PO Box 1127
Rotorua 3040
Ph: + 64 7 921 1883
Fax: + 64 7 921 1020
Email:info@ffr.co.nz
Web: www.ffr.co.nz

Theme: Diversified Species

Task No:F30104
Milestone Number:1.04.32

Report No. : DS048

Coast Redwood
(*Sequoia sempervirens*)
Development Plan

Authors:
D Meason, S Kennedy, L G Garrett, D Cown, L Barry,
C Todoroki, C Andersen, H S Dungey, P C Clinton, D J Cown

Research Provider:
Scion

Date: December 2012

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Following a recent resurgence in the popularity of coast redwood (*Sequoia sempervirens*, (D.Don) Endl.) as a potential plantation species, it is timely that the current management practices and marketability of this species undergo a review. The following report discusses current knowledge and understanding of coast redwood grown in New Zealand and recommends future work required for further development of this species after the end of the current Future Forest Research (FFR) Diversified Species programme. The recommendations in this report are separate from the FFR redwood milestones so cannot be funded by the current FFR programme. This report covers genetic material currently planted in New Zealand, silvicultural practices, wood quality and productivity. The potential benefits of planting this species over other species are outlined and a market analysis follows.

A brief summary of the findings of each section of this report follows.

1. Genetics

Coast redwood has been planted in New Zealand since 1860. Material currently in circulation came from a number of introductions, notably the Rotoehu provenance trail and the Kuser collection. Available material was planted in a number of benchmarking trials to enable comparison between clones in circulation. It is recommended that further selections be made from the most favourable provenances in California in the immediate future and planted out in a provenance trial to be combined later with select material from the recently established benchmarking trial to form a breeding population. This breeding population would provide a basis for future deployment populations, providing adaptation across a range of site types. Key selection attributes would be consistency in durability and increased wood density whilst maintaining or improving growth rates.

2. Site Productivity and Growth Models

Coast redwood has been in New Zealand for over 100 years; however, due to past failures the species was neglected until the last 20 years. The permanent sample plots (PSPs) are too few and geographic distribution is too limited to represent the potential distribution and growth in New Zealand. Understanding how site influences coast redwood productivity is especially important as it is sensitive to frost, soil water, soil fertility, and mycorrhizal associations. It is recommended that the number of PSPs be at least doubled. Data from an expanded PSP network would provide the data to improve significantly the redwood site index, the 400 index, site productivity model, and the Interim Growth Model. Redwood volume taper differs between fast and slow growing sites. Data available for volume taper equations are also limited. More volume and taper data collected from a range of sites would improve the accuracy of volume calculations.

3. Silvicultural Practices

Research in the last 20 years has improved our understanding of redwood establishment and management practices. However, there are a number of knowledge gaps remaining. The impact of stocking (tree density), growth and wood quality properties is unknown. More thinning trials are required. A greater research priority is the establishment of more pruning trials. A number of questions need to be addressed, including impact of heavy pruning on growth, risk of development of epicormic shoots, and economic effects of pruning on the final log value. It is recommended that new thinning and pruning trials be established using a simplified trial design that can “piggy-back” operational regimes used by industry. As redwood appears to be more responsive to silvicultural practices at a young age, it is recommended that these trials be established in stands less than 15 years old. It is also recommended that thinning trials have a control plot that has a stocking greater than 850 stems per hectare so that thinning dynamics can be determined in a shorter time frame.

4. Erosion Mitigation and Carbon

The current understanding of how redwoods contribute toward stabilising erosion-prone slopes and what contribution their biomass may have towards carbon sequestration is limited. Vegetation contributes to slope stability through added cohesion to the soil by the root system. Coast redwood has wide-spreading lateral roots, with greater potential for interlinking and grafting of roots with neighbouring trees. Coast redwood's strongest trait in erosion mitigation is its ability to coppice after harvesting, retaining the interlinking root biomass. How much of the root biomass remains alive after harvesting is, however, uncertain. For carbon accounting purposes, the greatest uncertainties come through the high variability in wood density and the allocation of both above and below ground biomass. There is some data available, but it is limited and needs improving to increase the robustness of carbon estimates.

5. Market Analysis

Underlying the success of coast redwood in New Zealand is confidence around the accessible markets available to promote the species. The market for carbon has provided forestry with additional revenue, and coast redwoods are potentially in a strong position to capitalise on this, especially for long-term planting in areas of environmental importance where harvesting for timber may not be a priority. However, the robustness of the carbon estimates needs to be improved for redwood before it can be included into the ETS system. The timber market holds promise due to the potentially shorter rotation ages necessary to get a product comparable to Californian young-growth redwoods and other substitute products, such as western red cedar. There is still, however, a perception that the quality of New Zealand-grown redwood timber is poor. New Zealand redwood products will have to improve to compete with the better perceived quality of US-grown redwood. While issues of optimal growing locations and silvicultural regimes have made progress, coast redwood may still be perceived as a risky investment in New Zealand because of poor wood quality perceptions. This risk may be over-rated with companies such as the New Zealand Redwood Company and the New Zealand Forestry Company Ltd. already investing. However, more evidence is required.

6. Wood Quality

New Zealand-grown redwood suffers from a poor perception in the marketplace, similar to (or poorer than) US second-growth timber which is acknowledged to have low wood density and poorer average durability for exterior uses. Without improvements in wood quality, New Zealand-grown redwood will continue to be regarded as a poor substitute for Californian redwood. There seems to be no doubt that planting will increased in the future, with the multiple aims of adding forest diversity, erosion control and producing timber and carbon credits. By selecting fast-grown material without genetic selection for quality, density and durability, markets will become less disposed to embrace the products. The most important characteristic, requiring urgent attention, is durability because this has been a selling point in the past, but tests have confirmed high variability mainly due to the relatively young age (durability increases with age up to several hundred years) and genetics. There are good prospects for genetic improvement, particularly if protocols are developed for NIR screening of progeny and validation in standard ground-contact field tests. Without the latter, changed durability ratings are unlikely to occur for a long time.

The recommendations outlined in this report should shape the research programme for the development of coast redwood as an up-and-coming species. A table outlining what and when recommended research should be conducted can be found at the end of this report. This timeline has been drawn up independent of FFR priorities across the whole Diversified Species research programme. In addition, the current FFR programme finishes in September 2013, and longer-term research will need to be prioritised and funded within the new FFR framework.

GENETICS

S. Kennedy and H. Dungey

History of Redwood Growth in New Zealand

Coast redwood (*Sequoia sempervirens*) was planted at many locations throughout New Zealand between 1860 and 1870. It was first planted by the New Zealand Forest Service in 1901 at Whakarewarewa Forest, Rotorua. This stand grew well, sparking interest in the species. Large areas of redwood were planted in both the North and South Islands between 1920 and 1945, but most failed due to poor siting and weed control [1]. Following these failures redwood fell from favour, continuing to be planted only by a few enthusiasts. In the 1990s, Bill Libby, Professor of Forestry at the University of California at Berkeley was able to rekindle interest in growing redwoods in New Zealand.

Genetic Stock in New Zealand

The origin and genetic diversity of early introductions of coast redwood to New Zealand is largely unknown. However, there are two groups of germplasm where we do know something:

1. In 1981 a coast redwood provenance trial was planted in Rotoehu forest, consisting of eight experimental seedlots from California and a seedlot collected from Whakarewarewa Forest. The trial did not get off to the best of starts and was abandoned soon after planting due to excessive weed growth. However, many of the trees did survive. The only real conclusion from the trial was that the seedlot from Whakarewarewa Forest was the slowest growing seedlot tested, indicating poor early collections or potential problems with inbreeding. Stump coppice was collected from a number of the better trees after the stand was logged.

2. The Kuser collection, named after Professor John Kuser who made the collection, consists of two random seedlings from 98 different stands located throughout the natural redwood range in America. Thirty-five clones from the Kuser collection were received in 1992 and a much more extensive collection of 182 clones of the original 198 Kuser clones was planted out in 11 trials across New Zealand from 2003 to 2006. In addition to these introductions a number of clones have been imported privately by industry in recent years.

To enable robust ranking of the genetic material currently in New Zealand, three redwood benchmarking trials were established in 2011. This brought available material into circulation from the Kuser collection, the Rotoehu provenance trial and private introductions (114 in total) for testing [2]. The planting of these trials was really important as it is the first time that different clones will be able to be compared using internationally accepted techniques.

Potential for Genetic Improvement

Coast redwood is the only hexaploid conifer, containing six sets of 11 chromosomes. It has a relatively large genome size of 31,500MB, one of the largest of the conifers. The genetic (allozyme) diversity of coast redwood measured by the percentage of polymorphic loci was 92% [3]. This raises the question: why does a species such as coast redwood which is presently found growing in a relatively small natural range still possess such a large genome with such high genetic diversity? It is not known why organisms retain parts of the genome that are of apparent little use or if these parts are still viable, being utilised under stress. Through tree breeding it is possible to utilise this large genetic variation to improve particular traits of interest such as growth and durability.

Coast redwood is one of the few known gymnosperms to re-sprout from stumps following natural disasters such as flooding or fire [3]. The trees' ability to coppice after the previous crop has been harvested is often cited as a potential benefit[4], removing the need to plant material to form the subsequent crop. This potential advantage comes into conflict with the notion of replacing existing redwood stands after harvest with improved material – the existing stumps may have to be poisoned or the coppice controlled, meaning that the gain from any improved material would have to be sufficient to justify such operational costs on replanted sites.

The coppice from felled trees remains juvenile, making it a convenient source of material from which to take cuttings which can later be bulked in the nursery, producing multiple clones of the same tree. Currently the majority of redwood material planted in New Zealand is from cloned individuals obtained from native stands in California. No redwood breeding programme currently exists to develop and improve coast redwood suited to New Zealand growing conditions.

Advantages of a Redwood Breeding Population

Currently there is no genetic improvement of coast redwood in New Zealand, just selection amongst clones in circulation. However, the recently established benchmarking trials [2] should provide an idea of which are the better clones. If using cloned material, it is recommended that multiple clones be represented across a forest to reduce the risk of large scale losses due to disease or changes in growing conditions [5]. A redwood breeding programme should be established to provide a base population for the selection of further clonal material or a source of improved seedling material. Selections from open pollinated crossing will lead to the promotion of desirable genes within the breeding population from which further superior individuals can be selected for seedling or clonal propagation for planting out into the forest. The establishment of a breeding programme would have the following advantages:

- Improvement in the consistency of wood durability and increasing wood density whilst maintaining or improving growth rates.
- Supply of material that is better adapted to New Zealand growing conditions and flexibility in the choice of material for planting across a range of sites.
- Diversity of favourable genotypes rather than dependence upon an individual that could be susceptible to disease outbreaks or changes in climate.
- Long-term diversity and resilience of coast redwood in New Zealand.

Recommendations

- It is recommended that a breeding programme is started for coast redwood (Figure 1).
- Analysis of the Kuser trials would provide an indication of the best area from within the redwood native range to make a plus tree seed collection from America. This collection would expand the genetic base for the most favourable provenance for growing in New Zealand. Seed would be collected from 100 plus trees.
- Open pollinated seed would be collected from the benchmarking trials. At least one trial would be rouged, retaining the best selections to produce open pollinated seed. These remaining trees would be stimulated to induce flowering. To capture as much genetic variation as possible, seed should be collected from all families remaining within the trial.
- Seed collected from the benchmarking trials and the collection from America would be planted out for testing in progeny tests.
- From these progeny trials the best individual from each family would be selected to roll over the next generation, and the best individuals from the best 20 families used to establish a seed orchard and clonal propagation cycle.

