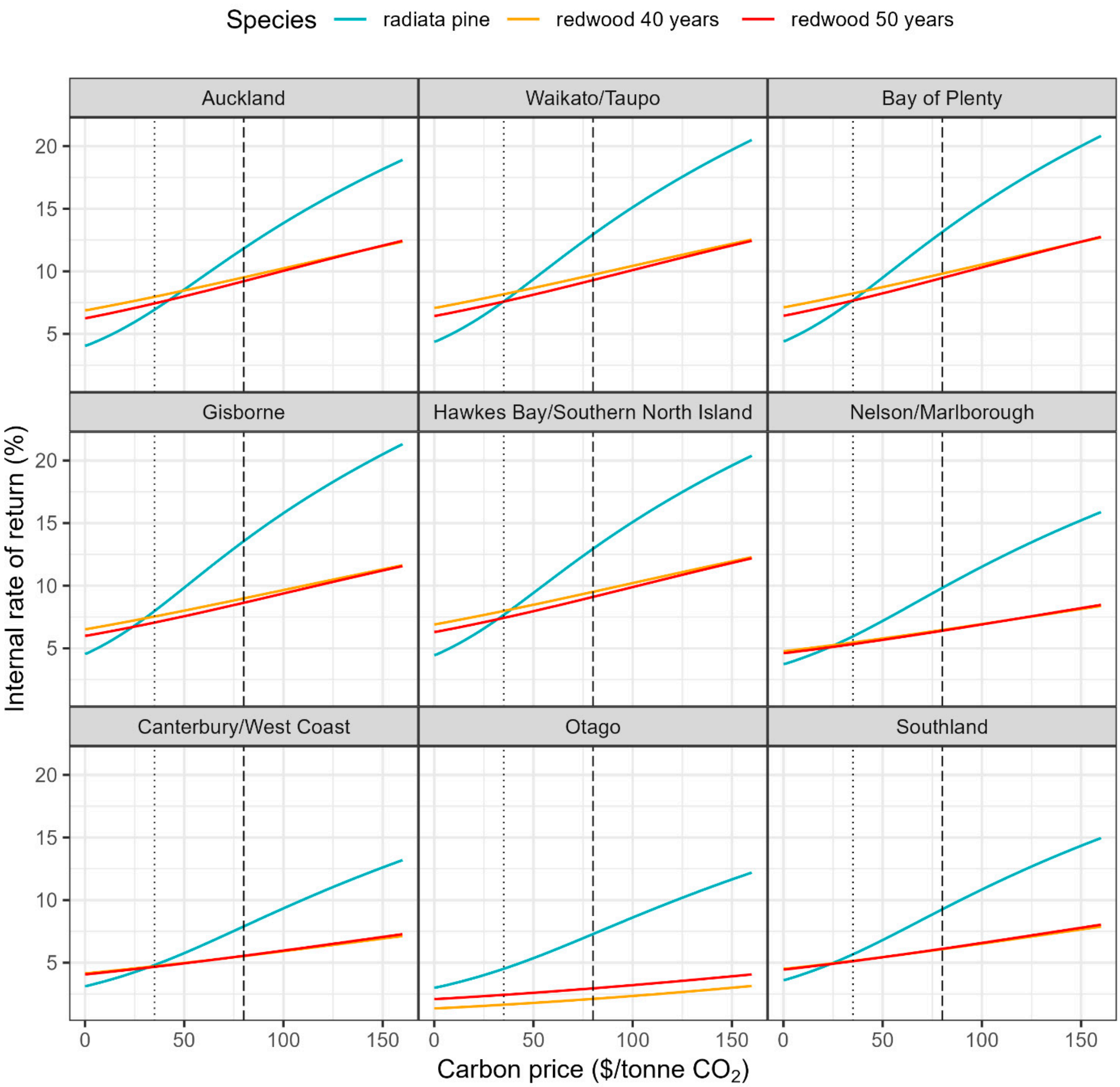

Figure 4. Relationship between internal rate of return and carbon price, by region, for radiata pine and redwood growing at rotations lengths of 40 and 50 years, using the mid-point averaging method. The nine regions in New Zealand (see Figure 1 for names and boundaries) have been sorted from north to south. The left dotted and right dashed vertical lines are drawn at carbon prices of 35 and 80 NZD/tonne CO_2, respectively.

Similarly, within the South Island the IRR of redwood, for timber-only regimes, exceeded that of radiata pine for all region by rotation length combinations, apart from the Otago region (Figures 4 and 5; Appendix A). Under the optimal rotation lengths for redwood, the values of IRR for redwood exceeded those of radiata pine by 0.91% for Southland (4.53% vs. 3.62%) to 1.03% for Nelson/Marlborough (4.78% vs. 3.75%) but were 0.90% lower than those for radiata pine within Otago (3.01% vs. 2.11%) (Appendix A).

