Effect of silvicultural regimes on carbon sequestration in *Pinus radiata* forest in Canterbury

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Abstract

This study explored effects of silvicultural treatments on carbon sequestration in juvenile *Pinus radiata* forest in Canterbury. Financial modelling was then employed to determine what regimes would be most profitable given current carbon prices. Deciding how best to manage stands for carbon sequestration is important given the thriving carbon market and the current climate crisis requiring us to reduce net GHG emissions.

Relevant literature noted that biomass growth is highly influenced by local environments and site factors. Analysing biomass assays with a tree-level mixed-effect model to predict biomass through time takes into account variance caused by local factors and was found to be an effective way to predict carbon stocks. A comparison against existing national models found that these could generally be applied to a Canterbury site, however a localised model is superior, with less variance in predictions compared to the existing national models.

A comparison of carbon estimates between the localised model based on biomass assays and the default yield table for Canterbury under the Emission Trading Scheme (ETS) showed that the default yield table markedly underestimated carbon stocks during the initial 15 years. This was most prevalent at the highest stockings where table carbon estimates were 67% less than localised model estimates based on biomass assessments.

The effect of initial stocking was found to significantly ($p<0.05$) influence carbon sequestration, and low (625 stems/ha), medium (1250 stems/ha) and high (2500 stems/ha) stockings were all statistically different from each other. The presence of weed control also had a statistically significant effect ($p<0.05$) on carbon sequestration however fertiliser did not. An interaction effect between stocking and weed control was only present early at age 5 and was likely due to different rates of canopy closure based on the varying stockings. These findings were similar to previous studies on biomass production where treatments that encouraged rapid above-ground growth such as high initial stockings were shown to sequester significantly higher amounts of carbon.

Financial analyses showed that a stand of 2500 stems/ha, no thinning, and a long rotation age of 44 years, returned the highest Land Expectation Value (LEV). Permanent carbon forestry also returned a high LEV and given a longer rotation age (>60 years) may be more profitable than rotational forestry. Forest managers aiming for higher biomass will need to sacrifice large piece size. Growing higher stocked stands with no thinning will require accepting a higher level of risk and ensuring there is a large enough market for lower grade timber.

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1. Introduction

1.1. Background

Climate change is a result of anthropogenic greenhouse gas carbon dioxide emissions (GHG). It is the single most important issue confronting our generation on a global scale. Forests are capable of minimising the effects of climate change and temporarily offsetting emissions by absorbing CO_2 during photosynthesis, acting as a carbon sink. Currently New Zealand has forest covering 10.1 million hectares or 38% of the land, with 1.7 million hectares of this being productive plantation forest (MPI, 2021a). *Pinus radiata* is the dominant forest species planted, amounting to 1.5 million hectares and 90% of the total stocked production forest area (NZFOA, 2019). In 2018, the forestry sector collectively removed 23.4 million tCO_2e from the atmosphere resulting in a 30% offset of New Zealand's total emissions for that year (MfE, 2021a).

The Emissions Trading Scheme (ETS) was established in 2008 by the New Zealand government to act as the primary mechanism to meet obligations under the first commitment period in the Kyoto Protocol between 2008-2012 (MfE, 2019). The ETS is a market-based approach where a New Zealand Unit (NZU) represents one metric tonne of CO_2. NZUs are traded between participants of the scheme, and emitters must acquire and surrender units to account for their GHG emissions. Forests planted on land that was not forested in 1989 can receive NZUs for carbon sequestered which can then be traded (EPA, 2021). Currently the ETS continues to be implemented as a key tool to meet international and domestic climate change targets which include the 2016 Paris Agreement and the 2002 Climate Change Response Act (MfE, 2021b). To meet these ambitious commitments for reducing emissions the ETS is undergoing transformations that will take effect on 1 January 2023. The changes will improve the accessibility of the system and specifically will have significant advantages for forestry participants (Te Ura Rākau, 2021). These include application of "averaging" on all newly registered forests as of 2023, replacement of a fixed price option with a cost containment reserve and enabling a minimum floor price of $20 (MfE, 2021b). Averaging partially removes the risk from the ETS, so encourages foresters to sell more of the allocated NZUs, thus increasing finance returns. It also reduces the complexity and compliance of the ETS. Replacement of the fixed price option, removes the price ceiling and allows for market growth.

In conjunction with reforming the ETS, the current market carbon price sits at $64.50 (CommTrade, 2021). These factors make rotational and permanent carbon forestry an increasingly attractive investment for landowners. When considering rotational forestry, the addition of carbon revenue has been shown to significantly increase the Land Expectation Value (LEV) and Net Present Value (NPV) for an investment (Manley & Maclaren, 2010). With increasing economic and environmental incentives, it is likely that carbon forestry will become more popular moving forward.

Production forests of radiata pine are typically planted as single-age monocultures, however silvicultural treatments and management practices can vary. Incorporating silvicultural treatments into a regime often enhances productivity and growth (Mohan et al., 2020). Returns from carbon trading have been found to be dependent on choice of silviculture, species and rotation age (Manley & Maclaren, 2010). For new plantings choosing silvicultural regimes that produce increased and early biomass can increase carbon stocks and therefore profitability in the ETS (Manley & Maclaren, 2009). Currently regimes that favour volume are increasing, with 55% of the radiata pine estate under an unpruned management regime (FOA, 2019). Typical silvicultural practices and management decisions are based around differing initial and final stockings, application of fertiliser and/or weed control and choices on thinning and pruning.

1.2. Purpose

Since the 1960s, a number of biomass studies have been conducted to estimate forest productivity and how it is influenced by forest management and silvicultural decisions. In recent years interest in accurate estimation of tree biomass for predicting carbon stocks has increased (Moore, 2010). This is a result of heightened need for accurate carbon accounting for both local and national GHG account reporting commitments. Currently there is a number of approaches for estimating tree biomass, including physiologically-based models, allometric equations and biomass expansion factors. Allometric equations are particularly useful as this allows prediction of individual tree total biomass using easily measured variables such as diameter and height. However, it is known that these equations are stand- and site-specific so when applied to a wider or national level can potentially cause high uncertainty where there is a range of stand structures, site factors and age classes (Moore, 2010). Therefore, for this analysis a mixed-effects model approach fitting localised allometric equations was created and used in order to most accurately predict tree biomass specific to the Canterbury site in question.

There is increasing interest in productive forest planting throughout New Zealand for economic and environment reasons. In 2019, 85,000 hectares of planting occurred comprising 22,000 hectares of new afforestation and 63,000 hectares of replanting. Opportunities for afforestation differ by region. Canterbury contained 94,782 hectares of radiata pine production forest as of 2019 (FOA, 2019). This is significantly less area than other regions and highlights an opportunity for future afforestation given the increasing profitability of carbon forestry to compete with previously unattainable farmland.

Given the increase in carbon forestry and the importance of *P. radiata* as a primary species, this research is focused on investigating the effects that silvicultural practices may have on above-ground carbon sequestration. Biomass data has been collected from the Canterbury region to develop a localised model to predict carbon content of juvenile radiata pine through time. Statistical analysis was undertaken to determine significant differences in carbon between silvicultural treatments. The results of this research will help landowners with interest in carbon forestry and forest managers determine the best silvicultural regimes for maximising profit in Canterbury's carbon forests.

1.3. Research Objectives

I. To assess and compare rates of above-ground CO_2 sequestration and C storage across differing silvicultural treatments in a juvenile *Pinus radiata* trial based in the dryland Canterbury region of New Zealand, by destructively sampling above-ground biomass and using past data from previous biomass studies.

II. To develop a localised individual tree model to predict biomass derived from the measurements of tree height and diameter. Make estimates of below-ground biomass and carbon based on above-ground measurements and supporting literature.

III. Compare carbon storage from the results of this study and current Canterbury ETS yield table and C_Change estimates.

IV. To examine the potential economic benefits in the ETS of stockings which give a higher CO_2 sequestration in comparison to stockings which produce lower CO_2 sequestration.

1.4. Hypothesis

H_0. Silvicultural practices did not influence CO_2 sequestration rates of radiata pine in Canterbury.

H_1. Silvicultural practices did influence CO_2 sequestration rates of radiata pine in Canterbury.

2. Literature Review

2.1. Emissions Trading Scheme:

The New Zealand government established the Emissions Trading Scheme (ETS) in order to meet New Zealand's Kyoto Protocol obligations during the first commitment period between 2008 and 2012 (MfE, 2019). Planted forestry was the first industry required to participate in the NZ ETS. Owners of forests established after 1989 receive credits for increases in carbon stocks, where each unit (NZU) represents one metric tonne of CO_2 (MfE, 2019). Units can be claimed for the annual change in carbon stocks (Manley & Maclaren, 2010). The objectives of the scheme are described as:

> "… The NZ ETS is the Government's principal policy response to climate change. Its objective is to support and encourage global efforts to reduce greenhouse gas emissions by: assisting New Zealand to meet its international obligations; reducing New Zealand's net emissions below business as usual levels. The NZ ETS requires all sectors of New Zealand's economy to report on their emissions and, with the exception of agriculture, purchase and surrender emission units to the Government for those emissions. This price on emissions is intended to create a financial incentive for investment in technologies or practices that reduce emissions, and for carbon removals from forestry by allowing eligible foresters to earn New Zealand Units (NZUs) as their trees grow and absorb carbon…" (MfE, 2015).

Participation in the ETS changes the economics of commercial forestry as it provides early cashflow for owners. Returns from carbon trading are dependent on choice of silviculture, species, rotation age and the price of NZU's (Manley & Maclaren, 2010).

Other schemes were also implemented aiming to encourage carbon sequestration through forestry planting, these included the Permanent Forest Sink Initiative in 2007 (PFSI) and the Afforestation Grant Scheme in 2008 (AGS) (Evison, 2017). The PFSI will be replaced with

Permanent Post-1989 initiative on 1 January 2023. This category will be eligible for post-1989 forests that will not be clear-felled for at least 50 years and will be on the stock change accounting approach (MPI, 2021b). The variety of schemes encouraging new forest planting indicate the importance of forests in reducing emissions to meet targets. However, it is noted that new planted forests should only be used to reach emission reduction targets earlier than can otherwise be achieved by reducing GHG emissions. Afforestation should be an "accelerator" to reach targets while new innovations to reduce emissions are being implemented (Evison, 2018). Net forest sequestration offsets 30% of NZ's gross emissions as of 2018 (Leaning & Kerr, 2018).

Previously the ETS had a fixed price option of $35 which allowed participants to pay cash rather than surrendering units. This essentially acted as a price celling. As of 2021, this has been replaced with the cost containment reserve under new price control settings. This reserve of NZUs will become available for sale if a trigger price is reached in auction, resulting in an ease in demand for emissions units. For 2021 the trigger price is $50, which the current market price of $50 has already been reached (MfE, 2021c). Updates to the ETS price control settings have meant an increase to the trigger price for sale of the reserve amount of NZUs. For 2022 the trigger price will move from $51 to $71 and even more drastically from $54 to $98 in 2025. This update is an acknowledgement that NZUs will become increasingly important in combating climate change hence this will be reflected in unit price. As NZUs are based upon a supply and demand market, the price increase is a reflection of demand for units rapidly rising. For investors the increase in the trigger price should be taken as a reliable forecast of carbon price in the near future. It should encourage investing in afforestation with a focus on regimes that will maximise carbon.

The averaging accounting method means that owners will earn credits up to the forests long-term average carbon stock based upon a set harvest age. The precision of averaging accounting will be determined by the age bands chosen. Age bands determine the level of flexibility a forest owner will have in harvesting at a different rotation ages. The age bands describe a range of tree ages where harvest can occur, and all trees are assigned to be the same average age. There are three band options, however this analysis will focus on option 3 – 5-year age bands. From 2023 all newly registered post-1989 forests will have to use the averaging accounting method (unless permanent forests). Forests established and registered prior to 2019 will remain using the carbon stock change method (MPI, 2021c).

Manley and Maclaren (2010), analysed the impact of the ETS on forest management. Results showed that at ‘high’ carbon prices of \$30/t CO_2 the most profitable radiata pine silvicultural regimes was a no thinning regime at 800 stems/ha. This was followed by a framing regime with a final crop stocking of 375 stems/ha and lastly a clearwood regime with a final crop stocking of 250 stems/ha. As carbon prices increase, regimes that increase the production of biomass, therefore carbon stocks, are favoured. It was concluded that regimes that have high final stocking, late thinning and lengthened rotation ages are most profitable. Ultimately the best strategies are those that favour volume per hectare over large piece-size.