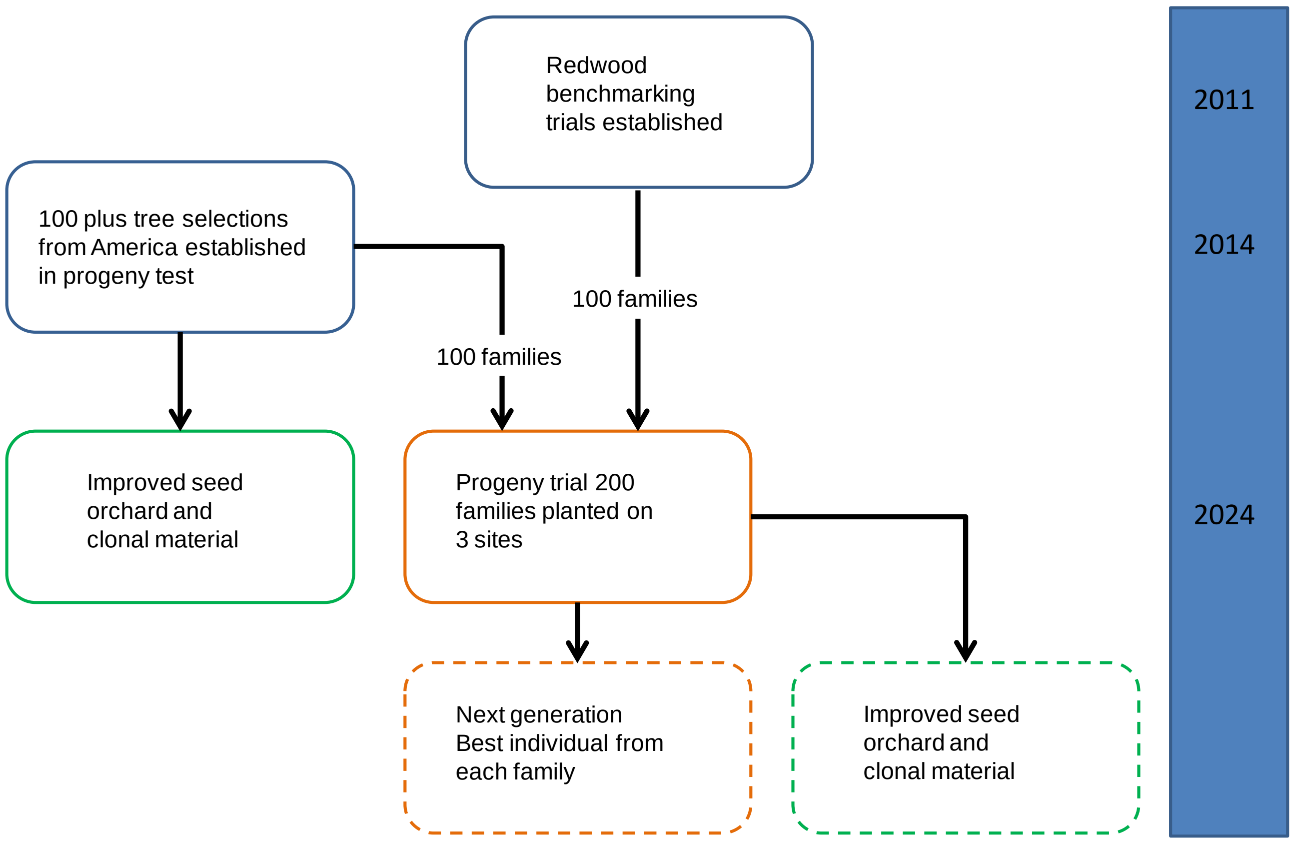

Figure 1: Diagrammatic representation of the proposed approach for the establishment of a coast redwood breeding programme.

Summary

- Given the current resurgence in the popularity of redwoods and the existence of a range of material in the Kuser and benchmarking trials, this is the ideal opportunity to establish a redwood breeding population. This breeding population would provide a basis for future deployment populations, providing adaptation across a range of site types, whose key selection attributes would be consistency in durability, increased wood density whilst maintaining or improved growth rates.
- A robust breeding programme will supply future improved genotypes for clonal testing and/or deployment.
- Collaboration among redwood companies will be vital for this breeding programme to be successful.

SITE PRODUCTIVITY AND GROWTH MODELS

D. Meason, C. Todoroki, and C. Anderson

Introduction

In the early 20th century, when timber yield was declining in New Zealand's indigenous forest, coast redwood was seen as a species with a high potential for plantation forestry. Attempts at large scale establishment throughout New Zealand failed, with a few exceptions [6]. One of the most notable exceptions is Whakarewarewa Forest. Reasons for these failures (which were not understood until much later) included planting in frost-prone areas, no weed control at establishment, and absence of suitable mycorrhizae[1, 6, 7]. These failures led to the false perception that redwood was unsuitable for New Zealand. Plantings and research in the last 20 years has demonstrated that with the right siting and establishment practices, redwood can be highly productive in New Zealand. People like Bill Libby were instrumental in reviving interest in the species; for example Libby's 1993 article in *New Zealand Forestry*[8]. As coast redwood was generally not seen as a viable forestry species until recently, site and productivity information is very limited. Industry and Scion have worked in collaboration since 2000 to develop a coast redwood permanent sample plot (PSP) network to collect site and productivity information. Industry developed the first empirical growth model for redwood grown in New Zealand. Research by industry and the FFR Diverse Forests plan has developed site productivity surfaces, and volume and taper equations. These are discussed below. These models have provided for the first time a reasonable prediction of site productivity and yield for sites throughout New Zealand.

Permanent Sample Plot Network

The number of PSP sites has expanded since the creation of FFR. The PSP database currently contains a network of 27 sites throughout New Zealand (Figure 2) with a total of 111 PSP plots. Typically there is only one PSP per site, with a few sites having more (up to 24 PSPs per site). Stand ages of PSPs, when measured, vary between <1 and 110 years, with the majority less than 35 years old. The number of individual plot measurements at each site is small with typically less than five measurements. Despite the expansion, the number of PSPs is limited and possibly misleading due to the low representation of older stands and limited plot numbers per PSP. There are regions that are likely to be suitable for coast redwood plantations, but are either under-represented (e.g.Taranaki and Manawatu) or not represented at all (e.g. Northland and Waiarapa). Any establishment of new PSPs to expand the network needs be prioritised for these regions.

Coast redwood's native habitat range in western North America is a mild climate with mean annual temperatures ranging between 10 ºC to 16 ºC, temperatures rarely dropping below -9 ºC or rising above 38 ºC, and with frost-free periods varying from 6 to 11 months of the year [9]. The presence of summer fog is a very important climatic factor in its natural range [9]. However, fog is not a factor in establishing redwood in New Zealand. The distribution of PSPs does not represent the potential climatic and biophysical range of coast redwood in New Zealand. For example, large areas of the Taranaki region could be suitable for coast redwood but the number of PSPs in the region is one (Figure 2). The climatic distribution in the PSP database is highlighted in Figure 3, with a limited range in total annual precipitation for a majority of sites between 1000 and 1300 mm. The limited range in climatic variables is also observed for mean annual temperature, mean annual maximum temperature, and mean annual minimum temperature (Figure 3). Coast redwood is known to be sensitive to out of season frosts. The current PSP network is located at sites with a low number of frost days, so the maximum level of frost day tolerance is unknown. Given the strong interest in expanding the current area planted in redwood, a high priority should be given to at least tripling the number of PSP sites. The new PSPs must be distributed over the range of potential climatic sites for coast redwood, with emphasis on inland sites that are vulnerable to frosts. These frost-prone sites will provide valuable information on coast redwood's tolerance for frost.

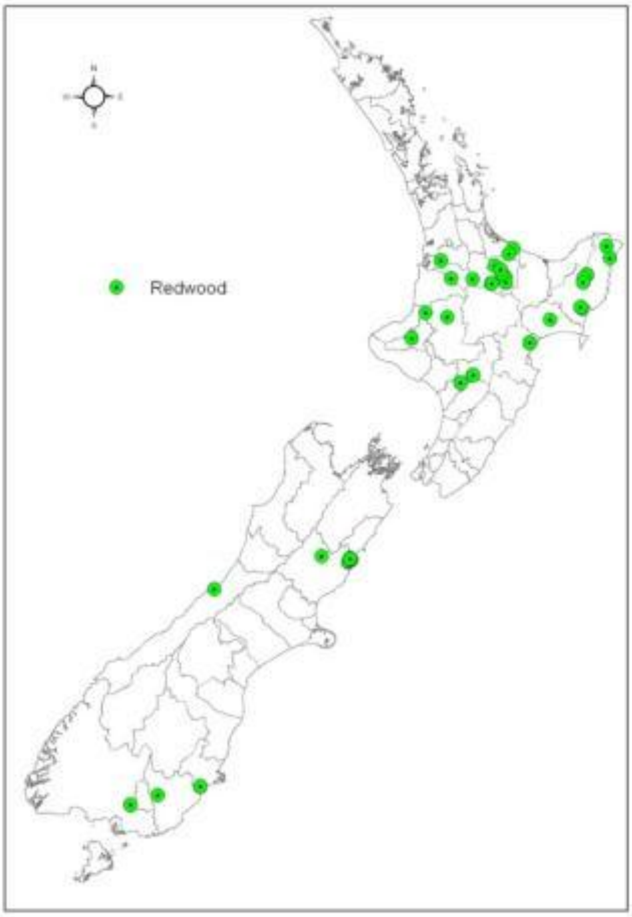

Figure 2: Location of coast redwood permanent sample plots in New Zealand.

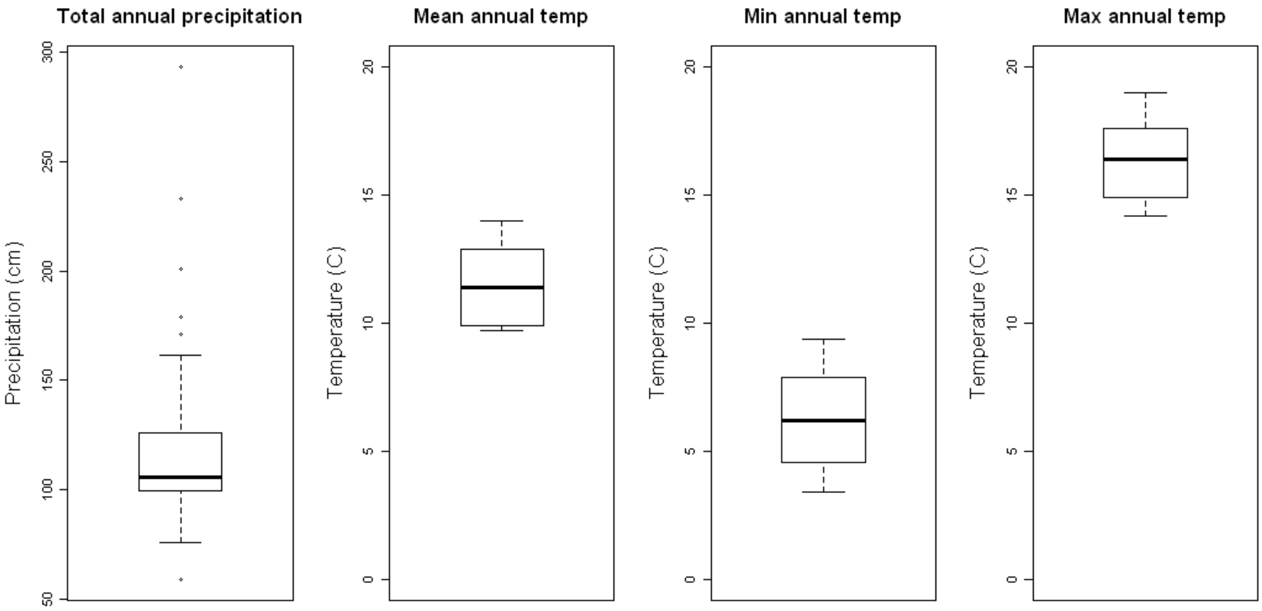

Figure 3: Box and whisker plot of coast redwood permanent sample plot climatology; total annual precipitation, mean annual temperature, mean annual daily minimum temperature, and mean annual daily maximum temperature.

Coast redwood productivity at some PSP sites can vary significantly from plot to plot. This would suggest that redwood can be very sensitive to soil water and fertility conditions. However, the extent of this sensitivity is not understood. This should become clearer as the PSP network is extended with new sites throughout New Zealand. Statistical analysis of redwood productivity between PSPs found that one of the important indicators of productivity was extractable soil phosphorus [10]. One potential reason why coast redwood is sensitive to site conditions is its roots' association with arbuscularmycorrhizae. This type of mycorrhiza grows poorly in cool conditions and is not efficient in extracting nitrogen and phosphorus bound in soil organic matter [11]. Thus, coast redwood performs poorly in soils that have most of the plant accessible nitrogen and phosphorus bound in organic matter. Davis [11] concluded that the arbuscularmycorrhizae association was the primary reason why coast redwood has to be located on sites with high soil fertility and water availability, and why they are commonly referred to as 'site demanding species'. A recent glasshouse study examined if nutrient availability for young redwood (<1-year-old) could be enhanced by growing it with tree species that had an ectomycorrhizal association [12]. Ectomycorrhizae are more efficient in extracting soil nutrients from soil organic matter, grow in cooler conditions, and may indirectly increase nutrient availability for arbuscularmycorrhizae and therefore redwood nutrient uptake. The greenhouse study found that associations with kanuka, radiata pine, Douglas-fir, and cypress either made no difference or suppressed coast redwood growth [12]. The lack of a redwood growth response was attributed to the faster growth rate of the other species [12]. The interaction of coast redwood with ectomycorrhizae-associated species for nutritional benefits is being currently investigated in the field in a trial set up at Conway Hill (North Canterbury) as part of the FFR Protecting and Enhancing the Environment through Forestry Theme[11].

The 400 Index and Interim Growth Model

Collaboration between Scion and industry before and after the establishment of FFR has led to the development of several productivity models. The models are complementary to each other.

An empirical growth and yield model that predicts basal area (BA), mean top height (MTH, mean height of the 100 largest diameter trees per hectare), and stand volume, was developed by industry and improved by Scion. Called the Interim Growth Model, it was constructed using data from stem analysis of trees from eight 20- to 30-year-old stands supplemented with data from a national series of 32 PSPs [10]. The project was initiated by NZ Forestry Limited and was jointly funded by NZF and The New Zealand Redwood Company. The model uses a common-asymptote Chapman-Richards function [13] to predict MTH, and for predicting BA uses an anamorphic Shumacher function [14] with the asymptote parameter varying as a function of stocking[10]. The model was later converted into an Excel-based growth calculator [15].