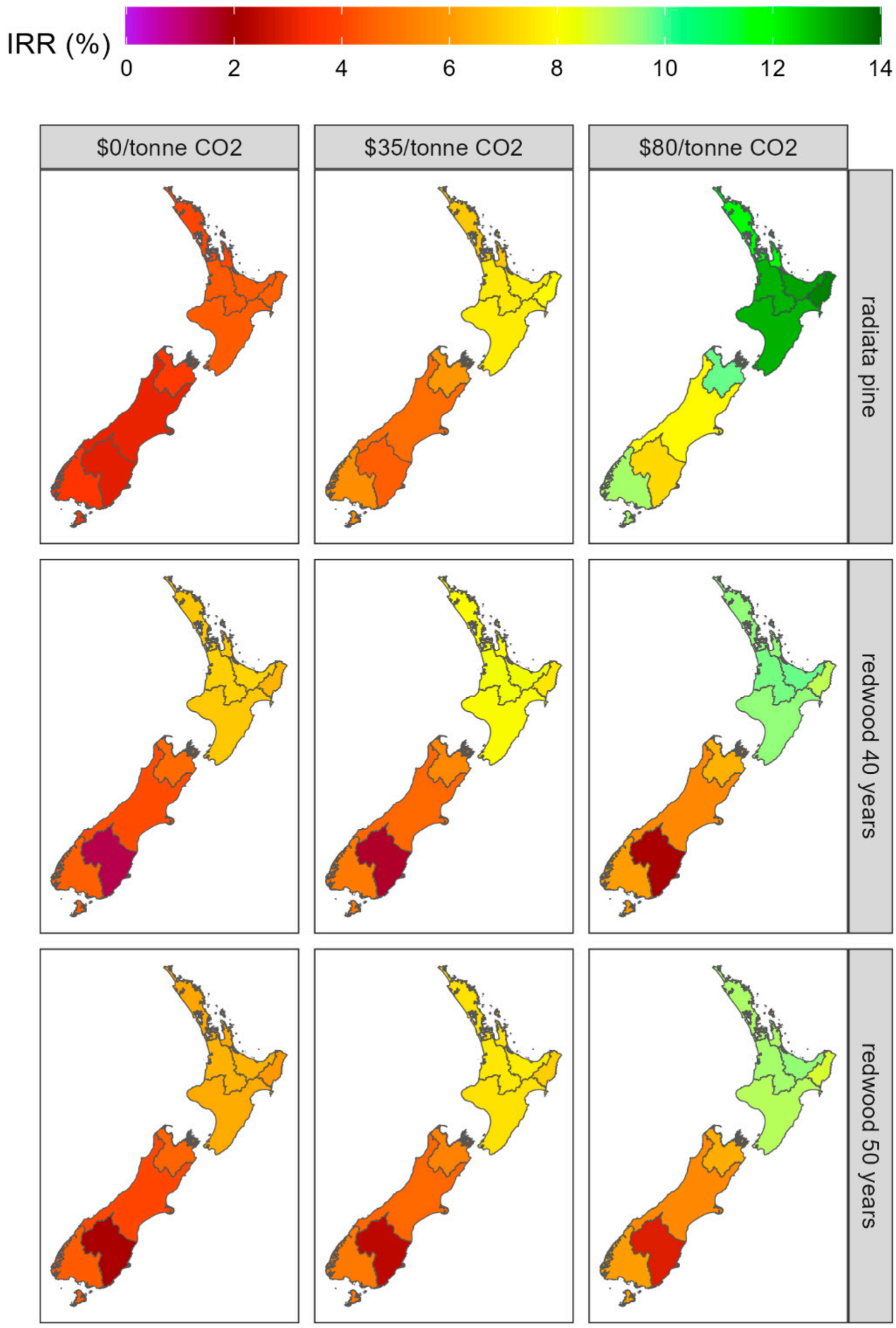

Figure 5. Spatial variation in internal rate of return (IRR) for (**top row**) radiata pine and redwood with a rotation length of (**middle row**) 40 years and (**bottom row**) 50 years. The IRR for all scenarios was determined for carbon prices of 0 NZD/tonne CO_2 (i.e., timber-only regime), 35 NZD/tonne CO_2, and 80 NZD/tonne CO_2, with mid-point averaging undertaken for these last two carbon price scenarios.

When revenue was derived from both carbon and timber, species differences in IRR depended on the carbon value, carbon averaging period, and rotation length. Within the

North Island, under both averaging periods, redwood IRR was higher than that of radiata pine within all regions apart from Gisborne, for the optimal 40-year rotation length at the lower carbon price of 35 NZD/tonne CO_2 (Figure 4; Appendix A). However, within the North Island, radiata pine became more profitable than redwood at higher carbon prices. Under the optimal 40-year rotation length and the legislated 22-year averaging period for redwood, this transition occurred at 29 NZD/tonne CO_2 for Gisborne and between 37 and 47 NZD/tonne CO_2 for the other four regions. Under mid-point averaging, this transition point was higher at 31 NZD/tonne CO_2 for Gisborne and between 39 and 50 NZD/tonne CO_2 for the other four regions (Figure 4).

Within the South Island, radiata pine had a higher IRR than redwood within Otago, across all carbon values (Figures 4 and 5; Appendix A). However, within the other three regions, redwood IRR exceeded that of radiata pine at lower carbon values. Radiata pine became more profitable than redwood in these regions as the carbon price increased; this transition point was reached between 23 and 31 NZD/tonne CO_2, under the optimal rotation length and 22-year averaging for redwood. Under mid-point averaging this transition point was reached at higher carbon prices ranging from 25 to 34 NZD/tonne CO_2 for these three regions (Figures 4 and 5; Appendix A).

4. Discussion

The establishment of redwood for timber was found to be more profitable than radiata pine within almost all New Zealand regions. Redwood is a financially attractive plantation option as growth rates over a 40- to 50-year rotation are high and particularly rapid after age 30. As redwood can be used for appearance grade timber, defect-free grades with heartwood attract very high prices, which far surpass those of radiata pine. Our results clearly highlight the importance of pruning, with on average 69% of the net log value derived from the lower pruned log. Within the South Island, the IRR of redwood regimes grown only for timber exceeded those of radiata pine in all regions apart from Otago, which was consistent with previous research that shows redwood grows more slowly in cold, dry climates [17]. For the majority of New Zealand regions, the optimal rotation length for timber regimes was 40 years, and the IRR declined with increasing rotation length.