While increasing average rotation age extends the period where plantation forests act as a carbon sink it is only a temporary solution. To ensure that plantation forests do not become a net source of carbon further afforestation is required. For new plantings choosing silvicultural treatments that produce increased and early biomass can increase carbon stocks and therefore will increase profitability (Manley & Maclaren, 2009).

Through participation in the NZ ETS the profitability of a new land planting for a forest managed for both timber and carbon can be increased. When the carbon price is high, the expected carbon revenue can often be high enough to encourage investors to start a new planting. The expected carbon revenue can cover the initial high land cost required so planting can begin, with no large cost to the owner. As of 2010 there were currently three million ha of agricultural land available costing less than \$7000/ha. This land would only be affordable for afforestation when traditional forestry is combined with carbon forestry and carbon prices are above \$30/t CO_2 (Manley & Maclaren, 2010). There is a strong correlation between LEV (Land Expectation Value) and the rate of afforestation. With higher carbon prices it becomes an increasingly key determinant for LEV (Manley, 2016)

<u>Targets:</u>

New Zealand met the first set target of reducing greenhouse gas emissions for the first Kyoto Protocol commitment period. This was to reduce net emissions to gross 1990 levels between 2008 and 2012 (MfE, 2019). Currently New Zealand has two greenhouse gas emissions reduction targets. The 2050 domestic targets set in legislation are to: have net zero emissions of all greenhouse gases other than biogenic methane by 2050; reduce biogenic methane emissions by 24 to 47% below 2017 by 2050, including 10% below 2017 biogenic methane emissions by 2030. The international target under the Paris Agreement is to reduce greenhouse gas emissions by 30% from 2005 levels by 2030 (MfE, 2020).

Yield tables:

Carbon stocks can be evaluated using a default look-up yield table or through the Field Measurement Approach (FMA) under the ETS. Owners of small forests (<100 hectares) must use the standard yield tables whereas owners of large forests (>100 hectares) or those that hold a covenant in the PFSI must use the field measurement approach (FMA).

The default carbon yield tables on MPI contain precalculated values of carbon stocks by age for a given forest type. These values are calculated using pools of above-ground live biomass, below-ground live biomass, fine litter and course woody debris. However, soil carbon is not included because it can be difficult to measure and the carbon changes are usually small (Manley & Maclaren, 2010). For radiata pine the standard yield tables are split by region based off differing regional averaged growth factors and rates. These tables do not reflect the diverse conditions at the individual forest level. The participant-specific tables provide a more accurate estimate of carbon stock levels of the specific forests, subject to the FMA, as they have been created specific to the forest based on inventory data collected in sample plots however, it uses national-level biomass equations (MPI, 2020).

A study done in costal Bay of Plenty compared the radiata pine carbon yield tables generated through the FMA and the default yield lookup tables offered by MPI (Pitcher-Campell, 2013). The study found for this particular forest the MPI standard lookup table gave a conservative estimate of carbon yield (131 NZU/ha) compared to the FMA estimate (247.8 NZU/ha).

2.2. Reporting Carbon Commitments:

New Zealand is required by the United Nations Frameworks Convention on Climate Change (UNFCCC) and previously Kyoto Protocol to report net carbon stock changes which includes those related to forests. The carbon pools that must be reported are above-ground live biomass, below-ground biomass, dead wood debris, litter and soil carbon. New Zealand has implemented the Land Use and Carbon Analysis System (LUCAS) monitored by the Ministry for the Environment to estimate the carbon stock and stock changes for its post-1989 forests (Beets et al., 2011).

2.3. The Forest Carbon Predictor:

LUCAS calculates carbon stocks using the Forest Carbon Predictor system version 3. This provides estimates for carbon pools in above-ground live biomass, below-ground biomass, dead wood and litter based on the plot data measurements, both ground based and LiDAR, and makes predictions over multiple rotations. The system includes, the 300 Index Model, the C_Change Model and a stem wood density model (Beets et al., 2011).

The 300 Index Growth Model and a wood density model combine together to provide the data required for the C_Change model to calculate carbon stocks per hectare on an annual basis over a rotation from a single plot measurement (Beets et al., 2011). The 300 Index Growth model uses plot and historical data to measure productivity for the mean stem volume annual increment for a stand aged 30 at 300 stems/ha. This gives a prediction of stem volume under bark across a rotation (Beets et al., 2011). A wood density model predicts the oven-dry wood density of annual growth sheaths of the stem (Beets et al., 2007). The resulting wood density annual growth increments are multiplied by annual stem volume increments, generated from the 300 Index model. The result is annual increments in stem wood dry matter for a whole rotation (Beets et al., 2011a).

The C_Change model then uses the outputs from the models to predict the carbon stock and stock changes contained in the stem, crown, roots, understorey and forest floor for a stand at any given age. The model assumes that dry matter is 50% carbon (Beets et al., 1999). The model was developed using a large dataset of radiata pine biomass data with a range of stockings predominantly from fertile central North Island sites. It uses growth partitioning functions to allocate carbon to each biomass component. The Forest Carbon Predictor joins detailed outputs from C_Change into above-ground biomass, below-ground biomass, dead wood, and litter which is four of the Good Practice Guidance pools required to be reported (Beets et al., 2011a; IPCC, 2003).

2.4. Localised Model

Differences in site and climate can greatly affect tree biomass and carbon and so applying a national biomass prediction model to a Canterbury site may cause uncertainties and inaccuracy in prediction. A large proportion of biomass data in many above-ground biomass models originates from the central North Island where sites are climatically and environmentally varied from Canterbury. Hence the Forest Carbon Predictor will not be used for this analysis. Moore (2010), built an above-ground biomass model to be applied nationally, however, it lacked data from trees grown in southern parts of the South Island including Canterbury. Consequently, it was predicted that the Moore's allometric equations would likely over-predict above-ground biomass if applied to stands in Canterbury. Hence Moore's models were not used for the majority of this analysis, except when doing a comparative analysis of models. Site and climatic differences have caused under and over predictions in the past where models have been applied to sites beyond those where fitting data was collected. Baker et al. (1984) applied equations developed by Madgwick (1983) which were largely derived from New Zealand data, to a site in Victoria, Australia. The equations were found to underestimate stem biomass by 19%. This was thought to be due to higher density in the Australian radiata pine, as density in the species varies by 25-30% across the latitudinal range and with variation in soil and temperature (Moore, 2010). Saremi et al. (2014) also found variations in radiata pine with local topographic factors. Different sites were compared in New South Wales, Australia and it was found that there was a significant relationship between diameter and local topography factors. Differences were observed where slopes less than 20° and positioned on southerly aspects resulted in significantly larger diameter than those on steeper north facing aspects. A larger diameter is closely related to larger total tree biomass. These observations support the idea that radiata pine biomass is highly susceptible to localised conditions and building a model that accounts for local site factors was therefore more accurate for this analysis. Balboa-Murias et al. (2006) found that the best methodology for assessing carbon pools through time is through individual tree biomass equations, dynamic growth models and measurement of carbon concentration in tree parts.

2.5. Model Validation and Improvement:

Good practice guidance for Land Use, Land-Use Change and Forestry activities (LULUCF) requires that estimates of national carbon stock changes to be unbiased, consistent, transparent and that uncertainties are identified and reduced over time (IPCC, 2003). There have been a number of studies that have reduced the uncertainties of the carbon stock estimates and improved the Forest Carbon Predictor system over time. Beets et al. (2011b), studied the reported inventory of carbon stock in New Zealand's post-1989 planted forest. As the estimation of carbon stock is done through a sample network of PSP's and LiDAR plots, the efficiency of LiDAR was assessed. The relationship between LiDAR metrics and live above-ground biomass obtained in the New Zealand post-1989 inventory plots were good (R^2= 0.81). This relationship provides confidence in using LiDAR in combination with ground field measurements to provide improved inventory.

Beets et al. (2012) also assessed the national inventory of carbon stock in pre-1990 planted forest. This is important for the Kyoto Protocol required estimate of carbon stock for deforestation of pre-1990 forest as well as proving that the forests are not a carbon source.

They found a very similar relationship between LiDAR and biomass measurements (R^2=0.80). By collecting data from a combination of ground plots and LiDAR, instead of using only ground plots the confidence interval for estimates reduces from 14.1% to 11.1% (Beets et al., 2012). This improvement of precision hence meets the good practice guidance set out for forest reporting (IPCC, 2003). LiDAR plots have the advantage of being easier to access and quicker but cannot gather all information such as stocking and management history (Beets et al., 2012).

Kimberly et al. (2007) formed new volume functions aiming to improve estimates of stem total volume under bark, which is a required input for the C_Change model which would perform well for a range of stand sites, ages and regimes. Predictions from existing individual tree functions in mature stands were combined with volume data from young stands to develop a new individual-tree and stand volume function for New Zealand radiata pine. The volume function must be accurate for both young and old trees as the C_Change model predicts carbon over an entire rotation. The new derived individual-tree volume function and stand-level volume function was fitted for the biomass data analysed, see equations 1 and 2 respectively (Kimberly et al., 2007).

$$v = h \times ba \times (0.860 \times (h-1.4^{-0.972}) +0.304) \qquad (1)$$

$$V = MTH \times BA \times (0.942 \times (MTH - 1.4)^{-1.161} + 0.317 \qquad (2)$$

2.6. Biomass Studies:

A study based in the North Island of New Zealand assessed carbon stocks of two radiata pine sites (Kinleith and Tarawera) at age 5 in both sites and then at age 15 (Kinleith site) and 16 (Tarawera site). Each site was planted at 2500 initial stems/ha with a split plot design (fertiliser). Both sites were thinned twice before the age of 11 to 500-600 stems/ha. The above-ground biomass was measured at both ages, while dead organic matter was only measured at the later age. Below-ground biomass was estimated via a root/shoot ratio instead of measurement. Soil carbon was not included in this analysis (Oliver et al., 2011).

Total carbon at Kinleith aged 15 and Tarawera aged 16 were estimated to be 346 tCO_2e/ha and 453 tCO_2e/ha respectively. Carbon stock for above-ground biomass, below-ground biomass, dead wood and forest floor litter was calculated for each site. For both sites approximately 64% of the total carbon stock was in live above-ground biomass and attached dead branches; 13% was in live roots, 16% was in stems, live and dead stumps, dead roots and woody debris and the remaining 7 % was in forest floor litter (Oliver et al., 2011). Carbon in the forest floor, stumps, debris and roots that remained after thinning amounted to 85 tCO_2e/ha at Kinleith and 104 tCO_2e/ha at Tarawera. This emphasises the result that thinning can have on carbon stocks, with much of the carbon lost or held up in the resulting debris. At age 15 in Kinleith, the carbon accumulation average in above-ground carbon was 14.5 tCO_2e/ha/yr and 18.2 tCO_2e/ha/yr for age 16 in Tarawera. When both live root biomass and dead organic matter pools were included, the average increased to 23 tCO_2e/ha/yr and 28 tCO_2e/ha/yr at ages 15 and 16 respectively (Oliver et al., 2011).

A stand of radiata pine aged from 2 to 22 years in Kaingaroa Forest was studied to characterise dry matter of above-ground biomass. (Madgwick et al., 1977). The study found that gross annual increment of dry matter (related to carbon accumulation) was greatest between ages 10-22 years at 24.6 t/ha, in comparison to 21.7 t/ha between ages 4-8 years. This suggests that carbon sequestration is most relevant during mid-rotation however, it emphasises that the early years are still important.