The Interim Growth Model was used to develop a site productivity index for coast redwood. The site index was defined as the height of the 100 largest diameter trees per hectare, 40 years after reaching breast height (1.4m) [10] (Figure 4a). This definition was necessary as poor weed control can dramatically slow seedling growth until trees overtop the weeds. With proper weed control, seedlings typically reach 1.4 m at three years [10].The model was also used to develop an index of stand basal area (BA) growth, 40/400 index. It was defined as the BA at breast height age 40 years for a stand growing at 400 stems ha^{-1}[10]. Site index and BA 40/400 was used to calculate a third measure of productivity, the 400 index. Modelled on the 300 index for*Pinusradiata*, it is a measure of under-bark stem volume productivity (m^3 ha^{-1} yr^{-1}) at breast height at age 40 years [10]. Stem volume under bark is calculated using the T458/F458 tree volume/taper functions [16].This allowed, for the first time, the ability to predict redwood volume productivity between sites (Figure 4b).

Despite the relatively small dataset behind the Interim Growth Model, the model has performed well in predicting growth at sites added to the redwood PSP network since the model's initial development [17].

Site Productivity Model

Site productivity models and maps of coast redwoods were developed by Palmer *et al*. [10]. They were based on data (23 plots) derived from the PSP database subject to the redwood trees being at least 15 years old and with screening for coppicing. The PSP data were used to develop multiple regression models of coast redwoods site index and 400 index using independent variables obtained from a wide range of environmental, biophysical, and climatic data [10].

Palmer *et al*. [10] found that temperature was important to coast redwood productivity, accounting for 55 and 71% of the variance in 400 index and site index respectively (Figures 4a and 4b). Furthermore, the final 400 index model accounted for 76% of the variance in the data. Independent model variables for the 400 index included mean spring air temperature, subsoil acid soluble phosphorus, and mean summer vapour pressure deficit, with these variables respectively accounting for 55, 16, and 5% of the variance. The final site index model explained 82% of the data variance using mean annual daily temperature (71%) and mean summer vapour pressure deficit (11%). Although some strong correlations were found, they must be interpreted with some caution. The current PSP network is very limited in distribution and the number of measurements per plot. It is likely that the statistical correlation analysis did not account for other factors that influence site productivity. For example, there is strong evidence that soil water has a strong influence on productivity. However, the model did not find measures of soil water and precipitation important predictors of productivity. The results from Palmer *et al*. [10] indicate the weaknesses of the current PSP network and the need to greatly expand the network. The results of the productivity model mean that it should predict productivity only for sites that fit into the climatic and biophysical range of the study. This means that using the site productivity surface to locate potential new sites for coast redwood should be done with extreme caution. Due to the model's weaknesses, it is recommended that the productivity model is improved as soon as more data become available. As coast redwood is a site-sensitive species, process-based modelling may be able to predict site productivity more accurately than empirical-based modelling. It is recommended that the feasibility of parameterising a process-based model for coast redwood be investigated, and determine if an empirical, process-based, or a hybrid approach is most appropriate.

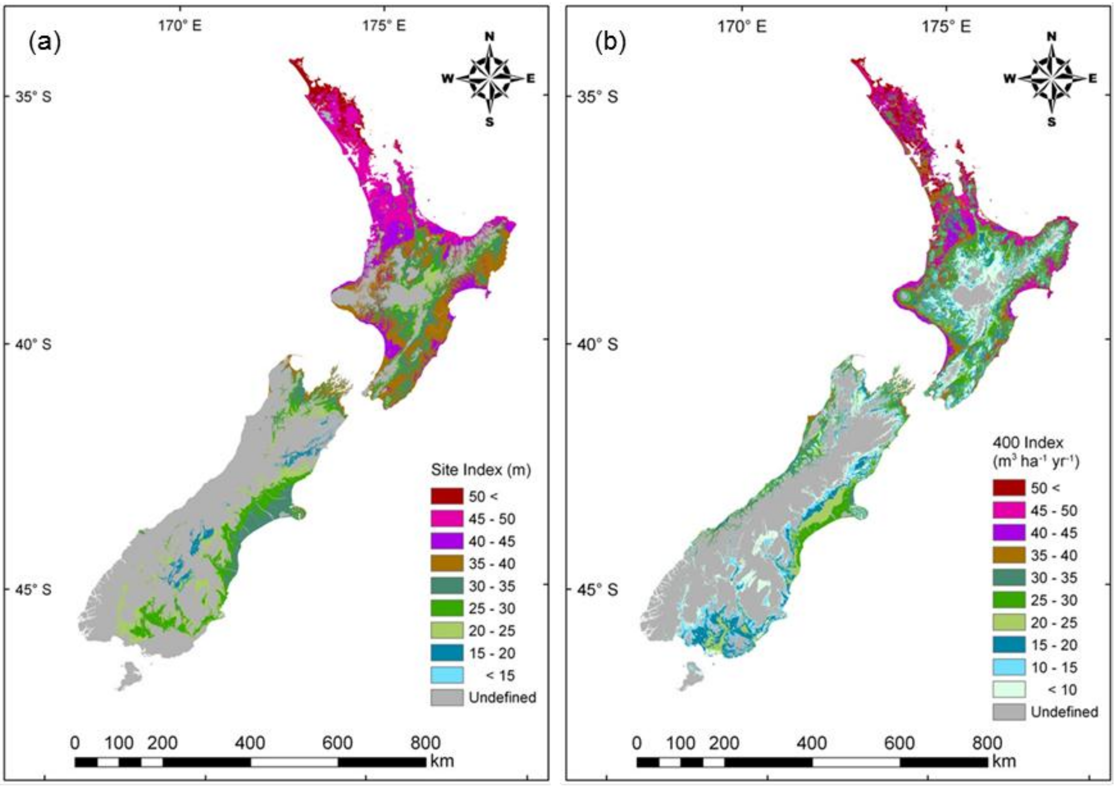

Figure 4: Coast redwood productivity surfaces as measured by (a) site index and (b) the 400 Index. From Palmer et al.[10]

Volume and Taper Functions

New Zealand coast redwood volume and taper function (T458/F458 function) was developed by van der Colff [16]. The functions were reviewed by Meason [18] who recommended the development of separate volume and taper equations for slow growing/low productivity sites whilst also recommending clear specifications for distinguishing between these site types. This is supported by a review and analysis of redwood commissioned by the NZ Redwood Company that found the T458/F458 function was unsuitable for estimating volumes/taper of smaller trees[19]. The review and analysis developed a new equation (T472/F472) that combined volume/taper data from the original T458/F458 function with new data from several tree sectional measurement studies collected between 2005 and 2009 [19]. The new T472/F472 function represents the best volume/taper function to date for coast redwood. Even with the new dataset increasing the number of trees to 322, the number is still low. This is especially a concern for coast redwood with its large taper and the variability in tree shape below 1.4 m. It is recommended that a taper study be performed on standing trees (with a large sample number and distribution). Failing that, new data should be added to the existing volume/taper function when any future log/sawing studies are undertaken.

Recommendations

Research is developing to understand site productivity and growth particularly with the close collaboration between Scion and the redwood industry. Priority research gaps that require future investigation are listed below with suggested options for addressing the gap.

Research gap	Recommended research for addressing gap
Limited distribution of PSP network.	Expand the number of PSPs by establishing new plots in existing and newly planted stands. Aim to maximise climatic distribution of PSP network.
Interim Growth Model prediction of growth and yield limited.	Improve model with data from an expanded PSP network.
Site productivity model limited ability to predict productivity at new sites.	Improve productivity model from expanded PSP network. Investigate if empirical, process-based, or a hybrid modelling approach is more appropriate for predicting productivity.
Volume and taper functions limited.	Improve function by a taper study of standing trees and/or adding data from future log/sawing studies.
Increasing nutrition for greater productivity and potential site selection.	Determine if fertiliser is required to increase productivity on low productivity sites. Expand current research on ectomycorrhizae to determine its importance on productivity.

SILVICULTURAL PRACTICES

D. Meason

Introduction

A number of different silvicultural trials have been established since 2000 by private industry, Scion and Future Forests Research (FFR) to develop best management practices for New Zealand-grown coast redwood. Knowledge and experience shared by industry was particularly useful in developing silvicultural trials. The FFR Diverse Forests Theme of redwood research has centralised and expanded this work to provide industry with the best possible information on silvicultural and management practices. Recent FFR research has dramatically improved our understanding of coast redwood silviculture, initiating a solid foundation of silvicultural knowledge. However, a number of knowledge gaps and challenges remain.

Establishment and Site Selection

Establishment practices are important to the success of coast redwoods and have been cited as one of the main reasons for planting failures in the 20th Century [1, 7, 20]. Early research by Bowles [21] showed that weed control and fertiliser application increased growth within the first three years after planting. Subsequent establishment practices by industry have developed a practical, robust method of establishing coast redwood even on ex-pasture sites and at low planting stockings [22]. Intensive weed control for the first 18 months after establishment dramatically improves the survival of seedlings. Typically this will involve a pre-planting spray, a release spray immediately after planting, and a second release at approximately 18 months [22]. More intensive weed control may be needed in areas less favourable for coast redwood (i.e. areas with lower rainfall). Fertiliser application is likely to be important at establishment on sites with low fertility [11]. In summary, intensive weed control is likely to be more important for successful establishment than fertiliser application.

Planting stocking can greatly influence growth and wood quality properties; however, the impact of stocking on coast redwood growth and wood quality is uncertain. Results from thinning trials indicate that coast redwood can grow vigorously at planting stockings greater than 1,000 stems per hectare (SPH) as it has a high tolerance to shade. However, current planting stockings are driven by the cost of planting stock. Current industry practice is to plant clones of parents that have desirable characteristics (e.g. growth and form, wood quality). The high cost of clonal material has reduced industry plantings to 500 – 800 SPH. Establishment with seedlings would be cheaper than the use of clones. However, redwood seedlings are still expensive and the economic pressure to establish with stockings less than 1,000 SPH would still be present if seedlings were used. In the last 10 years, industry has used low tree stockings at establishment, as well as pruning to control branch size. The successes achieved to date would suggest that coast redwood can indeed be successfully grown at these low stockings. If there is no impact on wood quality, this establishment approach could be a successful way to control costs in coast redwood establishment. However, no study has tested if this approach will produce the desired results. It is highly recommended that future research investigates whether the above methods of clonal selection and silvicultural practices will produce the expected wood quality at harvest. Silvicultural practices of pruning and thinning are discussed further below.

Pruning

Pruning is an important management tool to maximise the value of merchantable volume at harvest. Indeed, the low tree stockings commonly planted at establishment and the specifications of the highest value grades have made pruning a necessity for coast redwood. The potential return from pruning was indicated from a sawing study from a 38-year-old stand at Mangatu forest[23]. The study found that for the five highest valued log grades (clear all heart, clear heart, clear commons, heart B, and heart construction), this represented 28% and 64% of the log recovery for the unpruned and pruned trees respectively[23] (Figure 5). The study concluded that that although pruned logs represented 38% of recoverable volume from the 13 trees harvested, they contributed 50% of the gross timber value [23]. The same study found that the most important determinants of log value were the small end diameter of the log, quality of the pruning, heartwood content, and branch status. Several pruning trials were established in the early 2000s, most notably Tutira and its smaller sister trial Waerenga-O-Kuri. These trials investigated the impact of pruning densities on growth, pathogen resistance, and the development of epicormic shoots. The pruning trials have indicated that heavy pruning may have only a short-term impact on productivity. This was most clearly demonstrated at the Tutira trial where a light and a heavy pruning treatment were applied. The height growth rate of the pruned treatments was reduced after the first pruning treatment was applied. However, the growth rate of the pruned treatments was similar to the non-pruned treatments within two years of the application of the light pruning treatment and four years of the heavy pruning treatment [17]. The pruning trials would suggest that for stands less than 15 years old, heavy pruning has little long-term impact on growth rate. This effect may be confirmed by more recently established pruning trials, like Okota (Hunterville). It should be noted that coast redwood may not tolerate heavy pruning on drier, less favourable sites.