The markedly higher profitability of redwood on suitable sites under timber regimes was consistent with a previous non-spatial financial comparison between these species in New Zealand [19]. This analysis showed growth and rates of return on good quality sites were higher for redwood than radiata pine (IRR = 10.5% vs. 9.0%). The values of IRR for both species, from this previous study [19], were higher than those documented in this study. This difference occurred as the CPI adjusted total costs were markedly lower than those used here (e.g., the CPI adjusted mean land cost was 4125 NZD/ha vs. 10,000 NZD/ha used in this study), reflecting increases in costs and land values over the last two decades that have greatly exceeded inflation. In addition, the previous study did not include any annual or periodic costs, which are necessary and have a substantial impact on profitability. The IRR values described here are conservative and will be higher for landowners where no land purchase is required. It is also worth noting that the analyses used real costs and returns, yielding returns above inflation, and the IRR values would be higher using nominal values.

The profitability of redwood regimes increased substantially when the revenue was derived from carbon as well as timber. The values of IRR were markedly higher when carbon was accumulated to the mid-point, rather than the prescribed 22 years within the ETS. Over these additional nine years (ages 23–31), carbon accumulated at, on average, 93% of the maximum current annual increment, with the additional increment ranging from, on average, 139 tonnes CO_2/ha (40-year rotation) to 350 tonnes CO_2/ha (50-year rotation). Given the very high growth rates at this stage of the rotation, averaging to the currently legislated age of 22 years unduly penalises growers. In contrast, the legislated averaging age for radiata pine was very close to the mid-point of carbon allocation, which was consistent with previous research that also assumed a 28-year rotation length [31].

The optimal rotation length for redwood scenarios, sourcing revenue from carbon and timber, was strongly dependent on the region, averaging age, and carbon price. Under the legislated averaging age of 22 years, the 40-year rotation was most profitable across the carbon price range, and the IRR evenly declined with increasing rotation age across this range in almost all regions. This behaviour was observed as revenue from carbon for a given region did not vary between rotation lengths, and the higher revenues derived from timber for longer rotations did not compensate for the longer discounting period. This finding was consistent with [61], which shows the optimal rotation length for radiata pine is invariant to carbon price when an averaging age of 16 years is used as the earned carbon is fixed regardless of the rotation age. In contrast, for the scenarios that were averaged to the mid-point, the optimal rotation length for redwood was more dynamic and shifted from 40 years at low carbon values toward 50 years at a carbon value of 160 NZD/tonne, with the transition point occurring earlier in lower-productivity regions. This transition occurred as longer rotation lengths accumulated a higher total carbon than shorter rotations, and as the carbon price rose, greater weight was placed on this additional carbon, which increased the optimal rotation length.

Under scenarios where revenue was obtained from timber and carbon, IRR values were higher for redwood than radiata pine at low carbon prices but higher for radiata pine at moderate to high carbon prices. Assuming mid-point carbon averaging, this transition point was reached at between 31 and 50 NZD/tonne CO_2 for North Island regions and between 25 and 34 NZD/tonne CO_2 in the South Island regions, apart from Otago, where radiata pine had a higher IRR than redwood across all carbon values. The species choice will therefore depend, to some extent, on expectations concerning the future carbon price. A recent Climate Change Commission report indicated that the carbon price may be more constrained than previously thought due to a potential carbon oversupply in New Zealand during the 2030s, which could result in a reduction in carbon price in the next decade [30]. Although there is currently a floor price in the ETS of 35 NZD/tonne CO_2, the carbon price has mostly ranged from 5 to 25 NZD/tonne CO_2 between 2008 and 2020 and has only exceeded this floor price since 2020 [61]. Carbon prices are very sensitive to government intervention around policy settings within the ETS, and there is a current review of the ETS underway that may impact settings [61]. Consequently, the establishment of redwood may provide a conservative afforestation option that mitigates the risk of sustained low values for carbon.

The mid-point averaging age documented for redwood was likely to be conservative as this approach did not account for the slow decay rate of carbon remaining after harvest. The residual carbon left on site after harvest includes coarse woody debris and the root fraction, and further research should quantify changes in carbon for these components to refine the long-term average. Redwood coarse woody debris has been found to have very high decay resistance, which, when expressed as a half-life, ranges from 27 to 35 years for material in primary forests [62], greatly exceeding the documented half-life of 4–14 years for radiata pine [63]. Further research is required to determine the half-life of coarse woody debris in redwood plantations, which due to reduced heartwood is likely to be lower than the estimate for primary forests but significantly higher than that of radiata pine [64]. As redwood rapidly coppices from the cut stem, and these sprouts form the next crop, it is likely that a large part of the root system remains alive to support coppice growth. The retention of a large part of the root system between rotations will markedly increase the long-term average carbon, through ensuring there is always a significant baseline carbon level present after harvesting. In contrast to redwood, radiata pine roots decay rapidly once the stem is cut, and within a few years, there is very little of the root system visible in the soil [27,28]. Further research should more accurately quantify post-harvest changes in these redwood carbon pools, to refine the averaging age for this species. However, even without this adjustment, the proposed ages for averaging offer a safe conservative estimate, which is unlikely to result in carbon liabilities for the grower.