A study in Spain focused on effects of different silvicultural regimes on carbon sequestration for even-aged stands of radiata pine. For above-ground tree biomass the mean annual carbon sequestration ranged from 9.3 tCO_2e/ha/yr to 16.2 tCO_2e/ha/yr. At a stand level the carbon sequestration in total above-ground biomass in the whole rotation ranged from 264 tCO_2e/ha to 514 tCO_2e/ha. The lowest measurements had the lowest initial stocking of 1100 stems/ha, the worst site quality and a high thinning intensity of 35%. In comparison the largest measurements had the highest initial stocking of 2000 stems/ha, the best site quality and lowest thinning intensity of 15% (Balboa-Murias, Rodríguez-Soalleiro, Merino, & Álvarez-González, 2006). The biomass compartment with the highest carbon stock was the stem wood, which represented 74% of the total aboveground biomass, the bole section had the largest amounts of carbon stored (Balboa-Murias et al., 2006). When considering a higher initial stocking the total above-ground biomass had carbon pools that were 9-12 % larger than lower stockings(Balboa-Murias et al., 2006). They found that site quality was reported to have the biggest difference in carbon pools in aboveground biomass, when stocking and thinning remained constant, a 59% difference could be observed (Balboa-Murias et al., 2006). Similarly, an unthinned stand stocked at 2200 stems/ha was compared to a thinned stand to 160 stems/ha in central North Island, New Zealand (Beets & Pollock, 1987). It found that the unthinned and higher stocked stand had 230 t dry matter/ha compared to only 75 t dry matter/ha in the thinned and lower stocked stand. The dry matter increment peaked at age 12 years at 48 t/ha/year for the unthinned stand.

2.7. Soil Carbon:

A study of 26-year-old radiata pine on an agroforestry site near Rotorua examined the impacts of carbon cycling. The results determined that at 400stems/ha organic soil C at a depth of 0-0.5m was 286 tCO_2e/ha (Scott et al., 2006). The carbon accumulation in the forest floor during the first rotation was 33 tCO_2e/ha (Scott et al., 2006). Another central North Island radiata pine experiment aged 23 also studied soil carbon content. It found the soil carbon content averaged 393 - 451 tCO_2e/ha for a depth of 1 meter (Oliver et al., 2004). Parfitt et al. (1997) studied the soil chemistry of a 20-year-old radiata pine stand in Palmerston North. They found 151 tCO_2e/ha of organic carbon within a soil depth of 0-0.2m. However, these estimates are based off North Island studies where the soil type often differs from that of Canterbury soils. There is fewer studies done in Canterbury soils. Davis (2000), conducted a soil study done under radiata pine aged 25 at Teviotdale, Canterbury. It showed that at a soil depth between 0-0.3 meters the carbon content was measured at 266 tCO_2e/ha (Davis, 2000). A study measured soil carbon under a 10-year-old radiata pine in the Otago region. The results gave a carbon content value of 140 tCO_2e/ha for a soil depth of 0-0.1 m (Davis, 1994). Another study conducted in four planted sites across the Canterbury region provide average C stock totals of soil carbon (Colenso et al., 2020). However, these sites had been planted with native trees not radiata pine. The values generated in this study ranged from 409 tCO_2e/ha to 588 tCO_2e/ha for a soil depth of 0-0.3 m. (Colenso et al., 2020). Therefore, the total range of soil carbon values across New Zealand under radiata pine is highly variable and ranges between 55 and 451 tCO_2e/ha.

Soil carbon following harvesting, providing some slash remained had either very small changes or no effect at all to the soil carbon balance (Johnson, 1992). When site preparation occurs there is generally a net loss of soil carbon depending on the size and intensity of the disturbance (Johnson, 1992).

The addition of fertiliser and presence of particular nitrogen fixers was found to increase soil carbon, resulting in a long term improvement in site productivity as well as sequestering soil carbon (Johnson, 1992). Fertiliser increased primary productivity, with higher fertilization levels there were more pronounced results; a study done in New Zealand by Baker, Oliver, & Hodgkiss (1986), found that an application of mixed fertilizer initially on radiata pine caused a statistically significant increase in soil carbon by 115% in the top 5cm and a smaller non-significant difference of 6% in the top 1 m of soil.

2.8. Current Carbon Fraction and Ratio:

A carbon fraction is applied to dry matter biomass to estimate the carbon stock in a forest. The default carbon fraction used in New Zealand is 0.50 g C g^{-1} dm. Beets and Garrett (2018), developed New Zealand carbon fractions for radiata pine biomass components to improve the accuracy of carbon stocks estimates. The study used a subsample of tree components from 14 sites across New Zealand. The average carbon fraction was calculated for needles, branches, cones, stem wood, roots and stem bark. These were 0.514, 0.507, 0.519, 0.498, 0.501, and 0.539 g C g^{-1} dm respectively. The results indicate that the current default carbon fraction slightly underestimates carbon stocks. If carbon fractions were derived from biomass studies instead of the default fraction, then it is estimated that carbon stocks for the radiata pine estate will increase by 1%. This will consequently increase the accuracy and decrease the bias of the national reporting commitments under the Kyoto Protocol and UNFCCC (Beets & Garrett, 2018). Oliver et al. (2011) found that the average weighted carbon concentration for mid-rotation above-ground live tree biomass was 51.4-52 g/100 g of dry matter. This further suggests that the default carbon fraction value of 0.50 g C g^{-1} dm is underestimating carbon stocks in New Zealand (Oliver et al., 2011; Beets & Garrett, 2018).

Beets et al. (2007) studied the effect of stand age and environmental factors on the root/shoot ratio of radiata pine. Root/shoot ratios are an acceptable method for estimating root biomass when estimating carbon stocks (IPCC, 2003). Measuring the biomass of root systems is rarely done in biomass studies of radiata pine as it is difficult and expensive to extract. Studies that do extract root biomass measurements often differ significantly in the sampling methods, the soil depths assessed, and the root size fractions measured.

Beets et al. (2007), collaborated a collection of radiata pine biomass data from a wide range of sites with differing fertilisation and irrigation treatments and ages to derive an average ratio. They found that nine studies considered suitable for collaboration for this paper. The collaborated data included 484 trees ranging from 0-42 years old where the ratios ranged from 0.12-0.58. The average ratio was 0.19. However, they recommend that this ratio is increased to 0.20 due to an inevitable loss of fine root biomass in root extraction.

3. Methods

Site Description

Data was collected over the summer of 2020/2021 from a flat 7.5 ha site located in Rolleston, an area within the Canterbury region of New Zealand (latitude 43º 37.2' S and longitude 172º 20.4' E). The site was planted with *Pinus radiata* in 2005 so was measured at 15 years old. The site is approximately 50 m above sea level, and the mean annual rainfall is 645 mm with a monthly range between 41 mm and 66 mm. The average annual temperature is 16.7 °C.

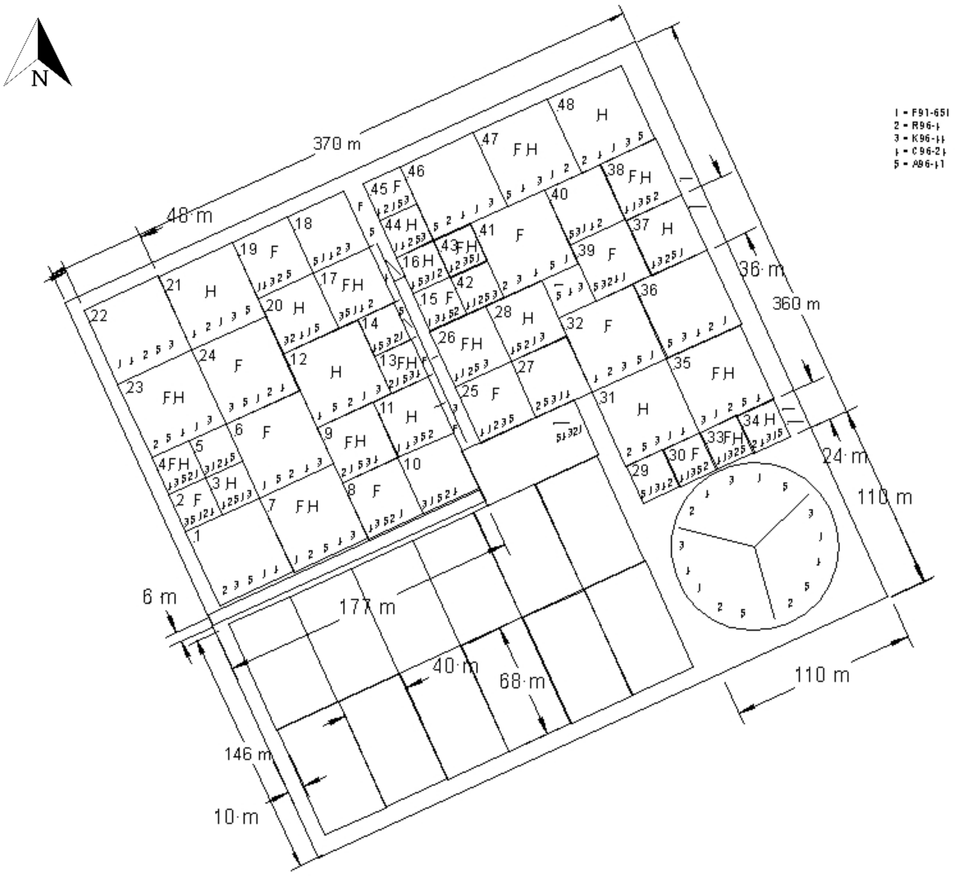

Figure 1: Plot layout for trial located outside of Rolleston in the Canterbury region. The numbers represent plot number, where the large, medium and small plots correspond to 625, 1250 and 2500 stems/ha respectively. F= fertiliser applied and H= herbicide applied.

Experimental Design

The experiment consists of 48 permanent plots arranged in a randomized complete block factorial split-split design with an arrangement of factors within each of the 4 complete blocks (Mohan, Mason, & Bown, 2020). The main treatment applied and the one primarily assessed in this study is three differing stockings of 625, 1250 and 2500 stems/ha and for each stocking the plot size varied from 0.25, 0.13 and 0.06 ha respectively (Lasserre, Mason,

& Watt, 2008). The first split includes four levels of fertilization and weed control applications (no treatments, both treatments, only fertilizer and only weed control). The second split occurred where five different clonal genotypes of P. radiata were assigned randomly to all plots. The factors are specified to more detail below:

1. Stocking (625, 1250 and 2500 stems/ha)
2. Weed competition (yes/no)
3. Fertilisation (NPKS + trace elements, yes/no)
4. 5 clones with pre-selected wood properties
    a. Low microfibril angle, high basic density
    b. Low microfibril angle, low basic density
    c. High microfibril angle, high basic density
    d. High microfibril angle, low basic density
    e. Extremely high microfibril angle, extremely low density
5. Wind sway (yes/no) for clones a and d

Sampling

Equal numbers of destructively harvested trees were obtained from all 48 permanent plots. In total 192 trees were harvested, however only 1 was used for this biomass study due to time constraints and the remainder was used for a separate wood quality study. To begin the process, a walkthrough of each of the plots was done where trees which were going to be destructively harvested were selected and marked on a map and spray-painted with their corresponding clone number. The selection criteria were 4 trees were selected from each of the 48 plots, one for each of the clonal genotypes 1, 2, 3 and 4 (no bound trees).

Previous measurements

Recordings of both height and diameter have been made by previous students most years for trees in the experiment since planting. This is excluding years 2006, 2007, 2011 and 2013, where measurements were not taken. The total number of measurements recorded over time for the site is 32,640. This dataset will be referred to as the "Rolleston dataset". The Rolleston dataset was used as the input for the localised individual tree biomass model. This enabled a prediction of carbon sequestration to be done through time for each of the plots which had differing silvicultural treatments.

Destructive Sampling for biomass assay

The standing selected trees were measured at 1.4 m and the over-bark diameter at breast height (DBH) was then recorded and marked using a tape and spray paint. If there was a defect at this point an average diameter was taken from slightly above and below this point. Following this, trees were then felled close to ground level using a chainsaw. Once felled, a measuring tape was used to measure the total tree height from the 1.4 m line (which was accounted for after) to the tip of the tree stem and then the height to the base of the living canopy. Each tree was then separated into sections labelled stem, branch, cones, foliage and bark. For each resulting whorl the height and diameter over stubs (DOS) was measured and recorded. A portable balance and bins were used to weigh the total fresh weight of all sections individually. The foliage was weighed to include both twigs less than 1cm in diameter and living foliage, where it was then subdivided into old foliage and new foliage, cones and small branches each weighed separately. Markings were made on the stem with spray paint beginning at 0.3 m and then upwards from 1.3 m at every 2 m point, to indicate where to cut the stem into disks for the separate wood quality study. If a marking fell upon a whorl another location above or below was selected and the height recorded.

The whole stem was then weighted. Stem disks with widths of 5cm were then cut at the markings and bark removed using chisels so that subsamples of both bark and stem could be immediately weighed fresh and then taken back to the laboratory for further weighing in paper bags. A subsample of each of the remaining were then also places in paper bags and weighed fresh in the field and taken back to the laboratory for further dry weight analysis.