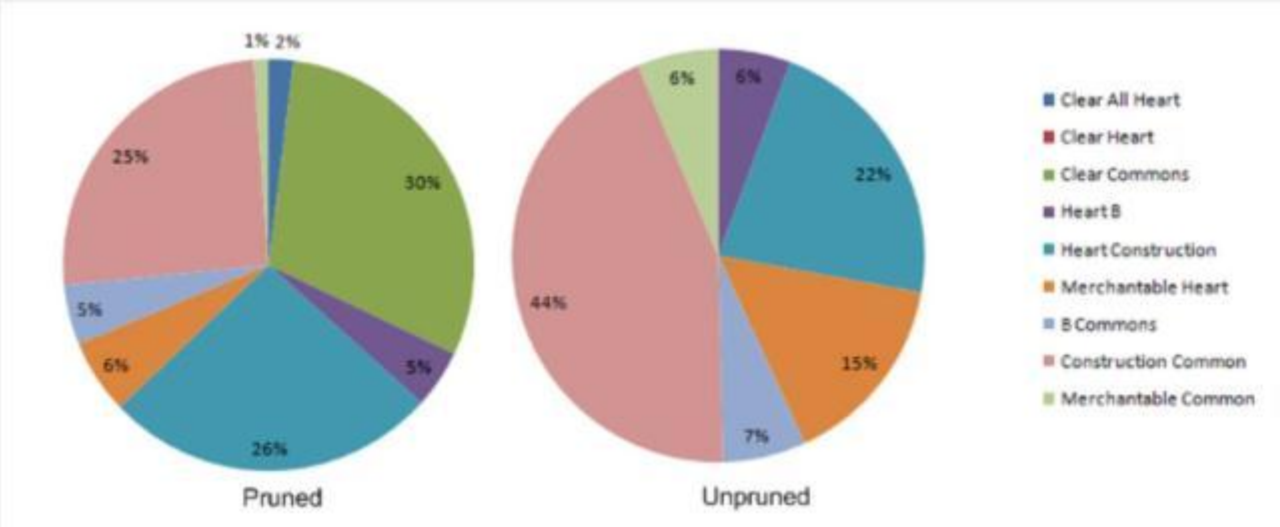

Figure 5: Log grade recovery from the Mangatu forest sawing study by pruning prescription. From Marshall et al.[23]

The Mangatu forest sawing study found that the quality of pruning was indicative of the log's value. Standing trees that were ranked with a prune log index greater than 7 had higher percentages of the high valued grades of clear all heart and clear commons (Figure 6).Significant log degrades occurred in this study from rot and insect damage, which was likely due to poor pruning practices[23]. Thus, pruning to a higher standard may increase the recovery of higher valued log grades. Despite the importance of pruning, heartwood is the single most important factor determining log grade. The Mangatu study found that a relatively young stand of 38 years can produce a large percentage of heartwood; 44% to 66% of the log[23].However, it was not possible to determine the heartwood content of a standing tree until it was sawn. Planting individual clones may reduce heartwood variability within a stand and may increase heartwood content for each tree. Research is required to determine if current clone selection techniques will produce the desired results. Wood quality has the biggest influence on the value of the merchantable volume. Challenges with coast redwood wood quality have been extensively discussed by Cown [24]. The conclusions from that report are discussed in the wood quality section of this report. It is recommended that silvicultural research focuses on developing a redwood prune log index so that the type of log at harvest can be predicted.

The development of epicormic shoots is of particular concern, as persistent epicormic shoots can cause major downgrade in log value, as the Mangatu sawing study demonstrated [25]. Pruning in winter drastically reduces the likelihood of persistent epicormic shoots forming [26]. The observed variability of the number of epicormic shoots sprouting among trees at the Tutira trial would suggest genetic variability in epicormic shoot proliferation. Thus, identification of provenances that do or do not minimise epicormic shoot sprouting may be possible. The potential of epicormic sprouts over a rotation remains a serious concern for low tree stocking and heavy pruning regimes.

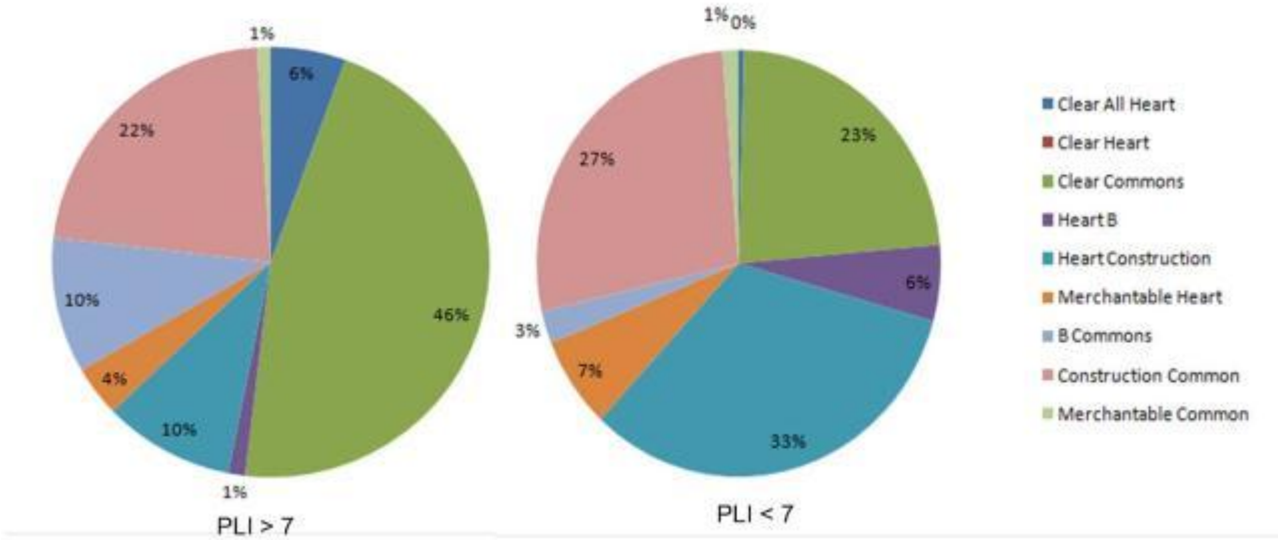

Figure 6: Log grade recovery from the Mangatu forest sawing study for trees that received high quality pruning (PLI > 7) and trees that received low quality pruning (PLI <7). From Marshall *et al*. [23]

Thinning

Coast redwood is a highly shade-tolerant species, so it can grow at high tree densities with little mortality for a number of years. There are currently seven thinning trials in New Zealand: Brann, Collings and Waiotapu in the Bay of Plenty, Mangatu and Waeregna-O-Kuri in the East Coast, Tutira in the Hawke's Bay, and Otago Coast in Otago. The trials that are well replicated are Tutira, Waiotapu, Mangatu, and Otago Coast. To date all but two of the seven thinning trials established in the 2000s has yet to show a response to the treatments [17]. One possible reason is that all the trials except Tutira and Collins were established in stands that were aged between 17 and 25 years. At this age range, coast redwood may be able to tolerate higher tree densities than younger or older stands. Another issue is that the unthinned control plots were at stockings of less than 1000 SPH. If there is a response to thinning in these trials, it is likely to take another 5 to 10 years after the last treatment before it becomes significant. The differences in establishment year (1969, 1997, and 2000) and stand ages when the plots were measured made it difficult to determine a thinning effect in the Brann's trial.

The Tutira and Collins trials have shown responses to thinning. At Tutira, the stand was planted at ~900 SPH and was thinned to three different intensities at ages 6, 10, and 13.When mean dbh increment between thinning treatments were examined, there were indications that the plots with the highest tree density (lightest thinning, 800 SPH) had a smaller dbh increment than the other two treatments at ages 9 and 11 (Figure 7). This may indicate a stem growth response with thinning trees to a final stocking of 600 SPH (medium thinning) and 350 SPH (heaviest thinning)[17]. Another possibility is that unfavourable climate conditions in those years reduced growth in the stand with the highest tree density due to intense competition[17]. However, by age 13 the growth rate of the highest density plots (lightest thinning) was able to catch up to the other two treatments (Figure 7).The results from Tutira suggests that redwood will respond to thinning for stands less than 10 years old and/or high productivity sites [17]. This is supported by results from the Collins trial, another young age trial. There is an apparent increase in height and DBH growth for the one stand that was thinned to 480 SPH at age eight [17]. However, the small number of plots means that more measurements are needed to determine if the thinning response is significant and sustainable.

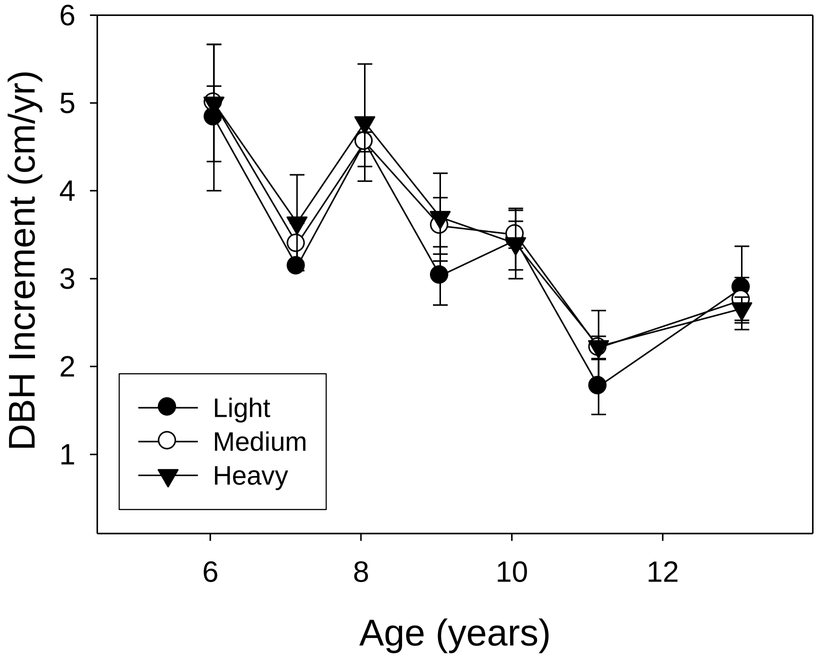

Figure 7: Tutira trial mean diameter at breast height (DBH) growth increment by thinning intensity as represented by final crop tree density; light thinning (800 sph), medium thinning (600 sph), heavy thinning (350 sph). All treatments unpruned. From Meason *et al*.[17]

Research from the United States has indicated that growing space for individual trees does have a major impact on tree productivity [27]. The importance of both tree growing space needed in New Zealand plantations and the stage in a rotation at which intraspecific competition is the greatest are unknown. Industry is currently planting at tree densities of 500 - 800 SPH. At these densities, it is likely that there will be sufficient growing space for the first 10 years of a rotation. However, after canopy closure growing space will be reduced and intraspecific competition is likely to be more intense. Thinning trials should be established to assess the importance of thinning after canopy closure, later in the rotation, and/or at tree densities greater than 1,000 SPH. Further, it is possible that thinning could be more important in less favourable sites where intraspecific competition for scarce soil resources may be more intense.

Recommendations

Research is developing into best silvicultural practices of coast redwood, with recent research in the FFR Diverse Forests Theme dramatically improving our understanding. Priority research gaps that require future investigation are listed below with suggested options for addressing the gap.

Research Gap	**Recommended research for addressing gap**
Impact of current clone selections and silvicultural practices on wood quality at harvest unknown.	Wood core study across a range of selected clones/provenances and silvicultural practices when trees reach an age to test wood quality
Growth response to thinning/optimal tree density for growth.	Establish new thinning trials and continue monitoring existing trials. 3 – 5 year measurement return period.
Growth response to pruning in stands less than 10 years.	Establish new pruning trials and continue monitoring the Tutira trial. As pruning trials are expensive to establish, piggyback industry management practices. 3 – 5 year measurement return period.
Log grade potential of pruned stands.	Select trees for harvest from existing pruning trials 10 to 20 years after last pruning lift to develop a prune log index of log value.
The persistence of epicormic shoots after pruning/thinning and effect on final log grade.	Develop monitoring scheme in existing and new pruning trials. 3 – 5 year measurement return period. Monitoring of pruning trials for epicormic sprouts should be a priority for the next 10 years to determine if epicormic shoots are a temporary or a persistent threat to wood quality. Tutira would provide an ideal trial for monitoring.

EROSION MITIGATION AND CARBON

L.G. Garrett and P.W. Clinton

Introduction

Soils underpin the profitability of the New Zealand forest industry. To ensure sustainability of the industry, this natural capital requires management to reduce degradation and enhance supporting processes [28]. Degradation through soil erosion is of concern particularly in hill country (slopes> 15º) in New Zealand (10 million hectares, 37% of national land area), of which the majority (63%) occurs in the North Island [29]. Moreover, with erosion, off-site impacts occur through increased sedimentation and flooding damage which have economic implications [30]. Forestry helps to mitigate erosion through changes in the mechanical and hydrological properties of the root-soil matrix to improve slope stability [31] and is promoted to protect highly erodible land [32]. Harvesting of steep hill country presents numerous challenges for erosion-prone land because of the “window of vulnerability” that develops following harvesting of one crop and prior to closure of the next crop’s canopy. During this time, there is increased potential for erosion to occur due to lack of canopy interception, soil saturation and loss of soil strength due to root decay. The projected increase in the frequency of extreme rainfall events may heighten this risk [33]. Finding solutions to reduce the window of vulnerability may lie in selecting specific tree species that retain soil stability after harvesting, reducing the critical period of high erosion risk. Coast redwood may be such a species.

Erosion Mitigation

The idea of using coast redwood to specifically address the mitigation of soil erosion in New Zealand has been around for some time, with an initial introduction by Burdon [34] in a 1975 article entitled “Is Coast Redwood an answer to the Mangatu problem?”. This was followed by an article by Clinton *et al*. [35] in 2009 entitled “Redwoods - what have we been waiting for?”. Both of these articles summarise why redwoods should be considered for erosion mitigation management. These articles identify an ideal tree species for erosion mitigation as having the following traits:

- Tolerance to New Zealand soil and climatic conditions.
- Easy to establish.
- An extensive root system that can tolerate wet conditions and burial in aggrading gullies.
- Capable of regenerating from sprouts or of coppicing freely.
- Long lived.
- No potential to become a pest.
- Production of high-quality timber of sufficient value that could be partially harvested.