Species selection should take into account social licence to operate considerations and potential damage from abiotic and biotic factors under the current and future climate. Radiata pine is susceptible to many diseases currently in New Zealand, which cause significant growth losses [21–24], and there are many pests and diseases outside the country that could seriously impact the species if introduced [21]. Radiata pine is susceptible to both wind and fire, and although these abiotic factors currently damage a relatively small proportion of the estate, impacts from both factors are expected to escalate considerably under climate change [21]. Although not as invasive as some wilding species, radiata pine is a persistent invader within many ecosystems throughout New Zealand [65]. The benefits of afforestation using radiata pine for controlling erosion are well understood and include a reduction in earthflow movement, land sliding, and gully erosion [26,66]. Among six different land vegetation types, radiata pine was found to provide very high erosion protection, as soon as 8 years after planting [26]. However, as the root system of radiata pine rapidly degrades when the stem is cut [27,28], there is a heightened risk soon after harvesting. During the six years following harvesting, the rates of erosion are markedly higher than those that occur under older stands and have been found to be similar to land underlying pasture, which was the least effective land cover for reducing erosion risk after high-intensity rainfall events [26].

In contrast, redwood is not significantly impacted by abiotic and biotic factors and has a more robust social licence profile than radiata pine. Redwood has a well-deserved reputation as a healthy species that does not suffer from any major pests or diseases [4,5]. The thick bark and lack of flammable resin within the wood confers fire resistance [8–10]. Redwood is resistant to strong winds [6], and little windthrow has been noted in New Zealand stands [7]. Redwood poses very little wilding risk to surrounding land as the species relies on vegetative as well as seedling reproduction [67] and inconsistently produces small cones with seeds that have very low viability. Redwood has a very dense, interlocking root system [10,66]. The combination of this feature with the ability of the species to coppice and maintain an active root system following harvest makes this a favoured plantation species for managing erosion risk during all stages of the rotation [66,68–70].

The novel methodology used here to compare species profitability at the regional level across an entire country could be readily transferred to other tree species and countries. The predictions of carbon and timber were underpinned by a volume productivity index (300 Index) that could accurately account for variation in site productivity and was derived from PSP data. In addition to radiata pine and redwood, this approach has been successfully used to predict the productivity of most of the other key plantation species within New Zealand, including, for instance, *Cypress* spp. [47]. One requirement of this method is that there are sufficient PSP data for the species that represent a wide age range and the site and silvicultural conditions over which the species of interest is grown. While radiata pine PSPs comprehensively cover New Zealand, further research should establish redwood PSPs in many South Island regions with sparse data coverage (e.g., West Coast), to improve confidence in the estimates of the 300 Index and carbon within these areas. Further research should also undertake a comprehensive survey of redwood basic density across environments as carbon estimates are sensitive to this attribute.

5. Conclusions

The legislated averaging age of 22 years for redwood under New Zealand's Emissions Trading Scheme significantly underestimates the actual mid-point of carbon sequestration, which was conservatively estimated to be 26, 28, and 31 years for rotations lengths of 40, 45, and 50 years, respectively. The optimal rotation length for redwood depended on the region, the carbon price, and the duration of carbon averaging; the values were most often 40 years but tended to converge toward 50 years as the carbon price increased, and many southern regions reached 50 years at high carbon prices. Under timber-only scenarios, redwood was more profitable than radiata pine within eight of the nine New Zealand regions. For regimes where revenue was derived from timber and carbon, redwood had a higher IRR than radiata pine at carbon prices ranging up to 29–50 NZD/tonne CO_2 for the North Island and 23–34 NZD/tonne CO_2 in all South Island regions apart from Otago. The IRR of radiata pine exceeded that of redwood at carbon prices above these values for the eight regions and at all carbon prices within the cold, dry Otago region. In contrast to radiata pine, redwood is less prone to damage from abiotic and biotic factors, does not pose a wilding risk, and can more effectively control erosion over the entire rotation. This research highlights the potential of redwood for further afforestation within New Zealand.

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Conflicts of Interest: Mark O. Kimberley was employed by the company Environmental Statistics Ltd. The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Variation in internal rate of return (IRR), by region, in relation to carbon price and averaging age, by species and rotation length. na = not applicable. In each row the bolded cells shaded in green represent the highest IRR for the three redwood rotation lengths, while the blue bolded underlined cells represent scenarios when radiata pine has the highest IRR.

Carbon Price ($NZD/t\ CO_2$)	Redwood Averaging Age	Region	Redwood IRR (%) 40 Years	45 Years	50 Years	Radiata Pine IRR (%)
0	na	Auckland	**6.89**	6.56	6.26	4.06
0	na	Waikato/Taupo	**7.08**	6.78	6.44	4.38
0	na	Bay of Plenty	**7.14**	6.77	6.46	4.41
0	na	Gisborne	**6.53**	6.30	6.00	4.56
0	na	Hawkes Bay/Southern NI	**6.92**	6.64	6.31	4.46
0	na	Nelson/Marlborough	**4.78**	4.76	4.62	3.75
0	na	Canterbury/West Coast	4.16	**4.16**	4.08	3.14
0	na	Otago	1.36	1.84	**2.11**	<u>3.01</u>
0	na	Southland	4.52	**4.53**	4.46	3.62
35	22 years	Auckland	**7.84**	7.46	7.11	6.93
35	22 years	Waikato/Taupo	**8.01**	7.64	7.27	7.59
35	22 years	Bay of Plenty	**8.11**	7.69	7.33	7.68
35	22 years	Gisborne	**7.38**	7.08	6.75	<u>7.97</u>
35	22 years	Hawkes Bay/Southern NI	**7.82**	7.49	7.11	7.66
35	22 years	Nelson/Marlborough	**5.33**	5.26	5.09	<u>5.95</u>
35	22 years	Canterbury/West Coast	**4.60**	4.56	4.45	<u>4.81</u>
35	22 years	Otago	1.56	2.03	**2.29**	<u>4.51</u>
35	22 years	Southland	**5.02**	4.99	4.89	<u>5.67</u>