Subsamples were then dried in the oven at 70 °C degrees until a constant mass was reached in regard to the last value measured and the dry mass of each section was calculated. The calculation of biomass was then done as seen in equation 1. Where TDW: total dry weight, TFW: total fresh weight, SDW: sample dry weight and SFW: sample fresh weight.

$$TDW = TFW * SDW/SFW \qquad (1)$$

List of samples collected

- 'Old' foliage sub-sample
- 'New' foliage sub-sample
- Branch sub-sample
- Stem sub-sample of 5cm disk
- Cone sub-sample

List of materials required

- *Secateurs*
- *Chainsaw*
- *Clipboard*
- *Paper and pencil*
- *Diameter tape*
- *30-meter tape*
- *Gloves*
- *Helmet with visor and earmuffs*
- *Chaps*
- *Plastic bags*
- *Paper bags*
- *Hitman*
- *Tree tap*
- *Saws*
- *Small balance with a battery included*
- *Large balance*
- *2 tarps (3 x 3 m)*
- *Bins*
- *Bark gauge*

Biomass Collaboration

The majority of this study was based on previously collected biomass studies done in the Canterbury region. Authors of published and unpublished studies were contacted to see if they would share their biomass data to collaborate for this study. In total data was combined from 5 different sites around the Canterbury region that equalled 476 trees. The locations of these sites were Rolleston, Dalethorpe, Dunsandel, Ahuriri and Lincoln. The data ranged in stockings, treatments and ages. The destructive sampled trees varied from age 1 to age 15. However, some studies lacked information, such as the stocking, which is a limitation of this analysis.

Independent Biomass Model Construction

To begin making the biomass model, explanatory and response variables were transformed to new variables by Box-Cox transformation to make distributions of the variables as close as possible to a normal distribution. A Box-Cox transformation is shown in equation 2 below, where V is the original variable, Vt is the variable after transformation and λ is the parameter in this transformation. Variables were transformed with a value of λ that was not equal to zero.

$$Vt = \begin{cases} \frac{V^{\lambda}-1}{\lambda} & \lambda \neq 0 \\ lnV & \lambda = 0 \end{cases} \qquad (2)$$

A linear mixed effect model was used to establish a total biomass model (lme) where experiment site was a random factor. The variable "d2ht" (where d2ht is equal to DBH x DBH x Height) was chosen as a possible explanatory variable. The root mean square errors (RMSE) and coefficients of determination (R^2) were then examined. Model bias and the residual distribution homogeneity were assessed in the residual plots with loess regression lines overlaid on the plots. The normality of residuals was also checked in residual histograms and by using a Shapirio-Wilk test.

After developing the total biomass model, it could then be applied to predict carbon sequestration for the Rolleston dataset by applying it to height and DBH measurements of individual trees at each measurement age. Above-ground carbon was assumed to be 50% of the above-ground biomass. Below-ground carbon was estimated as 20% of the above-ground carbon based on Beets et al (2007). Literature suggests 50% may slightly underestimate above-ground carbon however only by approximately 2% (Oliver et al., 2011; Beets & Garrett, 2018). The C_Change Model also uses 50% as a carbon fraction.

Statistical Analysis

A mixed effect model was created for analysing CO_2 stored in each plot in the Rolleston experiment. As the experiment has the treatments split by block and is a split-plot design, both block and stocking were random effects. Total carbon was the dependent value, and stocking, fertiliser and herbicide were independent variables. Linear models were fitted to logarithmically transformed data. A model was first made using a subset of the data at age 15 and another model was made using a subset of the data at age 5 years; to determine if there were differences through time. Type 3 Anova tests were run for each of the models. The threshold for significance was α=0.05. Factors greater than 0.05 were not considered significant and they were eliminated from the model in a stepwise fashion. Summary tables were made to show only the factors and interactions that were statistically significant. For the interactions and factors with more than two categories that were significant, a pairwise comparison test was run to determine which group differences are statistically significant.

Forecaster Analysis

Growth and carbon yield of the Rolleston tree crop for each treatment beyond the age of 15 years was estimated using the 300 Index growth and yield model. Outputs used were log grade yield and carbon yield, where the carbon yield was generated using the C_Change model developed by Beets et al. (1999). Six treatments were analysed in total, each of the three stockings with and without weed control. Inputs for Forecaster were determined from analysis in R and calibration runs on Forecaster, this was done separately for each of the silvicultural regimes. The inputs – Basal Area (BA), Mean Top Height (MTH), Diameter at Breast Height (DBH), Site Index (SI) and Correlation of Variations (CV) were all calculated using the dataset on R. Calibration runs were done on Forecaster to estimate the site 300 Index. The Function Set used in the Forecaster analysis is listed in Appendix 1.

Three regimes were analysed for each of the six treatments:

- Thinning to 625 stems/ha immediately and harvesting between rotation ages 20-60 years.
- No thinning and harvesting between rotation ages 20-60 years.
- Plant and leave with no thinning or harvesting, grow to age 60 years.

Economic Analysis
An economic analysis was done using Microsoft Excel. A net cash-flow analysis was completed for each regime and generated a maximum Land Expectation Value (LEV).

Cash flow input assumptions:

- Interest rate: Assumed as a base-case of 8%.
- Log yields: Generated using Forecaster for rotation ages between 20 and 60 years.
- Log grades: Predicted by Forecaster and are listed in Appendix 2.
- Carbon yields and bands: The first 15 years of carbon was based on the carbon model generated in R, using actual measurements from the stand. The remaining years used Forecaster carbon yield predictions estimated by the C_Change model. Five-year carbon age bands have been used in this analysis, which is option 3 under the Ministry of Primary Industries' Emission Trading Scheme regulations (2021d).
- Log and carbon prices: The base-case carbon price was $50/t based upon current carbon prices at the time of analysis (CommTrade, 2021). Log prices were assumed using a base case, derived using a 12-quarter moving average of recent log prices found on MPI, (June, 2021) on a $/tonne basis. These are listed in Appendix 2.
- Harvesting and transport costs: Harvesting costs were calculated using the equation: $30/piece size $^{0.6}$ (Prof. Rein Visser, pers. comm). Transport costs were generated using a base rate of $20/m^3 at age 20. Transport rate decreased by $0.30 for every 1-year increase in rotation age, as piece size increased.

- Additional assumptions: Further inputs for each regime are shown in Table 1. Note that thinning occurred immediately for only stockings 1250 and 2500 stems/ha as 625 stems/ha was the target final stocking.

Table 1: Inputs used for financial cash flow analysis.

OPERATION	ITEM	COST
Establishment	P. radiata planting stock	\$0.70/seedling
	Planting Rate	\$0.28/tree
	Land Preparation (Weed Control)	\$300/ha treated @ pre-planting \$150/ha @ yr1 625 stems/ha \$180/ha @ yr 1 1250 stems/ha \$210/ha @ yr 1 2500 stems/ha
Silviculture	Thinning to Waste	\$0.60/stem removed + \$70/ha entry. To occur immediately at age 16 years.
Harvesting	Transportation	\$20/m^3 - \$0.30/m^3 for each additional rotation age year
	Harvesting	\$(30/PieceSize^0.6)/m^3
Annual Payments	Forestry and Carbon Overheads	\$95/ha
	Fire Insurance	\$2/ha

4. Results

4.1. Carbon Differences:

Effects of stocking and weed control on carbon sequestration through time are highlighted in Figure 2. Higher stocking resulted in more carbon sequestered through time. An ANOVA test was carried out to determine if these differences in silvicultural treatments actually had a statistically significant effect on total tree carbon. Table 2 shows the ANOVA outputs for age 15. Stocking and weed control have a p-value of <2.2e-16 and 1.06e-05 respectively, therefore have a statistically significant effect on above-ground tree carbon. Carbon sequestration was 47 % more at 2500 stems/ha compared to 625 stems/ha at an age of 15 years. Fertilizer and interaction effects were also analysed, however, were not considered statistically significant. A pairwise comparison was done for stocking, seen in Table 3. The results suggest that each of the three stockings, 625, 1250 and 2500 stems/ha have statistically different above-ground carbon values.

An ANOVA was also done at age 5 to determine if silvicultural differences affected carbon differently in earlier years. The greatest difference in carbon sequestration rate between stockings occurred between ages 3 and 5 years where 2500 stems/ha had 3.5 times the carbon of 625 stems/ha. The results highlighted in Table 4, show that both stocking and weed control were statistically significant at age 5 in their effects on C storage. However, an interaction effect between stocking and weed control use was also statistically significant, which was not present in later years. This interaction is highlighted in Figure 2. The presence of an interaction effect in earlier years is likely explained due to different rates of canopy closure due to the varying stockings. Nearing or complete canopy closure reduces grass and weed competition. Quicker canopy closure occurs at higher stockings; hence the effect of herbicide is lesser on higher stocked stands than in stands planted at lower stockings with slower canopy closure and hence herbicide will have more of an effect.

The effect of clone type on above-ground carbon through time is shown in Figure 3. It suggests that Clones 1 and 3 sequestered carbon at a greater rate than the other clones. However, this result should be taken with caution. There is potential that the differences between clones is markedly overestimated, as the experimental design did not include buffer strips between clones. This could have resulted in reduced or enhanced growth between clones; therefore, the results should not be taken as representing differences between large mono-clonal stands in an unbiased manner. Because of this the effects of clones were not further analysed.

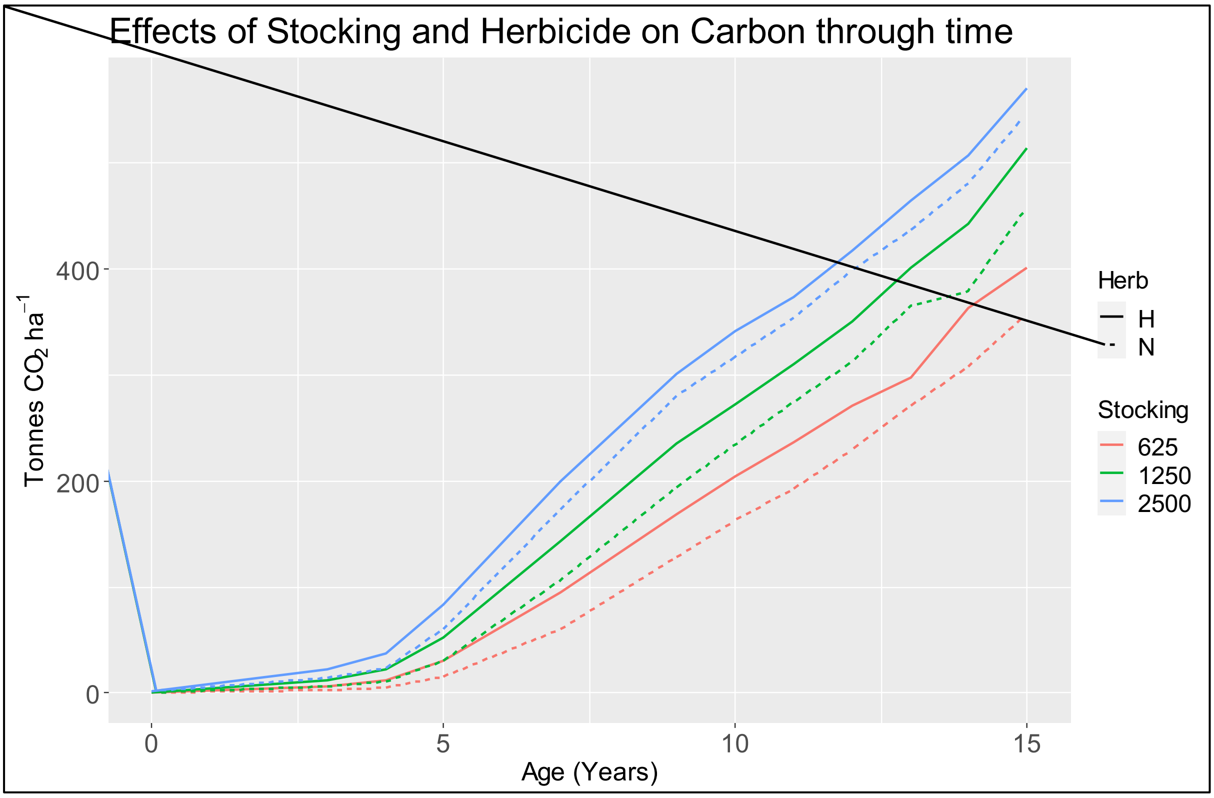

Figure 2: Effect of stocking and herbicide use on the total tree carbon stored between ages 0-15 years.