Coast redwood possesses most of these traits, making it an ideal candidate as a tree species for erosion control. Studies in New Zealand have started to address the question of effectiveness of coast redwood for erosion mitigation [36, 37], the latter study being undertaken through the current Future Forests Research (FFR) programme “Protecting and Enhancing the Environment through Forestry”. Internationally, research is limited and focused on erosion impacts after harvesting coast redwoods [38, 39].

Vegetation contributes to slope stability through added cohesion of the soil by the root system (root cohesion), increased rain interception and transpiration by the above-ground vegetation leading to decreased soil moisture levels, and capture of eroding soil in the above-ground tree components [31]. The ability of a tree species to function in stabilising a slope is dependent on the species characteristics as well as the soil type and site conditions. For example, if the soil is shallow, tall trees are more susceptible to falling over in wind storms, and therefore reduce slope stability [31]. The added cohesion that a root system gives to a soil is dependent on the root morphology (shape), tensile strength and the vertical and horizontal distribution and interlinking of roots [31]. There are no measured values of root cohesion for coast redwoods.

Coast redwood has wide-spreading lateral roots [9], which increases interlinking of roots of neighbouring trees. They have no taproot. Root grafting also occurs, further increasing the root cohesion over an area, but it is uncertain how many years it takes for root grafting to occur [35]. Observations of young trees (four years old or less) show coast redwood produces many fine lateral roots compared with *Pinus radiata*, which indicates that it has the potential to bind and hold the soil together more so than *P. radiata*[37]. Moreover, coast redwood is capable of surviving flooding and sedimentation on alluvial terraces and hill slopes [36]. It is also capable of coppicing after cutting and can sprout from fallen branches [9].

Coast redwood's strongest trait in erosion mitigation is its ability to coppice after harvesting, which keeps a proportion of the existing root system alive and functioning, contributing to maintenance of slope stability[34, 35, 37]. This reduces the window of vulnerability after harvesting. This is in contrast to *P.radiata,* where cohesion of the whole root system of the mature harvested stand decreases as the root mass decays and the young plantings become established. This window of vulnerability for *P.radiata* can last for 5 to 8 years after harvesting [40]. The ability of coast redwood to coppice does not entirely stop erosion, as the above-ground tree functions (rainfall interception, transpiration and trapping eroding soil) are lost with harvesting[38, 39]. Moreover, even though redwood stumps re-sprout quickly, a proportion of the original root mass dies and begins to decay, with minimum root cohesion expected about 10 to 15 years after clear cutting [39]. Partial harvesting may be an alternative option for reducing erosion risk with coast redwood [35]. Timing of thinning events should not coincide with minimum root cohesion, as thinning will remove some of the above-ground tree functions that contribute to reducing the risk of erosion [39]. Coast redwood demonstrates many of the desirable traits of an ideal tree species for erosion mitigation. There is little evidence to support the use of other tree species, particularly indigenous ones [41], in erosion control.

Biomass and Decomposition

Forestry has a large potential to be a carbon sink and thus mitigate the effects of climate change through carbon sequestration. New Zealand is committed to the Kyoto Protocol and in order to report on carbon, the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change and Forestry [42] has defined five separate carbon pools, live above-ground biomass, live below-ground biomass, litter, dead wood, and soil. In intensely managed planted *P. radiata* forest in New Zealand, for example, the amount of carbon in the separate pools can vary markedly by location and time, depending on the timing and intensity of silvicultural and harvesting operations [43]. For *P. radiata,* the carbon pools (excluding soil) are well predicted by the Forest Carbon Predictor which relies on the 300 Index growth model and a wood density model for predicting biomass and carbon stocks (50% biomass) [44]. For coast redwoods information to support such models is insufficient – for example, research on above-ground biomass in the New Zealand environment is limited to young trees [12, 37]. There is a volume and taper function available for a range of tree ages (see section: Site productivity and growth models), but the high variability in wood density values [45, 46] makes the above-ground stem biomass contribution towards carbon accounting purposes uncertain. McKinley and Cown [46] summarised New Zealand studies on redwood density and concluded that overall basic wood density is about 330 kg/m^3. Research in the Mangatu Forest found an average stem density of 323 kg/m^3 with relatively uniform density within a single stem, but considerable variation between stems, with differences of up to 120 kg/m^3[46]. Large density variability between stems has also been reported for other areas in New Zealand [20, 45] with little evidence of a strong regional effect as observed with *P. radiata*[20]. Genetic variability between redwood trees seems to be the origin of the large range in density observed [46]. Carbon sequestration estimates for redwood plantations have been made based on the limited data available [47] and they give an indication of the potential of redwoods as a carbon sink. However, for accurate carbon accounting and ETS reporting more data are required.

Roots make a significant contribution to the live biomass of trees and are, therefore, important to consider for carbon allocation. However, understanding the root biomass allocation of different tree species is difficult because root studies are expensive and data are limited. Typically root biomass is estimated by applying a ratio to the above-ground biomass which is easier to measure. This ratio is well established for *P.radiata* in which root biomass is equivalent to 20% of shoot biomass (root:shoot ratio = 0.2) [48]. Estimated root:shoot ratios have been reported to vary between 0.18 and 0.32 among boreal, temperate and tropical forest biomes[49]. In temperate forests root:shoot ratios were estimated to average 0.18 for coniferous species and 0.23 for deciduous species [49]. A few studies on the root biomass of young (4 years and less) coast redwood trees have been undertaken in New Zealand under the FFR Environment Theme [12, 37]. Phillips *et al*. [37] found mean root:shoot ratios for tree ages from 1 – 4 years, measured in the field, varied between 0.23 and 0.59, with generally lower ratios in the youngest aged trees and higher in the 4-year-old trees. In a glasshouse pot trial, Davis and Coker [12] found after one year's growth the root:shoot ratio of coast redwood was 0.99 compared to *P. radiata* of 0.61. The values from the glasshouse pot trial were high compared with the measured field trial, possibly due to a function of the glasshouse environment or higher recovery of roots. It is uncertain if the root:shoot ratio of coastal redwood will remain high throughout its life compared with other species, or whether it will become comparable to that of *Pinus radiata* (0.20). Clinton *et al*. [35] commented that observations of redwoods being slow to establish may be a result of the tree initially allocating greater quantities of photosynthetically fixed carbon to their root systems at the expense of stem growth. This would explain the high root:shoot ratio measured in the younger trees. There are no data for root:shoot ratios of older redwood trees.

There is no literature on the decay rate for coast redwood roots of any size. The ability for stumps to coppice does indicate that the root systems would remain alive after cutting and, therefore, be resistant to decay. This would be advantageous for carbon accounting purposes, as the root carbon biomass could be carried over into the next crop. However, a proportion of the original root mass does die and begin to decay after cutting, but the proportion that stays alive to allow for coppicing is uncertain [38, 39]. For the proportion that dies, the decay rate could be best estimated from the decay rate of the above-ground material [50, 51]. Redwood is very decay resistant [38]. Decay rate constants of above-ground coarse woody debris have been estimated in an old growth coast redwood forest in the United States (Humboldt Redwoods State Park, California) with a range from 0.022 to 0.026 yr^{-1}, which equates to 27 through to 32 years for 50% mass loss [52]. The decay estimate range would be the current best estimate for coast redwood above-ground coarse woody debris and therefore roots in the New Zealand environment. However, as New Zealand planted redwood forests are unlikely to be old growth, this estimate is possibly too slow. The decay rate range is similar to New Zealand's dominant indigenous tree species, which have a range estimated for above-ground coarse woody debris decay between 22 to 47 years for 50% mass loss [53], but much slower than *P.radiata* above-ground stem decay, 4 to 14 years for 50% mass loss [51]. The uncertainty around the woody debris decay rates for coast redwood in the New Zealand environment and the high variability in redwood wood density values [45, 46] which are used to determine mass loss with decay, makes the contribution of coarse woody debris towards carbon accounting uncertain. Improving confidence in estimates will take some time as the research gaps are addressed.

In addition to the limited information on below-ground biomass and carbon pools in coast redwood, there is no information available on how root biomass, fine root turnover and the decomposition of forest floor litter contribute to soil carbon pools [35].

Recommendations

There is limited research on using redwoods for erosion mitigation and in understanding the biomass allocation or decay. Recent research has been initiated in New Zealand by the FFR Environmental Theme to look specifically at redwoods for erosion mitigation. Priority research gaps that require future investigation are listed below with suggested options for addressing the gap.

Research gap	Suggested research for addressing the gap
Quantitative assessment of root cohesion with increasing tree age.	Measure root cohesion on different-aged tree stands. This also ties into the root biomass research gaps below. Determine when root grafting occurs, and how this contributes to root cohesion: Sample stand development sequence including thinning to establish the age at which grafting occurs and the extent with increasing stand age. Need to consider genetic variation and other factors that control this.
Selecting the best tree genetics for optimal root cohesion.	Include in the tree breeding programme consideration for enhancing root cohesion. This is relates to the root allocation issue below.
Live biomass allocation particularly in older trees.	Measure the root : shoot ratio of trees older than 4 years of age for example at canopy closure, age 20 years and pre-harvest. Could also look at fine root turnover and incorporation of root-derived carbon into soil organic matter. Measure wood density variation: Outer wood density over a range of ages and sites. Invest in further research to establish density profile pith to bark over a range of ages and sites to establish growth sheath density within genetic families. The latter requires a lot of knowledge on density heritability.
Decomposition of roots.	Measure root cohesion at different times after clear cutting. Need to consider if a harvested redwood stand will be replanted with improved seedlots/clones or rely on coppicing. Measure root tensile strength with decay. Measure decay rate of coarse woody roots. Estimate of the proportion of roots that die after thinning or harvesting. Assess root biomass before harvesting and subsequently immediately after harvest and perhaps annually up to canopy closure. This will contribute to an understanding of coast redwood impacts on soil stability and carbon turnover. Could also look at the effect of root grafting in partial cuts or thinning regimes, etc.
Effective tools to use for carbon sequestration for coast redwood.	Firstly improve volume and density estimates. Secondly improve other research gaps described above. The improved estimates can be included into a calculator for redwoods that estimates carbon sequestration throughout New Zealand.

MARKET ANALYSIS

L. Barry

Introduction

The potential for coast redwood (*Sequoia sempervirens*) to be a New Zealand success story like radiata pine (*Pinus radiata*) is not as simple as saying that a restricted supply in established markets (in the US for example) means that New Zealand has the green light for investment. There may be other hurdles which have to be scaled first, such as improving the quality of New Zealand-grown redwood timber. It does, however, create an opportunity to look closer at the potential for coast redwood in New Zealand. With companies already investigating this potential, the future certainly looks brighter than it did 20 years ago. The dawn of a carbon market and the increasing concern over other environmental benefits from planted forest, such as soil conservation, in New Zealand and abroad, also holds potential for an increase in coast redwood planting domestically.

Timber Market

Demand

Long-term changes in demand influence investment in forestry and the forest industry at an aggregate level. The key drivers of this demand are demographics, economic growth, regional shifts, and policies and regulations [54]. The overall production and consumption of sawn wood products is expected to increase at the global level after 2030. However, this aggregate increase in long term demand for forestry may have little bearing on the demand for New Zealand redwood timber production. The current recession has led to a downturn in the prices of all housing lumber commodities. Recently, however, there has been an increase in redwood lumber values [55].

Redwood is most commonly used for landscaping, for example, outdoor furniture, decking, fencing and weatherboards[56]. A sharp increase in regulation and bureaucracy has resulted in excessive costs for the production of old growth redwood stands in California, which provides an established market for these high-quality products. This has led Soper-Wheeler, a leading forestry company in California, to conclude that a reasonable rate of return from forestry is no longer possible in this region [57]. Essentially in the last thirty years, old-growth Californian redwood logs, which produce most of the clear lumber grades, have been priced off the market [58]. Secondary growth Californian redwood is apparently one of the woods most easily treated with preservatives and colorants [59] and so remains a strong competitor for New Zealand redwoods.

Figures for the production of redwood timber in the US from 1972 to 2002 present a relatively stable cyclical production which has become increasingly centralised in California [58]. In the long term we would expect this production to mirror the demand for redwood timber. So a fairly consistent demand for redwood in the US, at least, would be expected in the future. The US demand for redwood and western red cedar (*Thjujaplicata*), along with a reduced resource in California, will ensure a continuing demand for a similar material [60]. The next section outlines whether New Zealand is in a position to provide a similar material.