Table A1. *Cont.*

Carbon Price (NZD/t CO_2)	Redwood Averaging Age	Region	Redwood IRR (%)			Radiata Pine IRR (%)
			40 Years	45 Years	50 Years	
35	Mid-point	Auckland	**7.96**	7.70	7.44	6.93
35	Mid-point	Waikato/Taupo	**8.17**	7.87	7.58	7.59
35	Mid-point	Bay of Plenty	**8.23**	7.93	7.66	7.68
35	Mid-point	Gisborne	**7.54**	7.31	7.05	7.97
35	Mid-point	Hawkes Bay/Southern NI	**7.98**	7.71	7.43	7.66
35	Mid-point	Nelson/Marlborough	**5.46**	5.44	5.33	5.95
35	Mid-point	Canterbury/West Coast	4.71	**4.74**	4.67	4.81
35	Mid-point	Otago	1.64	2.16	**2.43**	4.51
35	Mid-point	Southland	5.14	**5.16**	5.12	5.67
80	22 years	Auckland	**9.26**	8.84	8.47	11.83
80	22 years	Waikato/Taupo	**9.38**	8.98	8.58	12.94
80	22 years	Bay of Plenty	**9.55**	9.11	8.73	13.13
80	22 years	Gisborne	**8.64**	8.30	7.93	13.55
80	22 years	Hawkes Bay/Southern NI	**9.16**	8.78	8.39	12.94
80	22 years	Nelson/Marlborough	**6.15**	6.02	5.81	9.82
80	22 years	Canterbury/West Coast	**5.25**	5.17	5.02	7.90
80	22 years	Otago	1.89	2.34	**2.57**	7.29
80	22 years	Southland	**5.77**	5.69	5.55	9.26
80	Mid-point	Auckland	**9.52**	9.38	9.21	11.83
80	Mid-point	Waikato/Taupo	**9.72**	9.49	9.30	12.94
80	Mid-point	Bay of Plenty	**9.81**	9.64	9.47	13.13
80	Mid-point	Gisborne	**8.99**	8.80	8.63	13.55
80	Mid-point	Hawkes Bay/Southern NI	**9.51**	9.29	9.10	12.94
80	Mid-point	Nelson/Marlborough	**6.46**	6.45	6.40	9.82
80	Mid-point	Canterbury/West Coast	5.53	**5.61**	5.55	7.90
80	Mid-point	Otago	2.11	2.67	**2.95**	7.29
80	Mid-point	Southland	6.08	6.11	**6.11**	9.26

References

1. Brown, J.E. *Monarchs of the Mist: The Story of Redwood National Park and the Coast Redwoods*; Coastal Parks Association: Pescadero, CA, USA, 1982.
2. Earle, C.J. *Sequoia sempervirens*. The Gymnosperm Database. 2018. Available online: https://www.conifers.org/cu/Sequoia.php (accessed on 22 June 2023).
3. Sillett, S.C.; Van Pelt, R.; Carroll, A.L.; Campbell-Spickler, J.; Antoine, M.E. Aboveground biomass dynamics and growth efficiency of *Sequoia sempervirens* forests. *For. Ecol. Manag.* **2020**, *458*, 117740. [CrossRef]
4. Bain, J.; Nicholas, I. Health. In *Best Practice with Farm Forestry Timber Species, No. 3: Redwoods—NZFFA Electronic Handbook Series No. 3*; Nicholas, I., Ed.; New Zealand Farm Forestry Association: Wellington, New Zealand, 2008. Available online: https://www.nzffa.org.nz/system/assets/2080/Redwoods_Handbook.pdf (accessed on 22 June 2023).
5. Peters, T.; Hardaker, A.; Dauksta, D.; Newman, G.; Lellig, C.; Healey, J. Top Five Alternative Conifer Tree Species in Great Britain: Main Report and Executive Summary. Welsh Government. 2021. Available online: https://woodknowledge.wales/wkw-resource/forestry/top-five-alternative-conifer (accessed on 22 June 2023).
6. Brown, I.; Low, C.; McConnochie, R.; Nicholas, I.; Webster, R. Site Selection. In *Best Practice with Farm Forestry Timber Species, No. 3: Redwoods—NZFFA Electronic Handbook Series No. 3*; Nicholas, I., Ed.; New Zealand Farm Forestry Association: Wellington, New Zealand, 2008. Available online: https://www.nzffa.org.nz/system/assets/2080/Redwoods_Handbook.pdf (accessed on 22 June 2023).
7. Rapley, S. Redwood in New Zealand. *N. Z. J. For.* **2018**, *63*, 29–33.
8. Jacobs, D.F.; Cole, D.W.; McBride, J.R. Fire history and perpetuation of natural coast redwood ecosystems. *J. For.* **1985**, *83*, 494–497.
9. Stuart, J.D. Fire history of an old-growth forest of *Sequoia sempervirens* (Taxodiaceae) forest in Humboldt Redwoods State Park, California. *Madrono* **1987**, *34*, 128–141.
10. Olson, D.F.; Roy, D.F.; Walters, G.A. *Sequoia sempervirens* (D. Don) Endl. Redwood. *Silv. N. Am.* **1990**, *1*, 541–551.