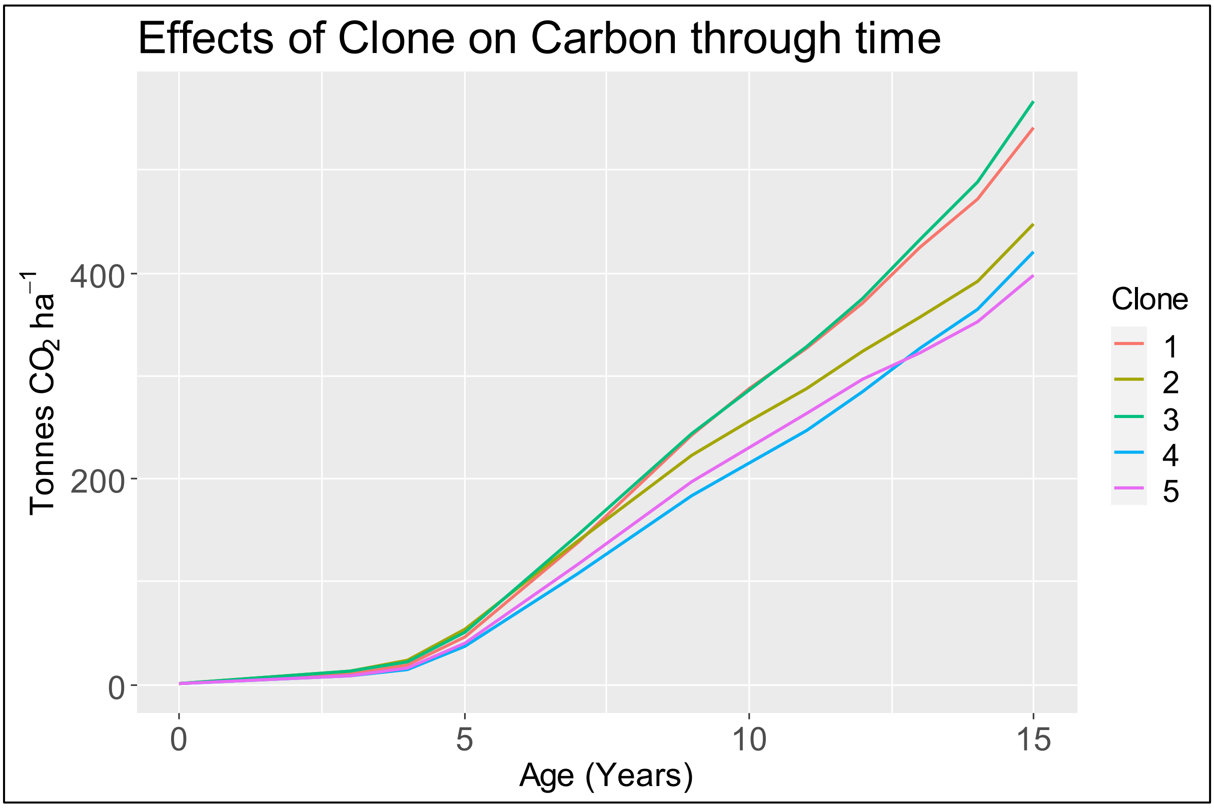

Figure 3: Effect of clone on the total tree carbon stored between ages 0-15 years.

Table 2: ANOVA output from R. Factors were only included if significant at age 15.

Age 15 ANOVA Significant Differences			
Factor	**Chisq**	**DF**	**P-value**
Stocking	256.149	2	< 2.2e-16
Herbicide	19.401	1	1.06e-05

Table 3: Pairwise comparison test for stocking effect at age 15.

Age 15 Pairwise Comparison Test						
Stocking	**Emmean**	**SE**	**DF**	**Lower CL**	**Upper CL**	**Group**
625	316	6.66	20.9	302	330	a
1250	406	6.66	20.9	392	419	b
2500	466	6.66	20.9	452	480	c

Table 4: ANOVA output from R. Factors were only included if significant at age 5.

Age 5 ANOVA Significant Differences			
Factor	**Chisq**	**DF**	**P-value**
Stocking	967.3752	2	< 2e-16
Herbicide	252.1540	1	< 2e-16
Stocking:Herbicide	6.7113	2	0.03489

Table 5: Pairwise comparison test for stocking effect at age 5.

Age 5 Pairwise Comparison Test						
Stocking	**Emmean**	**SE**	**DF**	**Lower CL**	**Upper CL**	**Group**
625	19.2	1.09	10.7	16.8	21.6	a
1250	34.5	1.09	10.7	32.1	36.9	b
2500	59.7	1.09	10.7	57.3	62.1	c

Table 6: Pairwise comparison test for the stocking:herbicide interaction effect at age 5.

Age 5 Pairwise Comparison Test							
Stocking	**Herb**	**Emmean**	**SE**	**DF**	**Lower CL**	**Upper CL**	**Group**
625	N	12.6	1.43	23.8	9.62	15.5	a
625	H	25.7	1.43	23.8	22.78	28.7	b
1250	N	25.1	1.43	23.8	22.13	28	b
1250	H	43.8	1.43	23.8	40.88	46.8	c
2500	N	50.1	1.43	23.8	47.1	53	d
2500	H	69.4	1.43	23.8	66.44	72.4	e

4.2. Carbon Comparison:

A comparison has been made of carbon sequestration rates from the results of this study and the current Canterbury ETS default look-up table and Forecaster (C_Change model) estimates. The carbon comparison only compares rates between ages 0-15 years. The carbon model developed in this study could only estimate carbon values where data was present in that year. Therefore ages 1, 2, 6 and 8 have no estimates and predictions only go until age 15. A comparison was made for each of the three stockings when weed control was applied, shown in Figures 4 and 5. For this comparison we are assuming that the developed localised individual tree model is most accurate as it is based on actual measurements.

The ETS carbon values appear to be markedly lower than localised carbon model estimates based on biomass assessments, especially at higher stockings. At 1250 stems/ha at age 10 years, the ETS default yield tables give an estimate of 147 t C/ha or 54% less than the measured estimate. This difference increases to 328 t C/ha or 63% less at age 15 years. The underestimation in carbon rates supports the suggestion that the default yield tables were designed to be conservative. The underestimation could be due to the fact that the look-up table values were derived from the average growth for the Canterbury and West Coast regions; hence a much wider area than what the localised carbon model is based on, resulting in lower accuracy. Figure 4 highlights that where the carbon measurement was made at a lower stocking (625 stems/ha), the ETS look-up tables were most similar. At age 10 years the look-up table estimate was only 80 t C/ha or 38% less than the localised measurements.

For each of the stockings, the Forecaster (C_Change) values appear to overestimate the carbon sequestered in earlier years, seen in Figure 5. From age 9 onwards the carbon sequestration slows and the carbon appears to have peaked in terms of sequestration rate. The Forecaster values suggest that carbon sequestration is particularly high and important in earlier years compared to later years. In comparison, the localised measurements had a steeper trajectory than the Forecaster predictions, especially from age 7 onwards. This suggests that the rate of carbon sequestration peaks around mid-rotation (assuming harvest at 28 years) and that the importance of carbon sequestration continues on into later years. This is most similar to what other literature suggests where the rate of carbon sequestration peaks at mid rotation. The different in estimates will most likely be because Forecaster uses C_Change which is a stand-level model in comparison to an individual tree-level model to predict values.

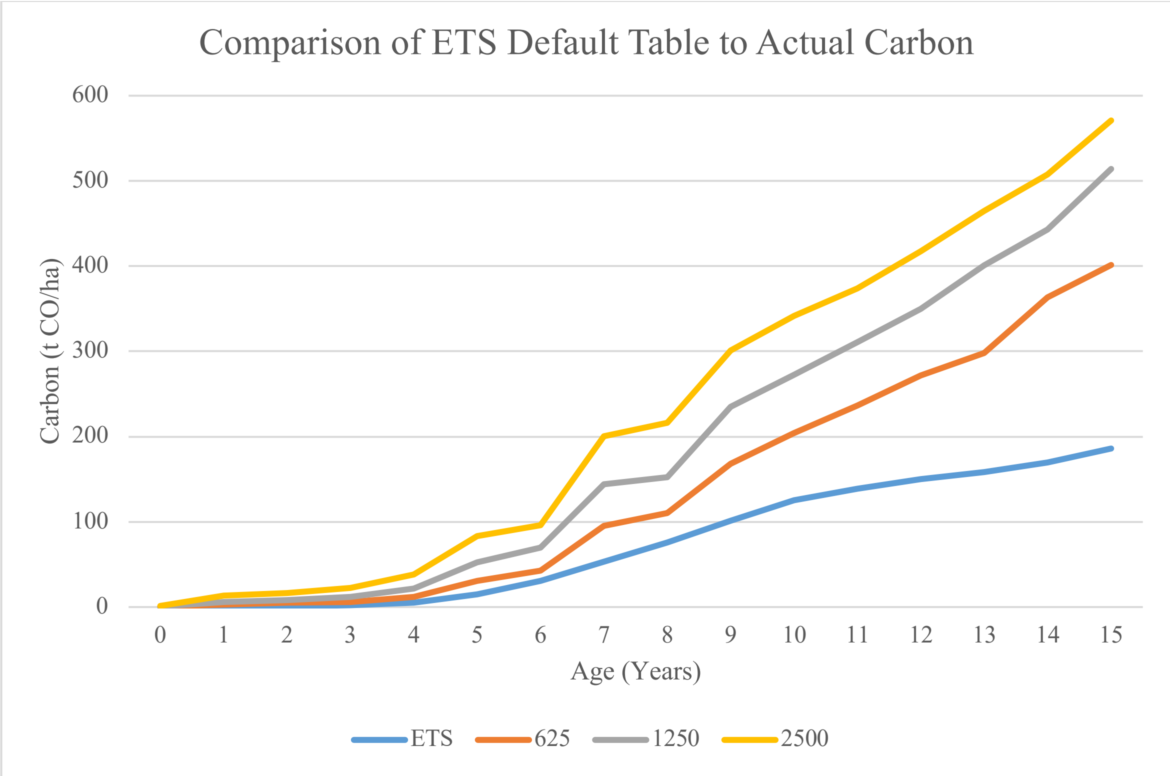

Figure 4: Comparison of carbon predicted by actual model and ETS default Canterbury yield table.

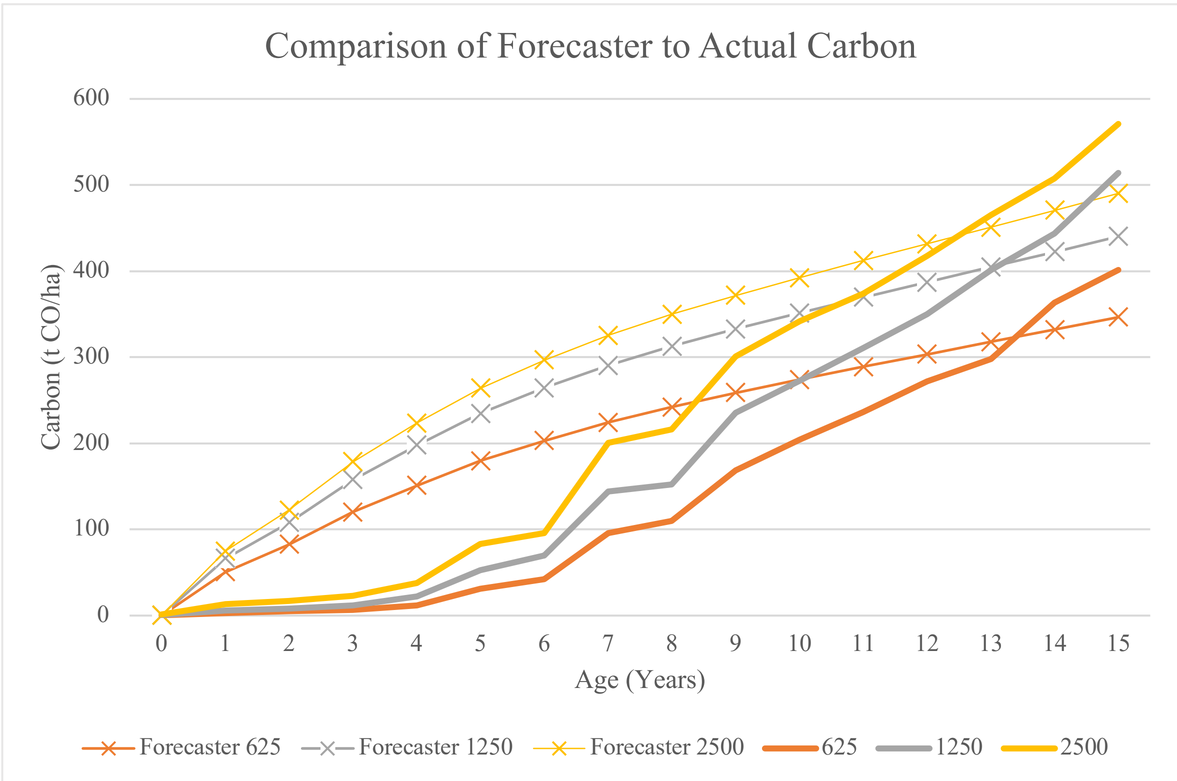

Figure 5: Comparison of carbon predicted by Forecaster (C_Change) and the localised model.