Supply

A report commissioned by, amongst others, New Zealand Forestry Ltd., shows redwood lumber prices increased steadily until 2000. After this, the supply in the US became critically low due to a log shortage brought on by stricter government regulations to protect two threatened species within the redwood region. As a result, the price almost doubled in the next quarter and led to an increased demand for substitute products, such as western red cedar and composites. Suppliers have indicated however, that if a reliable supply of redwood could be increased, the redwood market could be expanded back into its once traditional sales areas of southern California and Arizona [55]. New Zealand will need to improve its product performance by providing similar material to the second-growth stands in the US to be competitive in the market for redwoods [61]. Site selection is more important for coast redwood than radiata pine. However, there are impressive plantations of coast redwood growing at very productive rates in many parts of New Zealand [62]. Advances in silviculture have improved the quality of timber. Pruning, for example, has been found to improve log grade value substantially [63]. A target rotation length for New Zealand-grown coast redwood is 35 – 40 years[64], which is approximately half that of competing redwood stands in North America. This rotation length range is comparable to that of New Zealand's most dominant planted species, radiata pine [65], approximately 30 years. New Zealand-grown coast redwood may, therefore, offer a strong competitive market advantage over California-grown redwood and a potentially viable alternative to radiata pine forestry domestically.

Perceptions affecting Supply and Demand

An important factor when dealing with markets is not just the quality of a product but also the perceived quality, which can play a significant role in the demand for a product. User acceptability (wood quality) is expected to be a key driver of redwood as a successful plantation species[60]. Interestingly, interviews from producers in the US found that most *did not* have personal experience with New Zealand redwood but were almost universally of the opinion that it offered an inferior product to Californian redwood. While a producer who *did* have experience with New Zealand redwood described it as a "pretty consistent" product with California redwood [55].

Other Markets

Carbon

In recent years the introduction of a carbon market in New Zealand has provided an alternative revenue source for forestry to capitalise on. The Permanent Forest Sinks Initiative (PFSI), the Emissions Trading Scheme (ETS), and the Afforestation Grant Scheme (AGS) allow forest growers to receive revenue for carbon sequestration. The PFSI offers international credits for carbon sequestration, but requires forest permanency by entering into a 50-year covenant with the crown [66]. The PFSI is less risky than the ETS as it taps directly into an international carbon market, by offering internationally tradeable Assigned Amount Units (AAU).It is not suited for growers who are intending to harvest within 30 – 40 years. The ETS offers New Zealand credits or New Zealand Units (NZUs) for carbon sequestration and is a more flexible scheme in terms of harvesting. Although the ETS offers what is essentially a domestic currency for carbon, it may be subject to more volatility than an international carbon currency like the PFSI. Since its introduction, the ETS price for carbon credits has declined steadily from an initial price of $20 per New Zealand Unit (NZU) to approximately $7/NZU [67]. This steady decline has made the ETS look less and less appealing to forest growers since its introduction in 2008, but it does still provide additional revenue. Currently, limited data are available to report confidently on carbon sequestration for coast redwood plantations (see section: Erosion mitigation and carbon), and estimates made have given an indication of the potential for coast redwood to sequester carbon [47]. These early estimates indicate that in comparison to radiata pine, coast redwood offers greater carbon sequestration with longer rotations (> 40 years) [47].

A recent survey of perceptions around the best species to plant for different ecosystem service benefits found that the majority of respondents (42%) selected redwoods for fixing carbon due to longevity, high mean annual increment, and the potential to grow a very large volume tree in perpetuity [68].The Ministry for Primary Industry's report on the forestry sector suggests that with the ETS there may be a shift in investment towards longer lived, high volume species like redwoods as the balance between carbon price and harvesting becomes more significant in forestry decision making [69].

Soil Erosion

East Coast Forestry Project (ECFP) is a project in the Gisborne District that offers grants for planting on the worst 60,000 ha of eroding land [66]. Unfortunately, neither this programme nor the AGS offers a huge potential for redwoods. Coast redwood may be a key species for providing the valuable ecosystem service of erosion mitigation [35], and there is also the potential benefit for long-term planting from carbon sequestration, where early harvesting may not be a priority[47] . Yet there is little opportunity for growers to capitalise on the benefits of coast redwood over other species. The ECFP does not differentiate between the relative benefits gained from avoided erosion from planting different species. Although the AGS has environmental co-benefits as one of its aims along with carbon [66], it does not prioritise the potential improved environmental co-benefits from alternative species, other than providing a separate pool for indigenous planting [70].

Recreation

Recent research at Scion suggests that alternative revenues, recreation for example, may be available from forests. A recent study by Turner *et al*.[71] found that the recreational value of the Whakarewarewa forest in Rotorua, which has an internationally renowned redwood grove, was worth at least twice the timber value. There is certainly potential for forest growers to capture a portion of this value through gate fees. An important consideration, however, is the often conflicting values between recreation and timber production from forestry. In California, for example, harvesting levels on non-industrial lands are expected to decline as recreational values continue to exceed timber values [55].Therefore, decisions must be made early on as to the management goals of the forest because the provision of such services may incur additional costs.

Conclusions

The market for carbon has provided forestry with additional revenue, and growers of coast redwood are potentially in a strong position to capitalise on this, especially for long-term planting in areas of environmental importance where harvesting for timber may not be a priority. The timber market holds promise due to the potentially shorter rotation ages necessary to get a product comparable to that from Californian second growth redwood and other substitute products, such as western red cedar. There is still, however, an issue with the quality of New Zealand-grown redwood timber, which will have to improve to compete with the better perceived and actual quality of US-grown redwood. While issues of optimal growing locations and silviculture regimes have made progress, coast redwood may still be perceived as a risky investment in New Zealand. This risk may be overrated with companies such as the New Zealand Redwood Company and the New Zealand Forestry Company Ltd. already investing.

Recommendations

Underlying the success of coast redwood in New Zealand is confidence around the accessible markets available to promote the species. Priority research gaps that require future investigation are listed below with suggested options for addressing the gap.

Research gap	Suggested research for addressing the gap
Comparative analysis between western red cedar and New Zealand coast redwood.	Durability testing to compare New Zealand coast redwood with North American western red cedar, second- and old-growth timber, in order to test the validity of potentially distorted perceptions of New Zealand coast redwood quality.
Estimation of public economic benefit of avoided soil erosion from alternative plantation species, including coast redwood.	Economic analysis of the off-site (societal) costs. Investigate differences in water quality and infrastructural damage from planting coast redwoods compared with other plantation species, namely *P. radiata,* in order to guide more efficient and effective allocation of public funds, which encourage environmental benefits. This work would rely on an improved understanding of root cohesion, see section: Erosion mitigation and carbon.
More accurate measures of carbon sequestration for New Zealand coast redwood.	Reduce uncertainty for forest growers in accounting for carbon sequestration revenues and costs in cash flow analysis. See section: Erosion mitigation and carbon for recommendations on measuring density variation and root:shoot ratio in older trees.

WOOD QUALITY

D. Cown

Introduction

Redwood in the US is mostly used for building – decks, fences, outdoor furniture, weatherboards, window sashes, doors, blinds, interior trim – where durability, appearance and stability are major requirements. The supply of "old growth" lumber is now a small part of the market and the vast majority is from "second-growth" stands (less than 100years old), where the wood characteristics are somewhat different[72]. In particular, the heartwood is recognised as having only low to moderate decay resistance[73].

In New Zealand, redwoods have been a feature of the landscape since the 19th century, having been established as small plantations, shelterbelts and ornamentals throughout the country[74]. Many of the early Forest Service plantings throughout the country, however, were not successful, and the quality of the timber was disappointing compared to the US material[75].

Comparatively little work has been done on the wood properties and performance of New Zealand-grown redwood, and the acknowledged gaps are around characteristics such as density, stability and durability[76, 77] which could potentially affect export markets. Research to date has shown that basic wood properties are highly variable according to planting stock, site, silviculture and rotation age [78-82]. Experience suggests that the low wood density, low hardness and low-to-moderate durability could restrict end uses – for instance it was noted in 1944 that "it is brash, brittle, and altogether *punky"* [83]. Redwood heartwood is rated moderately durable in ground contact (15 years service) in the New Zealand Building Standards [84].

Without improvements in wood quality, redwood will continue to be regarded as a poor substitute for Californian redwood. An FFR strategy was proposed in 2009[85]. It was considered that the most important characteristics as far as the market is concerned are wood density and durability. This is still believed to be the case.

Density

Wood density values of redwood do not vary much within stems but can do so between trees[85]. Despite the big differences in crop age, the measured density of NZ redwood is similar to Californian old growth and second growth timber [86]. The average is around 330 kg/m^3, but with high tree-to-tree variation. Much of the variation in density is most likely genetic in origin, and documented stem differences of up to 120 kg/m^3 have been observed. Fortunately, there is a very good relationship between breast height (BH) outerwood density and whole stem, which means that if low density wood is considered undesirable, stems can be screened non-destructively and poor individuals identified. Unfortunately, as with most other exotic softwoods, there is a slight negative relationship between diameter growth and density [82]. However the prospect of very significant increases in density may offset this disadvantage. Some researchers have found that second-growth in high-stocked stands (ring width 2 mm) does not necessarily have lower density [72].

Improvement in redwood density is most likely to come from the selection of clones with average or above wood density. This would improve the hardness of timber products and have a significant impact on carbon forests [87].A good start would be a collection of 5-mm increment cores of some of the Kuser clones and others across several sites. The minimum requirement should be that they have at least 10 growth rings at BH. This will allow a database to be established of wood density and heartwood development from which heritabilities could be calculated and carbon models improved.

Stability

Redwood is renowned for low shrinkage and good dimensional stability[73]. Previous studies in New Zealand have confirmed this[78, 88].

Heartwood

Heartwood percentage in the 38-year-old stand ranged from 44% to 66%, confirming that redwood in New Zealand is a “heartwood” species. In this case stem values averaged 54%, decreasing progressively with stem height from an average of 21 growth rings at the base (46 – 67% area) to six growth rings at 25 m (30 - 35% area). Heartwood develops early in redwood – well before 10 years of age. While heartwood percentages varied somewhat between stems, it is probably not worthwhile to breed for higher heartwood content because the sapwood width is generally narrow (around 20 mm) and lost in processing[82].

Durability

Durability is one of the properties on which the reputation of redwood rests, but the performance in New Zealand has not warranted the highest rating in out-of-ground situations[84]. The heartwood of redwood has an Australian Standard AS 5604-2005 natural durability Class 2 durability (moderately durable, average life 15 to 25 years in ground contact) and is resistant to impregnation with preservatives. This class 2 classification is due to the variability in decay resistance from existing in-ground standard durability (grave yard) tests. Highly variable results from these tests are to be expected because the substances conferring durability (extractives) increase from pith to bark [89]. Extractives content of US-grown redwoods has been shown to be low near the pith (<5%), rising to 15-30% after 500-700 years. The extractive content of NZ redwood has not been measured, but the variable weight loss in decay tests[90] suggests that it is highly variable between stems and wood ages. The FFR study of near infra-red spectroscopy (NIR) in relation to the durability of redwood timber showed promising indicative results in that there was a good correlation between weight loss in laboratory tests and NIR spectra[91]. This study indicates that while there was high variability in the measured weight loss (from high to low durability, which agrees with long term ground-contact field test results), the technique can probably be used to screen young genetic material to identify those groups which will probably perform better. United States experience confirms that there are large differences between individual stems[92].

This can be advanced by developing a protocol for testing with 5-mm increment cores for screening genotypes, similar to that developed for cypresses with 10-mm cores[93].

Longer-term in-ground tests are necessary to validate genetic selections and eliminate poor performers as soon as possible.

Conclusions

The wood quality of plantation-grown redwood has been shown to be somewhat similar to old-growth US material in regard to wood density, heartwood formation and stability, but inferior in ground-contact durability. There is no reason to expect that plantation-grown redwood aged 30-50 years will be highly durable, since extractive content appears to increase significantly with age.

However, there are good prospects for genetic selection of superior material for all wood properties measured to date – between-tree variation being the main component.

Density: Wood density is normally moderately to highly heritable, and studies have shown a good range of variability. Density improvement should be a high priority, as the low values can limit utilisation options

Stability (shrinkage): Shrinkages are generally low in line with expectations, and are hence not high priority for improvement.

Heartwood: As for stability, measured values are similar to expectations, and not high priority for change.

Durability: This is a critical factor

Recommendations

Research gap	Recommended research for addressing gap
Wood density distributions and heritability	Collect 5-mm increment core samples from some of the Kuser clones and others across several sites. The minimum requirement should be that they have at least 10 growth rings at BH. This will allow a database to be established of wood density and heartwood development to be used in breeding selections and carbon models. **High priority.**
Stability	NZ redwod has similar shrinkage characteristics to US senond-growth and is not a priority area for research.
Heartwood Content	Studies in NZ and the US have shown variability in heartwood development. Extractives content is known to increase with tree age but has not been studied. The 5-mm cores colected for wood density should be analysed for water and methanol extractives. Medium priority.
Durability	This is the critical issue. There is an urgent need for development of a method for NIR analyses of 5-mm core samples to assign early “durability” ratings (age 10 – 12 years?). To reduce “noise”, assessment should be done on outer heartwood samples. Also develop an NIR test for redwood boards. **High priority.**

PRORITY RATING FOR RECOMMENDATIONS

The following section prioritises the recommendations for coast redwood after the end of the current Future Forests Research Diversified Species programme:

- Identify superior clones in circulation and develop a breeding programme for continued improvement of the species.
- Establish more silvicultural trials and develop a pruned log index of standing trees.
- Establish confidence around estimates on growth and yield, carbon sequestration, and erosion mitigation.
- Establish opportunities and confidence in potential markets through definition of the wood quality of the standing resources.