11. Knowles, F.B.; Miller, J.T. *Introduced Forest Trees in New Zealand: Recognition, Role, and Seed Source*; No. 13 The Redwoods. FRI Bulletin No. 124; New Zealand Forest Research Institute: Rotorua, New Zealand, 1993.
12. Arnaud, Y.; Franclet, A.; Tranvan, H.; Jacques, M. Micropropagation and rejuvenation of *Sequoia sempervirens* (Lamb) Endl: A review. *Ann. Des Sci. For.* **1993**, *50*, 273–295. [CrossRef]
13. Breidenbach, N.; Gailing, O.; Krutovsky, K.V. Genetic structure of coast redwood (*Sequoia sempervirens* [D. Don] Endl.) populations in and outside of the natural distribution range based on nuclear and chloroplast microsatellite markers. *PLoS ONE* **2020**, *15*, e0243556. [CrossRef] [PubMed]
14. Toral, I.; Caru, M.; Herrera, M.A.; Gonzalez, L.; Martin, L.M.; Miranda, J.; Navarro-Cerrillo, R.M. Clones identification of *Sequoia sempervirens* (D. Don) Endl. in Chile by using PCR-RAPDs technique. *J. Zhejiang Univ. (Sci. B)* **2009**, *10*, 112–119. [CrossRef]
15. SWP Research Partnership. The Specialty Woods Products Research Partnership. Final Report. 2015–2023. Available online: https://fgr.nz/documents/download/10702 (accessed on 7 October 2023).
16. Watt, M.S.; Kimberley, M.O. Spatial comparisons of carbon sequestration for redwood and radiata pine within New Zealand. *For. Ecol. Manag.* **2022**, *513*, 120190. [CrossRef]
17. Watt, M.S.; Kimberley, M.O.; Rapley, S.; Webster, R. Comparing volume productivity of redwood and radiata pine plantations in New Zealand. *For. Ecol. Manag.* **2021**, *500*, 119628. [CrossRef]
18. NZFOA. *New Zealand Forestry Industry, Facts and Figures 2021/2022. New Zealand Plantation Forest Industry*; New Zealand Forest Owners Associationa: Wellington, New Zealand, 2022. Available online: https://www.nzfoa.org.nz/resources/publications/facts-and-figures (accessed on 4 July 2023).
19. Maclaren, P. Realistic alternatives to radiata pine in New Zealand—A critical review. *N. Z. J. For.* **2005**, *50*, 3–10. Available online: https://fgr.nz/documents/download/2598 (accessed on 8 October 2023).
20. Watt, M.S.; Palmer, D.J.; Leonardo, E.M.C.; Bombrun, M. Use of advanced modelling methods to estimate radiata pine productivity indices. *For. Ecol. Manag.* **2021**, *479*, 118557. [CrossRef]
21. Watt, M.S.; Kirschbaum, M.U.F.; Moore, J.R.; Pearce, H.G.; Bulman, L.S.; Brockerhoff, E.G.; Melia, N. Assessment of multiple climate change effects on plantation forests in New Zealand. *For. Int. J. For. Res.* **2019**, *92*, 1–15. [CrossRef]
22. Watt, M.S.; Palmer, D.J.; Bulman, L.S. The ecomomic cost of Dothistroma needle blight to the New Zealand forest industry. *N. Z. J. For.* **2011**, *56*, 20–22.
23. Watt, M.S.; Rolando, C.A.; Palmer, D.J.; Bulman, L. Predicting the severity of *Cyclaneusma minus* on *Pinus radiata* under current climate in New Zealand. *Can. J. For. Res.* **2012**, *42*, 667–674. [CrossRef]
24. Watt, M.S.; Tan, A.Y.S.; Fraser, S.; Bulman, L.S. Use of advanced modelling methods to predict dothistroma needle blight on Pinus radiata at a fine resolution within New Zealand. *For. Ecol. Manag.* **2021**, *492*, 119226. [CrossRef]
25. Moore, J.R.; Watt, M.S. Modelling the influence of predicted future climate change on the risk of wind damage within New Zealand's planted forests. *Glob. Chang. Biol.* **2015**, *21*, 3021–3035. [CrossRef]
26. Marden, M.; Rowan, D. Protective value of vegetation on tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. *N. Z. J. For. Sci.* **1993**, *23*, 255–263.
27. O'Loughlin, C.L.; Watson, A.J. Root-wood strength deterioration in radiata pine after clearfelling. *N. Z. J. For. Sci.* **1979**, *9*, 284–293.
28. Watson, A.; Phillips, C.; Marden, M. Root strength, growth, and rates of decay: Root reinforcement changes of two tree species and their contribution to slope stability. *Plant Soil* **1999**, *217*, 39–47. [CrossRef]
29. Ministry for Primary Industries. Registering in the ETS with Post-1989 Forest Land. Available online: https://www.mpi.govt.nz/forestry/forestry-in-the-emissions-trading-scheme/joining-the-ets/registering-in-the-ets-with-post-1989-forest-land/ (accessed on 22 June 2023).
30. Climate Change Commission. Draft Advice to Inform the Strategic Direction of the Government's Second Emissions Reduction Plan. Available online: https://www.climatecommission.govt.nz/our-work/advice-to-government-topic/advice-for-preparation-of-emissions-reduction-plans/2023-draft-advice-to-inform-the-strategic-direction-of-the-governments-second-emissions-reduction-plan-april-2023/ (accessed on 22 June 2023).
31. Manley, B. Impact on profitability, risk, optimum rotation age and afforestation of changing the New Zealand emissions trading scheme to an averaging approach. *For. Policy Econ.* **2020**, *116*, 102205. [CrossRef]
32. Leining, C. A Guide to the New Zealand Emissions Trading Scheme: 2022 Update. Motu Economic and Public Policy Research. 2022. Available online: https://www.motu.nz/assets/Documents/our-research/environment/climate-change-mitigation/emissions-trading/A-Guide-to-the-New-Zealand-Emissions-Trading-System-2022-Update-Motu-Research.pdf (accessed on 22 June 2023).
33. Kimberley, M.O.; Watt, M.S. A Novel Approach to Modelling Stand-Level Growth of an Even-Aged Forest Using a Volume Productivity Index with Application to New Zealand-Grown Coast Redwood. *Forests* **2021**, *12*, 1155. [CrossRef]
34. Watt, M.S.; Kimberley, M.O.; Steer, B.S.C.; Neumann, A. Financial comparison of afforestation using redwood and radiata pine under carbon regimes within New Zealand. *Trees For. People* **2023**, *13*, 100422. [CrossRef]
35. Kimberley, M.O.; West, G.; Dean, M.; Knowles, L. Site Productivity: The 300 Index—A volume productivity index for radiata pine. *N. Z. J. For.* **2005**, *50*, 13–18.
36. Manley, B.; Maclaren, P. Potential impact of carbon trading on forest management in New Zealand. *For. Policy Econ.* **2012**, *24*, 35–40. [CrossRef]