4.3. Model Comparison:

Moore (2010) developed a series of tree models to predict above-ground biomass for radiata pine trees in New Zealand. Of the models that were developed models 6 and 7 appeared to give the best results and hence were applied to the Rolleston dataset for comparison. The residual distribution of model 6 and 7 is shown in Figure 6 and 7. It shows that for both models the variances on predictions are quite wide. However, for the Dalethorpe site the distribution of residuals suggests that the model fits well. Overall, both models do a relatively good job considering the models was built using random effects, yet the random effects were not the same as those in our model. Our final model has the advantage of having each of the experiments (sites) as random effects therefore much of the variance from the experiments (sites) has been removed resulting in the better residuals. Moore's model does not have this advantage so should not be directly compared to our final model. Overall Moore's models would be considered applicable for some Canterbury sites, such as Dalethorpe. The comparison shows that models built with data from the localised area have better accuracy as more of the variance can be accounted for.

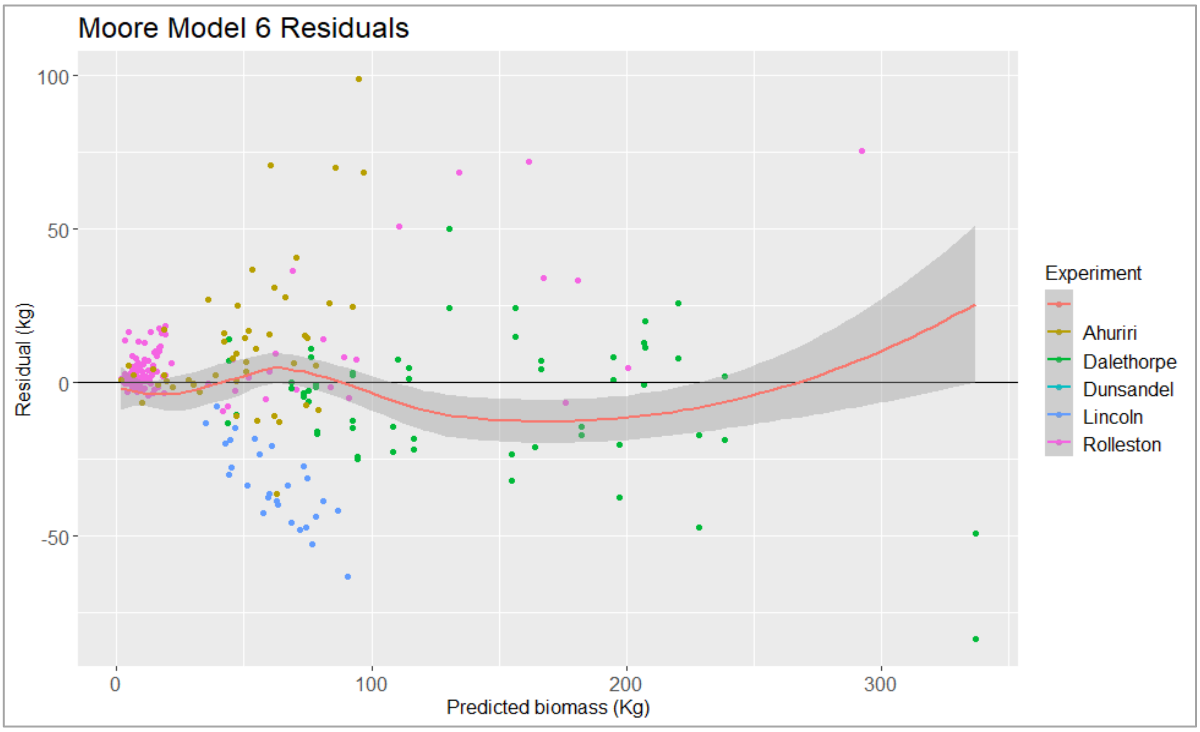

Figure 6: Distribution of residuals for Moore's Model 6.

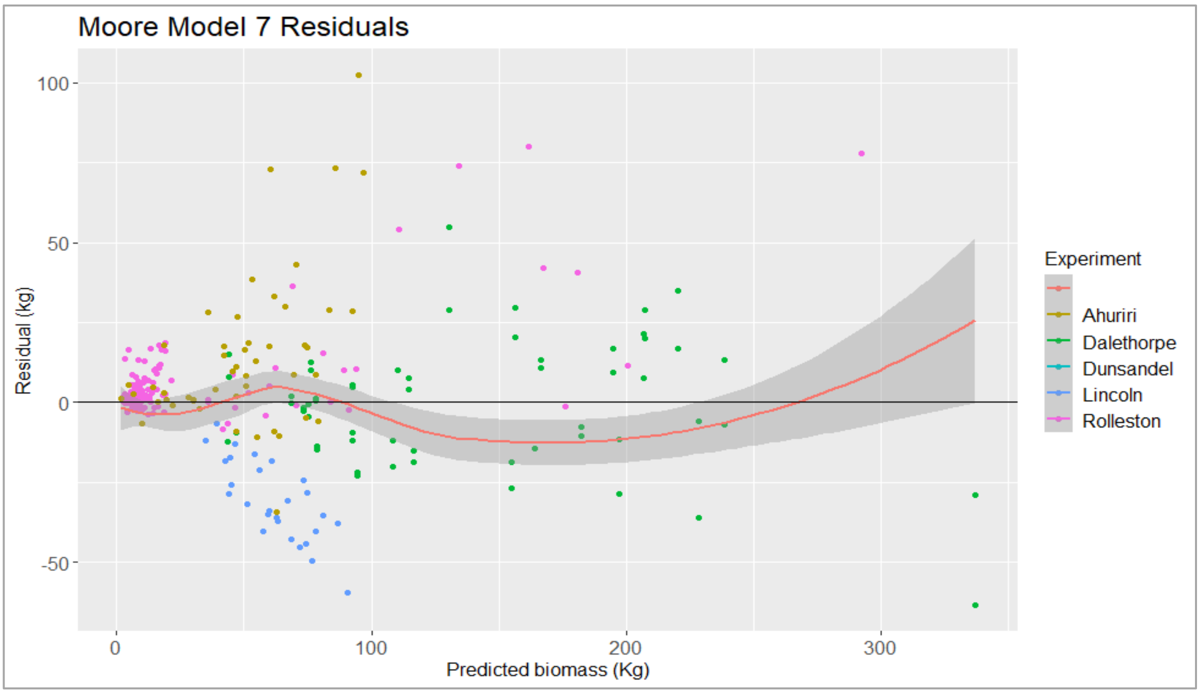

Figure 7: Distribution of residuals for Moore's Model 7.

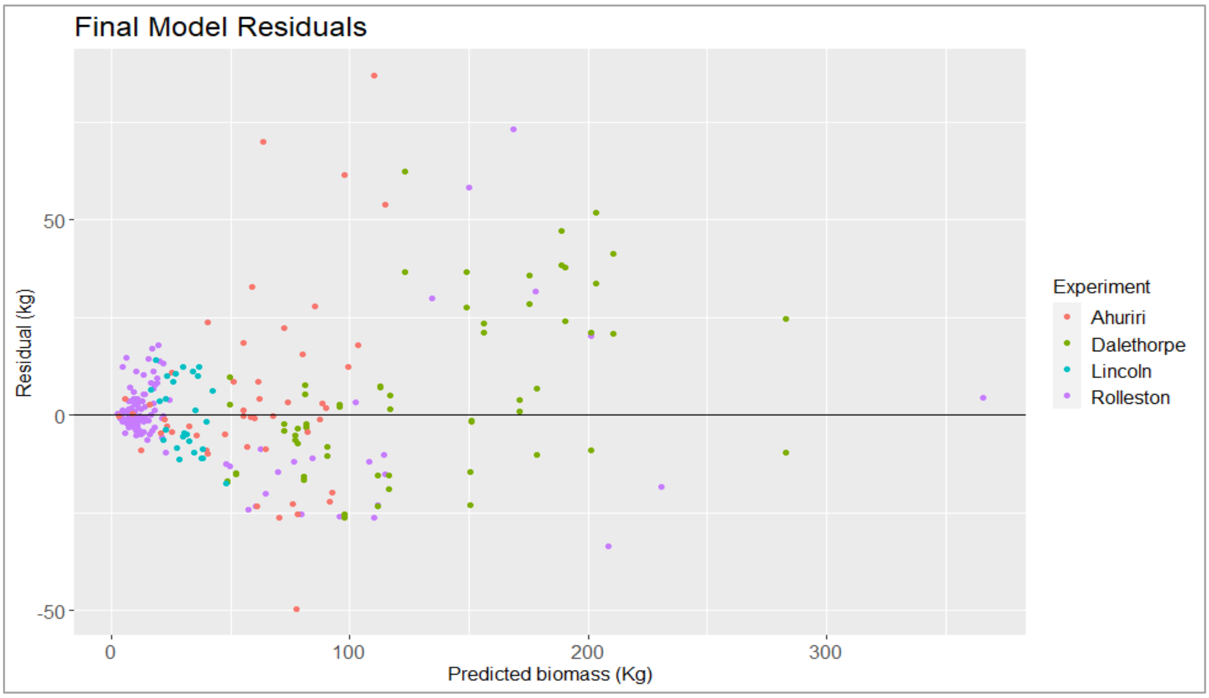

Figure 8: Our final model distribution of residuals.

4.4. Economic Analysis:

Initial results of the financial analysis are shown in Table 7 and Figures 9 and 10. These indicate that the most profitable regime returning the highest LEV was the no-thinning, harvest at optimum rotation age regime. The maximum this regime returned was $19,750/ha at age 44, this was at 2500 stems/ha and with no herbicide applied. Higher stockings resulted in larger biomass and therefore carbon stocks within the stand. Thinning stands appeared to reduce profitability in higher stocked stands (1250 and 2500 stems/ha). Thinning would increase the overall quality of log grades produced however at the expense of carbon stocks. If thinning was to occur, then the regime should be focused on maximising log grade profitability rather than carbon profitability. With a plant and leave regime (permanent forest) and harvest with no thinning regime, the LEV increased by an average of 32% and 22% respectively moving from lowest stocking to highest stocking. In contrast the harvest with thinning regime decreased the LEV by an average of 12% when moving from a lower stocking to a higher stocking (Figures 9 and 10).

Allowing for a lengthened rotation age enabled more accumulation of carbon sequestration and was therefore more profitable. This was particularly the case for permanent forests in a plant and leave regime where Figure 12 shows there was no peak in LEV within the initial 60 years analysed. LEV increased despite carbon sequestration slowing and the time value of money. This would indicate that for permanent forestry a much longer rotation age is probably financially optimum.

To highlight the importance of carbon in forest profitability, an analysis was done where carbon revenue was removed, see Appendix 3. For each of the regimes evaluated, the only positive LEV occurred at 625 stems/ha and with harvesting between ages 31 and 39 years. All other regimes returned a negative LEV. A further analysis was done where the carbon price was set at $98/t as per the MfE (2021c) indicative trigger price set for 2025. This shows that with the most profitable regime, LEV is capable of reaching $39,622/ha, see Appendix 4. Carbon revenue has therefore become a key player in rotational and permanent forestry.