Redwood Breeding Programme

Immediate priority – Provenance evaluation and selection
Identify the provenance best suited to New Zealand growing conditions, through assessment of three of the better Kuser trials that were established between 2003 and 2006. The results should determine from which provenances in North America a seed collection from 100 plus trees will be made to supplement current material in New Zealand. Assessment of the Kuser trials for wood quality to indicate potential wood quality changes with site.

Five year priority – Assessment of benchmarking trials
Assessment of the three benchmarking trials for growth and form; heartwood will also be assessed, but once the trees are slightly older. These results will be used to rate most of the current clones in circulation and identify future selections for inclusion in a breeding programme.

Ten year priority – Establishment of progeny tests
Initiate the establishment of progeny tests that combine material from the benchmarking trials and the plus tree collection from North America. Work will also need to be conducted around inducing early flowering of trees and propagation to ensure smooth implementation of the breeding programme.

Site Productivity and Growth Models

Immediate priority – Increase number of plots in the permanent sample plot (PSP) network
The limited distribution of the current PSP network is hampering prediction of growth and productivity of this site-sensitive species. The establishment of more PSPs over a wider range of potential sites, with emphasis in regions likely to be suitable for plantations, will allow the development of more accurate siting and more robust models in the future.

Five year priority – Volume and density estimates
The latest volume/taper studies have indicated that redwood grown on cooler, less productive sites, has less of a taper than more productive sites. However, there are not enough data to develop a separate taper/volume equations for less productive sites at present. Improved tree volume and taper functions will allow more accurate prediction of the merchantable volume throughout New Zealand. Wood density is an important indicator of wood quality. Sampling wood density throughout the country, with different growth rates and provenances, will provide a simple and comprehensive picture of wood quality. Volume and wood density are also important for predicting carbon sequestration (see below).

Ten year priority – Improve productivity and growth models
Regular measurements from an expanded PSP network over a 10-year period will create a large database of redwood growth and productivity throughout New Zealand. The addition of this

database to current productivity and growth and yield models will vastly improve the accuracy of coast redwood growth predictions. It will take time before sufficient plots are established and measurements taken to determine productivity dynamics. Parameterisation of a process-based model or a hybrid approach with empirical modelling could be used to develop robust models in a far shorter period.

Silvicultural Practices

Immediate priority – Establishment of thinning and pruning trials
Establish more thinning and pruning trials by "piggy backing" industry's operational regimes with a simplified trial design. The trials should accomplish the following: 1) increase the geographic distribution of existing trials, 2) establish trials in stands less than 10 years old, 3) the control for a thinning trial should have a tree density of greater than 1,000 stems per hectare. Establishing new trials immediately will mean that meaningful results can be collected in 5-10 years' time.

Five year priority –Development of a pruned log index
The ability to predict log value of standing trees accurately will create much needed certainty of the value of stand for owners and investors. This study should be started at the earliest in five years' time, as a number of PSPs will be old enough to assess wood quality and log value. A range of sites with differing pruning quality and growth rates will need to be assessed.

Ten year priority – Sawlog studies
The Mangatu sawing study was invaluable in understanding the potential log value, but this was from one site with poor silvicultural practices. More sawing studies are required to determine if current management practices deliver the promised timber grade return. In ten years' time, several silviculture trials will be old enough to determine if current management practices can provide logs with the most valuable timber grades. Like the prune log index, a range of sites with differing growth rates should be assessed.

Carbon Sequestration

Immediate priority – Volume and density estimates
Tree volume and density also explain the majority of carbon sequestered on a forested site. Establishing these estimates can be relatively quick, and therefore will make an immediate improvement in carbon sequestration estimates. With improvement in the genetics, these estimates can be more precisely estimated.

Five year priority – Biomass allocation
Estimates for biomass allocation will secondly improve carbon sequestration and allow for the calibration of C_Change [43]. To establish biomass allocation above and below ground over a range of tree ages requires biomass studies at an individual stand level, with a minimum of 8 sites required to initiate the calibration of C_Change. It is possible to undertake two sites per year.

Ten year priority – Biomass allocation and decomposition
An improved genetic understanding and knowledge on the heritability of wood density will contribute greatly to carbon sequestration estimates. Further biomass allocation studies will further improve allometric equations used in models. Understanding other carbon pools will require an improved estimate of coarse wood debris decay rate, proportion of roots that die after thinning or harvesting, and soil carbon input through fine root turnover and incorporation.

Erosion Mitigation

Immediate priority – Redwoods on erodible sites
The immediate priority is greater knowledge of redwood stands that are currently on sites susceptible to erosion. Establishing some new sites will add to future understanding of the effectiveness of coast redwood for erosion mitigation.

Five year priority – Root cohesion
A quantitative assessment of root cohesion with increasing tree age and with thinning and harvesting would improve confidence in the effectiveness of coast redwoods in erosion mitigation.

Ten year priority – Root cohesion with decomposition
Adding to the understanding of root cohesion is the impact of thinning or harvesting on root decomposition and loss of strength.

Market Access

Immediate priority – Perception comparative analysis
A comparative analysis between western red cedar and New Zealand coast redwood would immediately improve understanding of the perceptions of New Zealand coast redwood. This could allow for immediate positive response in plantings in New Zealand, particularly as corrective measures can be undertaken to address weaknesses in the perceptions.

Five year priority – Public benefit from avoided soil erosion and carbon markets
An understanding of the public benefit from avoided soil erosion with redwood planting can be gained in conjunction with the root cohesion studies. Moreover, greater confidence around carbon markets will be gained in conjunction with carbon sequestration measurements.

Ten year priority – Perceptions and market analysis with improved data
More accurate market analysis can be undertaken with improved data on user perceptions and market access.

Wood Quality

Immediate priority – Perception comparative analysis
New Zealand redwood currently suffers from poor perception in the marketplace (this may be somewhat debatable), and needs to be reversed by promoting all its uses and establishing high visibility utilisation trials (weatherboards, furniture). Now that the proof of concept has been completed for the NIR spectroscopy prediction of durability in laboratory tests, there is an urgent need to establish a protocol for testing genetic material at an early age. This will involve further trial on 5-mm increment cores and laboratory Sutter Block Tests from a range of 10-year-old material to confirm the validity of the approach for density and durability.

Five year priority – Initiate selections for durability
Use the core/NIR method to perform selections from clones to start the durability and density breeding programme.

Ten year priority – Density and durability validation
Validate the selection of material for improved durability and density.

Topic	Immediate priority	Five year priority	Ten year priority
Redwood breeding programme	Collection of further suitable material from North America	Assessment of the benchmarking trials	Establishment of two progeny trials
Site productivity & growth models	PSP expansion	Volume and density	Improve growth and productivity models
Silvicultural practices	Establish new thinning and pruning trials	Pruned log index	Sawlog studies
Carbon sequestration	Volume and density	Biomass allocation	Decomposition studies
Erosion mitigation	Redwoods on erodible sites	Root cohesion	Root cohesion with decomposition
Market access	Perception comparative analysis	Public benefit from avoided soil erosion and carbon markets	Perceptions and market analysis with improved data
Wood Quality	Work on market perception and develop protocol for NIR sampling using increment cores	Select young genetic material for durability and density using NIR spectroscopy	Confirm durability selections with material in ground-contact field tests

ACKNOWLEDGEMENTS

We wish to thank FFR for funding this work. We would like to thank various members of the redwood industry for sharing their expertise and knowledge for this report. We would like to give a special thanks to Paul Silcock of New Zealand Forestry, Simon Rapley of the New Zealand Redwood Company, and Dave Cown of Scion for providing valuable information for the market analysis section. We would also like to thank Murray Davis for reviewing the erosion mitigation and carbon sections. Finally thanks to Ruth Falshaw, Heidi Dungey, and FFR for reviewing the report.

REFERENCES

1. Knowles, F.B., and Miller, J.T., *Introduced forest trees in New Zealand: Recognition, role and seed source, 13 the redwoods.* FRI bulletin no. 124. Rotorua, New Zealand Forest Research Institute. (1993).
2. Stovold, G.T., *Establishment of Redwood Benchmarking Trials.* FFR file note (in preparation): (2012).
3. Rogers, L.D., *Genotypic diversity and clone size in old-growth populations of coast redwood (Sequoia sempervirens).* Canadian Journal of Botany, ***78***, pp. 1408-1419. (2000).
4. O'Hara, K.L., and Berril, J.-P., *Dynamics of coast redwood psrout clump development in variable light environments.* Journal of Forest Research, ***15***, pp. 9. (2010).
5. Burdon, R.D., and Aimers-Halliday, J., *Risk management for clonal forestry with Pinus radiata - analysis and review. 1: Strategic issues and risk spread.* New Zealand Journal of Forestry Science, ***33*** (2), pp. 156-180. (2004).
6. Brown, I., Low, C., Nicholas, I., and Webster, R., *Chapter 1 - Introduction.* In Best practice with farm forestry timber species. No. 3: Redwoods, I. Nicholas, Editor p.: NZFFA Electronic Handbook Series. (2008).
7. Weston, G.C., *The role of exotic genera other than Pinus in New Zealand forestry.* . (Forest Research Institute no. 10). Rotorua. (1971).
8. Libby, W.J., *Redwood- an addition to exotic forestry?* New Zealand Forestry, ***38***, pp. 4. (1993).
9. Olson, D.F.J., Roy, D.F., and Walters, G.A., *Sequoia sempervirens (D. Don) Endl. Redwood.* In R.M. Burns and B.H. Honkala (Eds.), In Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654 (Vol. 2, pp. 877). U.S. Department of Agriculture, Forest Service, Washington, DC. (1990).
10. Palmer, D.J., Watt, M.S., Kimberley, M.O., and Dungey, H.S., *Predicting the spatial distribution of Sequoia sempervirens productivity in New Zealand.* Unpublished report no. 16989. Rotorua; New Zealand Forest Research Institute: (2009).
11. Davis, M., *Mycorrhizas and new species mixture trials.* Technical Report FFR Radiata Management theme. Unpublished report no. 18014. Rotorua; New Zealand Forest Research Institute: (2010).
12. Davis, M., and Coker, G., *A glasshouse study of tree species in mixtures.* Technical Report FFR Radiata Management theme: (2011).
13. Richards, F.J., *A flexible growth function for empirical use.* Journal of Experimental Botany, ***10***, pp. 290-300. (1959).
14. Schmacher, F.X., *A new growth curve and its application to timber-yiled studies.* Journal of Forestry, ***37***, pp. 819-820. (1939).
15. Kimberley, M., Beets, P., Van der Colff, M., and Dean, M., *Updated redwood calculator.* File note no. DSFN-026. Unpublished report. Rotorua; New Zealand Forest Research Institute: (2011).
16. van der Colff, M., *Volume and taper Equations for Redwood in New Zealand.* Unpublished report. Rotorua; New Zealand Forest Research Institute: (2005).
17. Meason, D.F., Grace, J.C., and Todoroki, C., *Sequoia sempervirens silvicultural practices review and data analysis.* Future Forests Research, Diverse Forests Theme. Unpublished report. Rotorua; New Zealand Forest Research Institute. (2012).
18. Meason, D.F., *Review of Sequoia sempervirens taper functions.* Rotorua: New Zealand Forest Research Institute. (2010).
19. van de Colff, M., *A new taper equation for Sequoia sempervirens in New Zealand.* Unpublished report no. 17959. Rotorua; New Zealand Forest Research Institute: (2010).
20. Young, G., *Density investigations in redwood (Sequoia sempervirens) grown near Hokitika.* FRI Output No. 00643 (unpublished): (1983).
21. Bowles, G.P., *Establishing Redwood (Sequoia sempervirens).* New Zealand Tree Grower, ***November***. (1980).
22. Nicholas, I., and Rapley, S., *Chapter 6 - Establishment.* In Best practice with farm forestry timber species. No. 3: Redwoods, I. Nicholas, Editor p. 30-31. (2008).