37. Dean, M.K.M.O.; Silcock, P.; Webster, R. Pruning and Thinning. In *Best Practice with Farm Forestry Timber Species, No. 3: Redwoods—NZFFA Electronic Handbook Series No. 3*; Nicholas, I., Ed.; New Zealand Farm Forestry Association: Wellington, New Zealand, 2008. Available online: https://www.nzffa.org.nz/system/assets/2080/Redwoods_Handbook.pdf (accessed on 22 June 2023).
38. Assmann, E. Die Bedeutung des „erweiterten Eichhorn'schen Gesetzes" für die Konstruktion von Fichten-Ertragstafeln. *Forstwiss. Cent.* **1955**, *74*, 321–330. [CrossRef]
39. Henriksen, H.A. *Sitkagranens Vækst og Sundhedstilstand i Danmark*; Kandrup & Wunsch's bogtr: København, Denmark, 1958; Volume 24.
40. Kennel, R. Die Bestimmung des Ertragsniveaus bei der Buche. *Forstwiss. Cent.* **1973**, *92*, 226–234. [CrossRef]
41. Schmidt, A. Ertragsniveau und Standort dargestellt am Beispiel der Kiefer. *Forstwiss. Cent.* **1973**, *92*, 268–274. [CrossRef]
42. Hasenauer, H.; Burkhart, H.E.; Sterba, H. Variation in potential volume yield of loblolly pine plantations. *For. Sci.* **1994**, *40*, 162–176.
43. Vanclay, J.K.; Skovsgaard, J.P.; Hansen, C.P. Assessing the quality of permanent sample plot databases for growth modelling in forest plantations. *For. Ecol. Manag.* **1995**, *71*, 177–186. [CrossRef]
44. Skovsgaard, J.P. *Management of Sitka Spruce without Thinnings: An Analysis of Stand Structure and Volume Production of Unthinned Stands of Sitka Spruce (Picea sitchensis (Bong.) Carr.) in Denmark*; Forskningsserien; Forskningscentret for Skov og Landskab: København, Denmark, 1997.
45. Skovsgaard, J.P.; Vanclay, J.K. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. *For. Int. J. For. Res.* **2008**, *81*, 13–31. [CrossRef]
46. Watt, M.S.; Kimberley, M.O. Comparing regional variation in carbon sequestration for radiata pine and redwood throughout New Zealand. *N. Z. J. For.* **2022**, *67*, 12–21.
47. Kimberley, M.O.; Watt, M.S. Growth Models for Even-Aged Stands of *Hesperocyparis macrocarpa* and *Hesperocyparis lusitanica*. *Forests* **2023**, *14*, 105. [CrossRef]
48. Beets, P.N.; Kimberley, M.O.; Paul, T.S.H.; Garrett, L.G. Planted Forest Carbon Monitoring System--forest carbon model validation study for Pinus radiata. *N. Z. J. For. Sci.* **2011**, *41*, 177–189.
49. Kimberley, M.O.; Beets, P.N. National volume function for estimating total stem volume of *Pinus radiata* stands in New Zealand. *N. Z. J. For. Sci.* **2007**, *37*, 355–371.
50. Beets, P.N.; Roberston, K.A.; Ford-Robertson, J.B.; Gordon, J.; Maclaren, J.P. Description and validation of C_Change: A model for simulating carbon content in managed Pinus radiata stands. *N. Z. J. For. Sci.* **1999**, *29*, 409–427.
51. Garrett, L.G.; Kimberley, M.O.; Oliver, G.R.; Pearce, S.H.; Beets, P.N. Decomposition of coarse woody roots and branches in managed Pinus radiata plantations in New Zealand–A time series approach. *For. Ecol. Manag.* **2012**, *269*, 116–123. [CrossRef]
52. IPCC. *Good Practice Guidance for Land Use, Land Use Change and Forestry*; Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., et al., Eds.; Institute for Global Environmental Strategies (IGES): Hayama, Japan, 2003.
53. West, G.G.; Moore, J.R.; Shula, R.G.; Harrington, J.J.; Snook, J.; Gordon, J.A.; Riordan, M.P. Forest management DSS development in New Zealand. In *Implementation of DSS Tools into the Forestry Practice*; Tucek, J., Smrecek, R., Majlingova, A., Garcia Gonzalo, J., Eds.; Technical University of Zvolen: Zvolen, Slovakia, 2013; pp. 153–163.
54. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023. Available online: https://www.R-project.org/ (accessed on 22 June 2023).
55. Ministry for Primary Industries. Wood Product Markets Data. Available online: https://www.mpi.govt.nz/forestry/forest-industry-and-workforce/forestry-wood-processing-data/wood-product-markets-data/ (accessed on 6 October 2023).
56. Silcock, P. Sawing and Wood Quality Studies on Pruned Redwood. New Zealand Tree Grower—August Issue. 2008. Available online: https://www.nzffa.org.nz/farm-forestry-model/resource-centre/tree-grower-articles/august-2008/sawing-and-wood-quality-studies-on-pruned-redwood/ (accessed on 27 September 2023).
57. Manley, B. *Afforestation Economic Modelling. Report Prepared for MPI*; University of Canterbury: Canterbury, New Zealand, 2021. Available online: https://www.mpi.govt.nz/dmsdocument/50302-Afforestation-Economic-Modelling-Report (accessed on 22 June 2023).
58. West, G. Small-Scale Grower Harvest Costs and Returns. Report for New Zealand Farm Forestry Association. 2019. Available online: https://www.nzffa.org.nz/farm-forestry-model/the-essentials/roads-earthworks-and-harvesting/reports/report-small-scale-grower-harvest-costs-and-returns/ (accessed on 7 October 2023).
59. Ministry for Primary Industries. Managing Exotic Afforestation Incentives: Regulatory Impact Statement. Available online: https://www.mpi.govt.nz/dmsdocument/53992-Managing-Permanent-Exotic-Afforestation-Incentives-Regulatory-Impact-Statement (accessed on 22 June 2023).
60. Climate Change Commission. Ināia Tonu Nei: A Low Emissions Future for Aotearoa. 2021. Available online: https://www.climatecommission.govt.nz/our-work/advice-to-government-topic/inaia-tonu-nei-a-low-emissions-future-for-aotearoa/ (accessed on 22 June 2023).
61. Manley, B. Impact of carbon price on the relative profitability of production forestry and permanent forestry for New Zealand plantations. *For. Policy Econ.* **2023**, *156*, 103057. [CrossRef]
62. Busing, R.T.; Fujimori, T. Biomass, production and woody detritus in an old coast redwood (*Sequoia sempervirens*) forest. *Plant Ecol.* **2005**, *177*, 177–188. [CrossRef]