Table 7: Summary of Land Expectation Values (LEVs) under different regimes and silvicultural treatments.

Weed Control	Stocking	Thin and harvest	No thin and harvest	Plant and leave
Weed control	**625**	$ 16,853.58	$ 16,853.58	$ 13,477.64
	1250	$ 15,379.60	$ 18,111.44	$ 15,681.99
	2500	$ 14,084.71	$ 19,265.90	$ 16,819.75
Without Weed control	**625**	$ 15,164.38	$ 15,164.38	$ 12,320.91
	1250	$ 14,682.32	$ 17,111.36	$ 14,753.31
	2500	$ 14,486.80	$ 19,750.06	$ 17,219.12

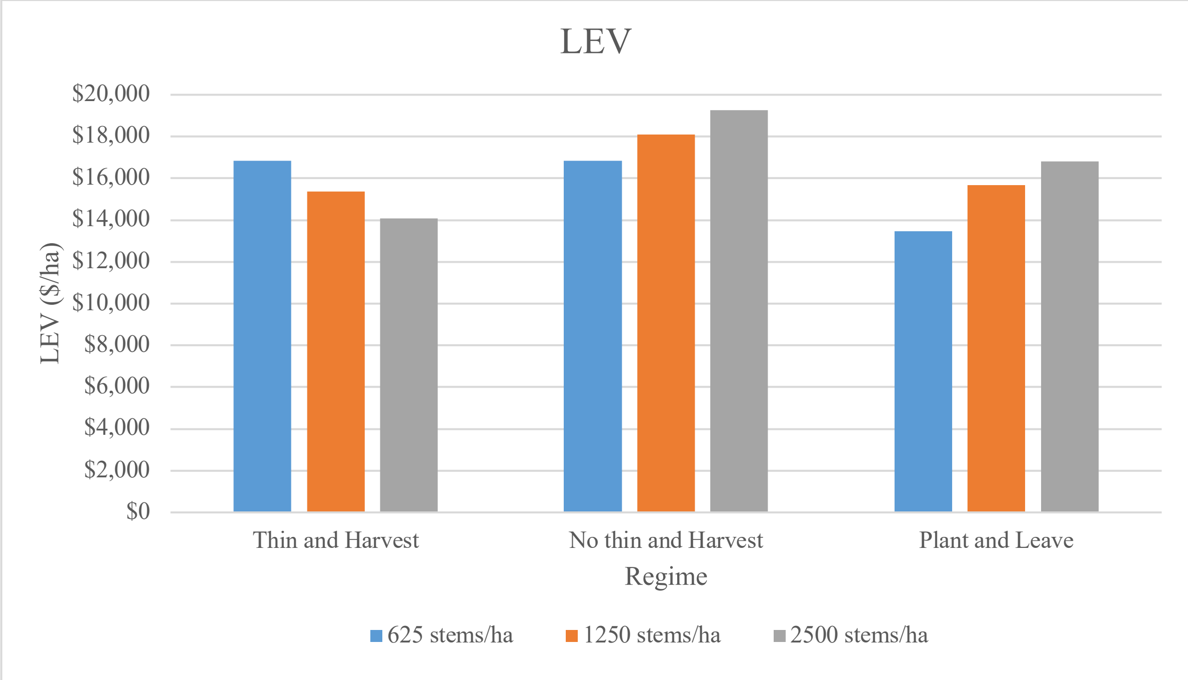

Figure 9: Maximum LEV of regimes with different stockings and weed control applied.

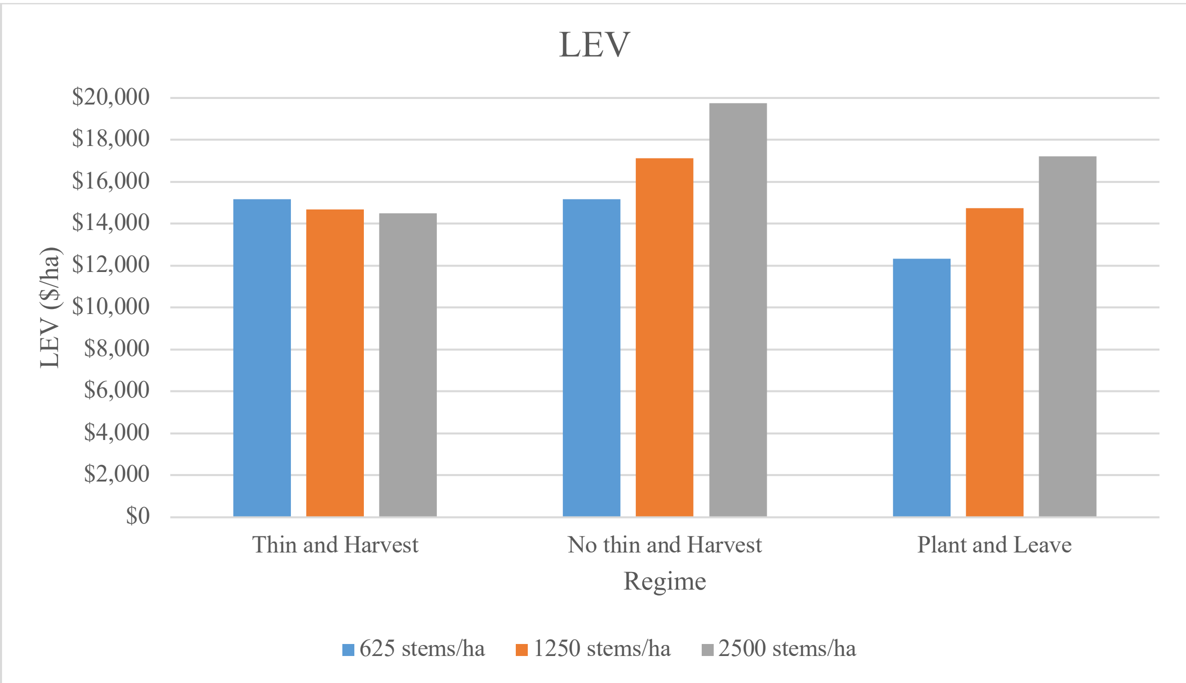

Figure 10: Maximum LEV of regimes with different stockings and no weed control applied.

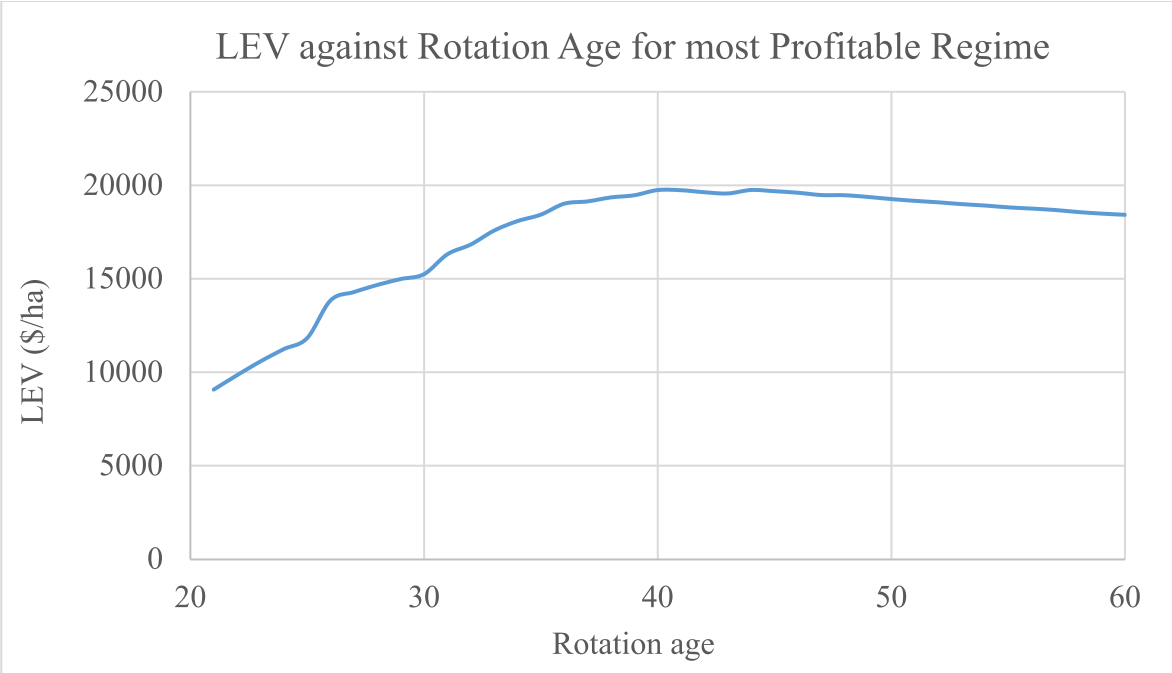

Figure 11: LEV of most profitable regime (2500 stems/ha with no thinning and harvest at age 44) against rotation age.

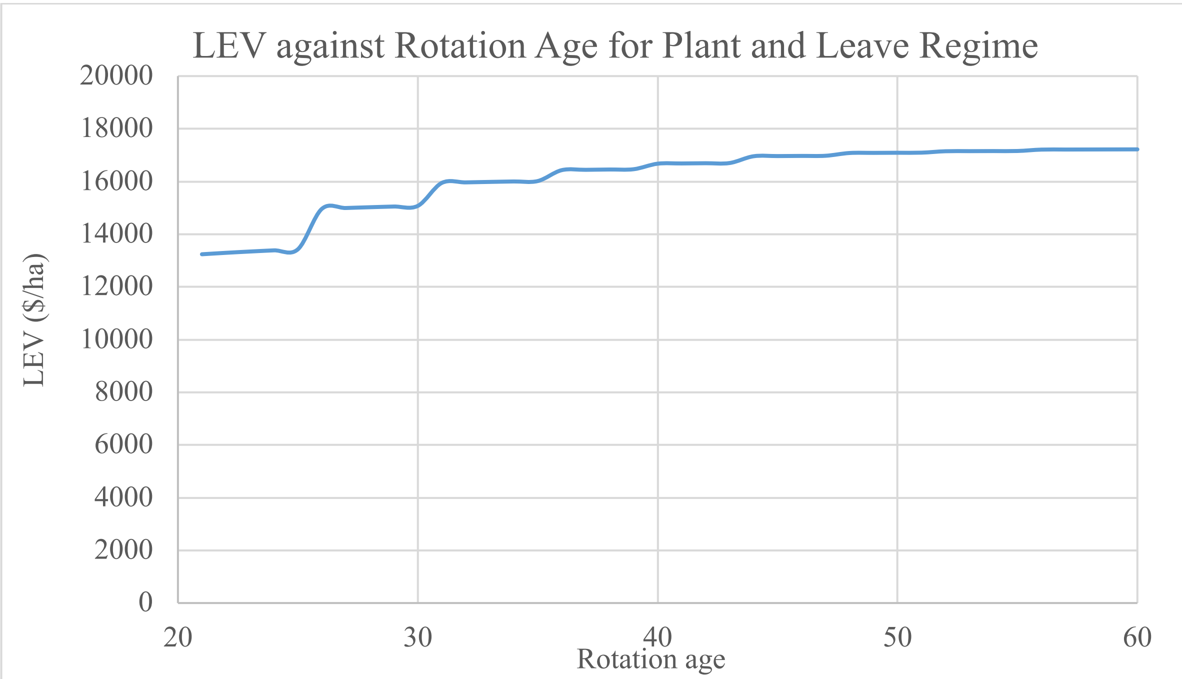

Figure 12: LEV with no peak in the initial 60 years for a permanent plant and leave regime at 2500 stems/ha and no weed control.

5. Discussion

5.1. Model

Total above-ground biomass was predicted using the variables height and DBH. The choice of explanatory variables is well justified. Madgwick et al. (1977), concluded that total above-ground dry matter biomass is closely related to height and basal area. Basal area is a function of DBH hence the use of both variables was well justified. The effects of creating a localised biomass model instead of utilising an existing model were unknown and the benefits were uncertain. It is known that local topographic factors such as slope, aspect and other local growth factors have a significant relationship with diameter and hence biomass in radiata pine plantations (Saremi et al., 2014 & Moore, 2010). The model was developed using a mixed modelling approach to account for random disturbances caused by site/experiment and methodological differences in biomass studies. This model was only intended to be applied at a localised level suited to forests in the Canterbury dryland region. Moore (2010) built a biomass model aimed to predict total above-ground biomass of individual radiata pine trees for carbon accounting purposes. He developed allometric equations to estimate biomass using a similar mixed modelling so to avoid bias estimates, however, his was intended to be applied at a national level. Moore's model applied to the Rolleston data, did a relatively good job in providing an unbiased estimate of biomass in trees, but had a wider distribution of residuals than the model developed using local data. Mixed effect models using allometric equations to predict biomass have proven to work well under both localised (model developed locally) and national scenarios (Moore's). Future use of such models should be encouraged and investigated for further uses in the forest industry.