23. Marshall, H., Silcock, P., and Cown, D., *Sawing Plantation Redwood.* Unpublished. (2010).
24. Cown, D.J., *Redwood wood quality strategy.* (2009).
25. Marshall, H., and Silcock, P., *Mangatu redwood sawing study report, Part 1.* Future Forests Research, Diverse Forests Theme. Unpublished report no. 18060. Rotorua; New Zealand Forest Research Institute: (2009).
26. Meason., D., Nicholas, I., Silcock, P., and Dean, M., *Coast redwood (Sequoia sempervirens) silviculture trial. Guthrie Smith Arboretum – Tutira, Hawke's Bay. FFR field trip August, 26 2009.* Unpublished verbal presentation. Rotorua; New Zealand Forest Research Institute: (2009).
27. Berril, J.-P., *Coast redwood stand growth and leaf area index: the influence of site quality.* Doctor of Philosophy dissertation, University of California at Berkeley, USA. (2008).
28. Dominati, E., Mackay, A., and Patterson, M. (Eds.), *Modelling the provision of ecosystem services from soil natural capital*. Modelling the provision of ecosystem services from soil natural capital. Brisbane, Australia: 2010 19th World Congress of Soil Science, Soil Solutions for a Changing World. (2010).
29. Basher, L.R., Botha, N., Dodd, M.B., Douglas, G.B., Lynn, I., Marden, M., McIvor, I.R., and Smith, W., *Hill country erosion: a review of knowledge on erosion processes, mitigation options, social learning and their long-term effectiveness in the management of hill country erosion.* Landcare Research Contract Report LC0708/081: (2008).
30. Jones, H., Clough, P., Höck, B., and Phillips, C., *Economic costs of hill country erosion and benefits of mitigation in New Zealand: Review and recommendation of approach.* Prepared for Ministry of Agriculture and Forestry. Contract number 74701: (2008).
31. Stokes, A., Norris, J.E., van Beek, L., Bogaard, T., Cammeraat, E., Mickovsdi, S.B., Jenner, A., Di Iorio, A., and Fourcaud, T., *How vegetation reinforces soil on slopes.* In J.E. Norris, et al. (Eds.), In Slope Stability and Erosion Control: Ecotechnological Solutions (pp. 290): Springer. (2008).
32. MAF, *Sustainable land management hill country erosion programme.* MAF, Wellington, New Zealand: (2010).
33. Watt, M.S., Kirschbaum, M.U.F., Paul, T.S.H., Tait, A., Pearce, H.G., Brockerhoff, E.G., Moore, J.R., Bulman, L.S., and Kriticos, D.J., *The effect of climate change on New Zealand's planted forests: Impacts risks and opportunities.* Prepared for The Ministry of Agriculture and Forestry: (2009).
34. Burdon, R.D., *Is coast redwood an answer to the Mangatu problem.* New Zealand Journal of Forestry, ***20*** (1), pp. 148-152. (1975).
35. Clinton, P.W., Phillips, C.J., and Coker, R., *Redwoods - what have we been waiting for?* New Zealand Tree Grower, ***30***, pp. 3-5. (2009).
36. Marden, M., *The tolerance of Sequoia sempervirens to sedimentation, East Coast Region, New Zealand.* New Zealand Journal of Forestry, ***38*** (3), pp. 22-24. (1993).
37. Phillips, C.J., Marden, M., Lambie, S., Watson, A., Ross, C., and Fraser, S., *Observations of below-ground characteristics of young redwood trees (Sequoia sempervirens) from two sites in New Zealand - implications for erosion control.* Plant and Soil, pp. 1-16. (2012).
38. Madej, M., *Redwoods, restoration, and implications for carbon budgets.* Geomorphology, ***116***, pp. 264-273. (2010).
39. Ried, L.M., and Keppeler, E.T., *Landslides After Clearcut Logging in a Coast Redwood Forest*. In Redwood science symposium: coast redwood forests in a changing California, Santa Cruz, California. (2011).
40. Phillips, C.J., and Watson, A.J., *Structural tree root research in New Zealand: a review*. Lincoln: Manaaki Whenua Press. (1994).
41. Watson, A.J., and Marden, M., *Live root-wood tensile strengths of some common New Zealand indigenous and plantation tree species.* New Zealand Journal of Forestry Science, ***34*** (3), pp. 344-353. (2004).
42. IPCC, *Intergovernmental Panel on Climate Change. Good Practice Guidance for Land Use, Land-use Change and Forestry*: The Intergovernmental Panel on Climate Change (IPCC), Japan. (2003).
43. Beets, P.N., Robertson, K.A., Ford-Robertson, J.B., Gordon, J., and Maclaren, J.P., *Description and validation of C_Change: A model for simulating carbon content in managed*

Pinus radiata stands. New Zealand Journal of Forestry Science, ***29*** (3), pp. 409-427. (1999).
44. Beets, P.N., Kimberley, M.O., Paul, T.S.H., and Garrett, L.G., *Planted Forest Carbon Monitoring System – forest carbon model validation study for Pinus radiata.* New Zealand Journal of Forestry Science, ***41***, pp. 177-189. (2011).
45. Dean, M., Low, C., McKinley, R., and Page, D., *Chapter 2 - Timber properties and markets.* In I. Nicholas (Ed.), In Best practice with farm forestry timber species. No. 3: Redwoods (pp. 13-18). (2008).
46. McKinley, R.B., and Cown, D.J., *Sawing and Wood Quality Studies on Pruned Redwoods from Mangatu Forest.* Technical Report FFR Diversified Species theme: (2008).
47. Turner, J.A., West, G., Dungey, H., Wakelin, S., MacLaren, P., Adams, T., and Silcock, P., *Managing New Zealand planted forests for carbon.* A review of selected scenarios and identification of knowledge gaps. Report to the Ministry of Agriculture and Forestry 130pp. (2008).
48. Beets, P.N., Pearce, S.H., Oliver, G.R., and Clinton, P.W., *Root/shoot ratios for deriving below-ground biomass of Pinus radiata stands.* New Zealand Journal of Forestry Science, ***37*** (2), pp. 267-288 (2007).
49. Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E., and Schulze, E.D., *A global analysis of root distributions for terrestrial biomes.* Oecologia, ***108***, pp. 389-411. (1996).
50. Garrett, L.G., Kimberley, M.O., Oliver, G.R., Pearce, S.H., and Beets, P.N., *Decomposition of coarse woody roots and branches in managed Pinus radiata plantations in New Zealand - A time series approach.* Forest Ecology and Management, ***269***, pp. 116-123. (2012).
51. Garrett, L.G., Kimberley, M.O., Oliver, G.R., Pearce, S.H., and Paul, T.S.H., *Decomposition of woody debris in managed Pinus radiata plantations in New Zealand.* Forest Ecology and Management, ***260*** (8), pp. 1389-1398. (2010).
52. Busing, R.T., and Fujimori, T., *Biomass, production and woody detritus in an old coast redwood (Sequoia sempervirens) forest.* Plant Ecology, ***177*** (2), pp. 177-188. (2005).
53. Beets, P.N., Hood, I.A., Kimberley, M.O., Oliver, G.R., Pearce, S.H., and Gardner, J.F., *Coarse woody debris decay rates for seven indigenous tree species in the central North Island of New Zealand.* Forest Ecology and Management, ***256*** (4), pp. 548-557. (2008).
54. Food and Agriculture Organization, *Part 2: Adapting to the future* Rome: FAO. (2009).
55. Kent, N., and Williams, J., *Redwood Market Aspects*. Confidential report, Unpublished. Kent & Associates Environmental Resource Solutions, Inc. (2011).
56. NZWood, *Redwood*. Retrieved June 1st, 2012, from http://www.nzwood.co.nz/species/redwood
57. Holmes, J., *New Zealand - A great place to do business*. Feature. (2003,
58. Dean, M., Low, C., McKinley, R., Page, D., and Webster, R., *No. 3: Redwoods.* In I. Nicholas (Ed.), In Best practice with farm forestry timber species (pp. 6). New Zealand: Wade-Cornell. (2002).
59. Wilcox, W. (Eds.), *Coast redwood as a future supplier of wood products*. Coast redwood as a future supplier of wood products. Humboldt State University, California. (1996).
60. Cown, D., *Redwood in New Zealand - an end user perspective.* New Zealand Journal of Forestry, ***52*** (4), pp. 35-41. (2008).
61. Knowles, L., *Product performance of Redwood (Sequoia sempervirens) in New Zealand - How does it perform, and canit be improved?* In CHH workshop, (2002).
62. Libby, W., *An update from California on coast redwood.* In New Zealand Tree Grower. (2007).
63. Marshall, H., Silcock, P., and Cown, D., *Sawing Plantation Redwood*. , Unpublished. (2010).
64. NZ Logger, *The future may be in Redwood.* In New Zealand Logger. Print media copyright association. (2009).
65. Forest Owners Association, *New Zealand plantation forest industry: Fact and figures*. Wellington: FOA. (2009).
66. Ministry of Agriculture and Forestry, *Review of MAF afforestation schemes*. Wellington. (2011).

67. OM Financial Ltd., *Commtrade carbon*. Retrieved March, 2012, from https://www.commtrade.co.nz/
68. Bayne, K., and Coker, G., *Functional forests within New Zealand - Which species should we plant?* Future Forest Research. (2011).
69. Ministry of Agriculture and Forestry, *A forestry sector study*. Wellington. (2009).
70. Silvester, W., Barton, I., Berg, P., and Campbell, I., *Forestry and carbon sequestration: A review of the options for planting and regenerating indigneous forest*. Tane's Tree Trust Newsletter. Retrieved from http://www.tanestrees.org.nz/publications.html. (2008,
71. Turner, J., Dhakal, B., Yao, R., Barnard, T., and Maunder, C., *Non-timber values from planted forests: recreation in Whakarewarewa forest.* New Zealand Journal of Forestry, ***55*** (4), pp. 24-31. (2011).
72. Resch, H., and Arganbright, D.G., *Variation of specific gravity, extractive content and tracheid length in redwood trees.* Forest Science ***14*** (2), pp. 148-155. (1968).
73. USDA, *Wood Handbook: Wood as an Engineering Material.* Forest Products Laboratory General Technical Report FPL-GTR-113: 486pp. (1999).
74. Knowles, F.B., and Miller, J.T., *Introduced forest trees in New Zealand: recognition, role and seed source. 13 The redwoods. .* FRI Bulletin No 124: 31pp. . (1993).
75. Brown, I., *Redwoods – an overview.* New Zealand Tree Grower. , ***February*** pp. 4-5. (2007).
76. Cooke, J., and Satchell, D., *Action groups enjoy diversity of new farm park. .* New Zealand Tree Grower, November 2007, pp. 18-19. (2007).
77. Poole, B., *On overview of alternative species plantations in New Zealand. .* New Zealand Tree Grower, November 2007: 3-4. (2007).
78. Colbert, C.M., and McConchie, D.L., *Some physical properties of New Zealand-grown redwood.* FRI Bulletin No. 26 pp. 11pp. (1983).
79. Cornell, W., *2002 The New Zealand redwood growers' handbook. .* Diversified Forests Ltd.: 53pp. (2002).
80. Cornell, W., *A love-hate relationship with redwood. .* New Zealand Tree Grower, February 2007:19. (2007).
81. Cown, D.J., *Redwood in New Zealand - an end-user perspective.* New Zealand Journal of Forestry, ***52*** (4), pp. 35-41. (2008).
82. Cown, D.J., and McKiney, R.B., *Wood properties of 38-year-old redwood from Mangatu forest.* New Zealand Journal of Forestry, ***54*** (2), pp. 25-32. (2009).
83. Clifton, N.C., *New Zealand Timbers. The complete guide to exotic and indigenous woods (revised edition).* G P Publications, 10 Mulgrave Street, Thorndon, Wellington., pp. 170pp. (1994).
84. NZS3602, *Timber and wood-based products for use in building.* NZ Standards. (2003).
85. Cown, D.J., *Redwood Wood Quality Strategy.* FFR Report FFR DS008: 18pp. (2009).
86. Luxford, R.F., and Markwardt, L.J., *The strength and related properties of redwood.* Technical Bulletin 305. Washington, DC: U.S. Department of Agriculture, Forest Service. 55 pp. (1932).
87. Wallwork, C., and Rapley, S., *Coast redwood is the ideal crop.* New Zealand Trtee Grower, November 2009: 5-7. (2009).
88. Young, G.D., *Density investigations in redwood (Sequoia sempervirens) grown near Hokitika. .* FRI Output No. 00643 (unpublished). (1993).
89. Wilcox, W.W., and Piirto, D.D., *Decay resistance in redwood (Sequoia sempervirens) heartwood as related to color and extractives.* Wood and Fiber ***7***(4), pp. 240-245. (1976).
90. Jones, T.G., Meder, A.R., Low, C.B., O'Callahan, D.R., Chittenden, C.M., Ebdon, N.J., Thumm, A., and Riddell, M.J.C., *Natural durability of the heartwood of coast redwood [Sequoia sempervirens (D.Don) Endl.] and its prediction using near infrared spectroscopy. .* Journal of Near Infrared Spectroscopy., ***19***, pp. 381-389. (2010).
91. Cown, D.J., *NIR Studies of Redwood (Sequoia sempervirens) Durability: Critical Analysis.* FFR Report (submitted August 2012): 4pp. (2012).
92. Clark, J.W., and Scheffer, T.C., *Natural decay resistance of the heartwod of coast redwood Sequoia sempervirens (D.Don) Endl.* Forest Products Journal, ***33*** (5), pp. 15-20. (1983).
93. Jones, T.G., Low, C.B., Meder, A.R., O'Callahan, D.R., Milne, P.G., Chittenden, C.M., Ebdon, N.J., and Dungey, H.S., *Cupressus lusitanica, C. macrocarpa, Leyland and Ovens*

Cypress Diameter Growth, Heartwood Content, and Durability and its Prediction using Nearinfrared Spectroscopy. FFR Report DS034: 22pp. (2011).