63. Garrett, L.G.; Kimberley, M.O.; Oliver, G.R.; Pearce, S.H.; Paul, T.S.H. Decomposition of woody debris in managed Pinus radiata plantations in New Zealand. *For. Ecol. Manag.* **2010**, *260*, 1389–1398. [CrossRef]
64. Jones, T.G.; Low, C.B.; O'Callahan, D.R.; Chittenden, C.M. Variation in the wood properties of coast redwood trees in New Zealand. *N. Z. J. For. Sci.* **2014**, *44*, 11. [CrossRef]
65. Bellingham, P.J.; Arnst, E.A.; Clarkson, B.D.; Etherington, T.R.; Forester, L.J.; Shaw, W.B.; Sprague, R.; Wiser, S.K.; Peltzer, D.A. The right tree in the right place? A major economic tree species poses major ecological threats. *Biol. Invasions* **2023**, *25*, 39–60. [CrossRef]
66. Phillips, C.J.; Marden, M.; Lambie, S.; Watson, A.; Ross, C.; Fraser, S. Observations of below-ground characteristics of young redwood trees (*Sequoia sempervirens*) from two sites in New Zealand–implications for erosion control. *Plant Soil* **2013**, *363*, 33–48. [CrossRef]
67. O'Hara, K.L.; Cox, L.E.; Nikolaeva, S.; Bauer, J.J.; Hedges, R. Regeneration dynamics of coast redwood, a sprouting conifer species: A review with implications for management and restoration. *Forests* **2017**, *8*, 144. [CrossRef]
68. Burdon, R.D. Is coast redwood an answer to the Mangatu problem? *N. Z. J. For.* **1975**, *20*, 148–152.
69. Marden, M. The tolerance of *Sequoia sempervirens* to sedimentation, East Coast region, New Zealand. *N. Z. For.* **1993**, *38*, 22–24.
70. Garrett, L.G.; Clinton, P.W. Erosion mitigation and carbon. In *Coast Redwood (Sequoia sempervirens) Development Plan*; Scion (New Zealand Forest Research Institute Limited): Rotorua, New Zealand, 2013. Available online: https://www.researchgate.net/publication/327634451_New_Zealand%27s_Coast_Redwood_Forestry_Development_Plan (accessed on 4 August 2023).