5.2. Implications for Forest Managers

As a forest manager, these results may suggest alternative ways of managing a plantation stand of *Pinus radiata* than what has been typical in the past. The results show that regimes that favour higher biomass production have higher profitability given the current carbon market. The most profitable regime had a high initial stocking of 2500 stems/ha with no thinning and harvesting. Regimes that included thinning reduced biomass and therefore had reduced profitability. Manley and Maclaren (2010), also found that regimes with no thinning, lengthened rotation ages and high initial stocking were most profitable, because biomass and therefore carbon stocks were highest. Forest mangers growing large-piece sizes or clearwood should now consider switching to growing for small-piece size but higher biomass to increase profitability.

High stockings of 2500 stems/ha may be the most profitable, however will need to be planned carefully by forest managers. Sourcing a high quantity of radiata pine seedlings may mean sourcing seedlings from outside the region, maintaining a strong relationship with a supplier or paying a higher price to secure and compete for the seedling stock. Planting large areas at a higher stocking could be done over consecutive years to produce a mixed age class forest stand that will still sit within 5-year age bands under ETS averaging. The advantage of this is more flexibility over sourcing seedlings and when it comes to harvest. Accepting higher risks of windthrow, fire or pest/disease events may also be necessary when managing higher density stands. Harvesting a highly stocked, unthinned stand will be more difficult and the resulting log grades will be of low quality. This lower grade wood could still be utilised if sold through appropriate markets. The biomass fuel for energy market is already a thriving sector in New Zealand and is expected to rise as demand increases for sustainable carbon-neutral energy sources (Biomass Association, 2021). Forest managers should utilise this market for harvesting highly stocked stands. Other market options include selling to mills that produce engineered wood products utilising lower grade wood, such as MDF or particle board.

As an investor, the results from this analysis will give confidence in purchasing land for afforestation at higher land costs. Manley (2016), found there was a strong correlation between LEV and the rate of afforestation, where carbon is an increasingly key factor in the total LEV. The expected carbon revenue would cover initial land costs, with no large cost to the owner as cashflow from carbon could begin early. Beef and Lamb New Zealand (2021), provided an indicative land market value of Northern-Central South Island Hill Country of $6,000/ha for Class 2 Hill farm. At a carbon price of $50+ forestry is very competitive here. For the more productive finishing farmland the land market value fetches $19,000/ha so forestry can be competitive but only when using the most profitable regimes and strategic silvicultural treatments. The most productive mixed finishing farmland value is $34,000/ha so forestry may be unable to compete with this at today's C prices. However, if carbon prices continue to rise closer to $100/tonne of CO_2 then it is likely that investors in forestry could compete for productive finishing farmland (Appendix 4). As the Ministry for the Environment (2021c) has set the indicative trigger price at $98/t in 2025, it is not unreasonable to assume that carbon prices are expected to rise to these much higher prices, making forestry very competitive in the future. Beef and Lamb NZ land prices are indicated in Appendix 5.

5.3. Future Carbon Accounting

In the future, research should focus on more accurate carbon accounting techniques, considering the findings of this report. Accurate carbon accounting will be particularly important if forests are grown for permanent forestry where carbon is the sole source of income or in a harvest regime that is primarily focused on carbon production. Forest managers will be interested in the best way to account for their carbon stocks so that credits are not being under-allocated. These findings estimate that the current ETS Canterbury default look-up tables may underestimate carbon by up to 67% when applied to highly stocked stands. The default tables do not reflect a full range of growing factors such as silvicultural practices and initial stocking at an individual forest level (MPI, 2020). Developing localised biomass models like the one used in this study, that reflect actual region-specific growing conditions would be beneficial. This reflects the fact that biomass growth is highly reliant on local conditions (Moore, 2010). Variables such as DBH and height are easy and cost-efficient to obtain and has proven to predict biomass well so long as local biomass equations have been developed.

It is a requirement for all participants with less than 100 hectares of post-1989 forest land to use the default tables. Essentially the ETS works so that currently accurate carbon accounting is only accessible for forest owners that have over 100 ha where the Field Measurement Approach (FMA) is applicable. The FMA is similar to that of the biomass prediction models used here, except that national-level biomass equations are used. A study in coastal Bay of Plenty found that using the FMA gave a carbon yield that was 89% more than that of the default yield tables (Pitcher-Campell, 2013). Use of generic default tables should be replaced or at least non-compulsory so that owners of smaller forests have the choice of using more accurate modelling methods. Using and investing in localised models may be more costly for an owner short-term however predicting accurate carbon stocks will most likely pay off especially on fertile sites. These results have shown that even in a lowland Canterbury site that is considered relatively unproductive, the default tables still underpredict. Accurate carbon accounting should also be a bigger priority for LUCAS under the Ministry for the Environment who are in charge of estimating carbon stock changes for all post-1989 forests. Carbon reporting is important for complying with the UNFCCC who require accurate reporting of net carbon stock changes related to forests (Beets et al., 2011b). Good practice guidance for Land Use, Land-Use Change and Forestry activities (LULUCF) states that estimates of carbon stock changes to be unbiased, consistent, transparent and that uncertainties are identified and reduced over time (IPCC, 2003).

5.4. Comparisons with Previous Findings

The findings from this report found that carbon sequestration was significantly greater at highest stockings of 2500 stems/ha than lower stockings. Applying weed control also meant significantly greater carbon sequestration than when weeds were not controlled. These findings are similar to those found by Balboa-Murias et al. (2006) where effects of silvicultural regimes on carbon sequestration were analysed for even-aged stands of radiata pine in Spain. They found that the largest carbon measurements also came from stands with the highest initial stocking of 2000 stems/ha and which had the lowest thinning intensity. The lowest carbon measurements were taken from stands with the lowest initial stocking of 1100 stems/ha and the highest thinning intensity (Balboa-Murias et al., 2006).

Higher stockings have the highest carbon sequestration partially because growth of above-ground biomass increases with planting density (Mohan et al., 2020). With higher stockings there is more rapid occupation of the site, so the overall stand grows at a faster rate (Mohan et al., 2020). The stem is known to hold up to 74% of the total above-ground biomass in radiata pine (Balboa-Murias et al., 2006).

Application of weed control led to higher carbon sequestration. Weed control reduces the competition for resources, particularly water as the Rolleston site is particularly drought-prone in summer. It is possible that the reduction of competition for water from weeds meant for lower biomass portioning to the root system and instead favoured above-ground biomass production which holds more carbon (Mohan et al., 2020). The interaction effect that was found was likely due to the fact that where stands were more highly stocked there was faster canopy closure so the effect of weed control on carbon sequestration was lower, with trees more rapidly dominating the water cycle.

The highest rate of carbon sequestration occurred between ages 5 and 9 years. However, beyond this, the rate of carbon sequestration did not slow much from ages 9 to 15 years. The model only predicted carbon stocks until the final measurements which stopped at the age of 15 years. Beyond this point the rate of carbon sequestration should not be assumed as it is outside the model’s range. Another New Zealand study done in Kaingaroa found that the greatest rate of biomass production (related to carbon sequestration rate) occurred between the ages 10 and 22 years. However, they also found that initial carbon sequestration was also very important between ages 4 and 8 years with high biomass production (Madgwick et al., 1977). This is similar to this study's findings and emphasises that carbon sequestration should not be underestimated in early years in the rotation. Early carbon sequestration can be an important source of early cash-flow for forest managers.

5.5. Limitations

While environmental and economic incentives for wide-scale afforestation are high, recently there has been political and social controversy surrounding carbon forestry. A volunteer pro-farming group called "50 Shades of Green" concerned about the threat that exotic forest planting for carbon poses to pastoral hill country farms. The group's main argument is focused on increased carbon farming coming at the expense of food production and loss of rural sheep and beef farming communities. PWC (2020), estimates the economic impact of integrating sheep and beef farm with forestry activity. It is assumed that forestry will only replace the least productive 10% of sheep and beef farms when considering both plantation and permanent forestry. Nevertheless, it is important to note that anti-forestry groups will be a potential barrier for carbon forestry to occur as a large part of the forestry industry relies on the social licence to operate.

While results indicate that more highly stocked regimes generate a higher income, such stands may be more highly susceptible to stand damage due to wind, fire and pests (Moore & Quine, 2000, & Cruz et al., 2017). An example of this is *Sirex noctilio* or sirex wood wasp, a pest of radiata pine forests. Sirex wood wasps lay eggs and deposit the fungus, S*phaeropsis sapinea* into living trees. They can kill trees or significantly reduce tree growth (Ryan & Hurley, 2012). Silvicultural management can significantly influence susceptibility of trees to attack. One of the largest factors that can influence tree stress and therefore susceptibility is stand density. In higher stocked stands there is a greater proportion of supressed trees that is more vulnerable to attack. The susceptible trees enable sirex wood wasp to establish in a stand and allow populations to grow. When populations are high sirex have been known to begin attacking even the healthy trees (Ryan & Hurley, 2012). This may become a barrier to planting at higher densities in permanent carbon forests.

Another limitation for this analysis is that it is only based in Canterbury. Currently Canterbury has only 6% of the total plantation forest area as at 2019 (NZFOA, 2019). Growing conditions in Canterbury differ significantly from other areas of the country, so results should not be extrapolated to fit regions with vastly different climatic conditions, e.g.) West Coast.

The financial analysis used actual measured carbon rates up until age 15 years. However, following this age, there were no further height and DBH data which meant the analysis required the use of Forecaster carbon estimates based on the C_Change model beyond the age of 15. Given the comparison of the localised model predicted carbon and Forecaster carbon estimates in the first 15 years, this may result in a slight underestimation of carbon in the second half of the rotation. This limits the accuracy of the financial figures produced however the use of Forecaster carbon estimates still appears to be more accurate than using the ETS default yield tables as it accounts for site specific conditions.

6. Conclusion

Stocking and weed control were statistically significant silvicultural factors affecting above-ground carbon sequestration in juvenile radiata pine. A significant interaction effect on carbon sequestration between stocking and weed control at age 5 was also present. Fertiliser did not produce a statistically significant effect on carbon storage. Carbon sequestration was 47 % more at 2500 stems/ha compared to 625 stems/ha at an age of 15 years. The greatest difference in carbon sequestration rate between stockings occurred early between ages 3 and 5 years, where higher stockings had 3.5 times the amount of carbon than that of lower stockings. This difference however, then decreased with age.

The individual tree biomass model used for this analysis was compared to Moore's (2010) individual tree model. A comparison of both models' distributions of residuals showed that Moore's model did a relatively good job when being applied to the Rolleston dataset. Moore's model showed some higher variance in biomass predictions however, this is expected and highlights the importance of developing models that are site specific where variance from sites can be removed via random effects.

Comparisons between the localised model biomass predictions, ETS default yield table carbon and Forecaster predicted carbon were made. They showed that given the localised model is accurate, the ETS default tables markedly underestimated carbon sequestration during the first 15 years. At the highest stockings, the ETS default tables give a carbon value 67% less than what the localised biomass model predicts. Forecaster predicted carbon via the C_Change model, overestimated carbon for initial years and estimated a slower trajectory for carbon sequestration in later years.

Financial analyses showed that the most profitable regime had a stocking of 2500 stems/ha and no thinning or weed control applied. Harvested at an optimum rotation age of 44 years it returned an LEV of $19,750/ha. When adopting a permanent forestry regime, an LEV of $17,219/ha was achieved at 2500 stems/ha. In both permanent forestry and rotational forestry with no thinning, LEV increased by an average of 32% and 22% respectively moving from lowest stocking to highest stocking. By contrast the harvest with thinning regime decreased the LEV by an average of 12% when moving from a lower stocking to a higher stocking. Regimes which favoured higher above-ground biomass production were ultimately favoured.

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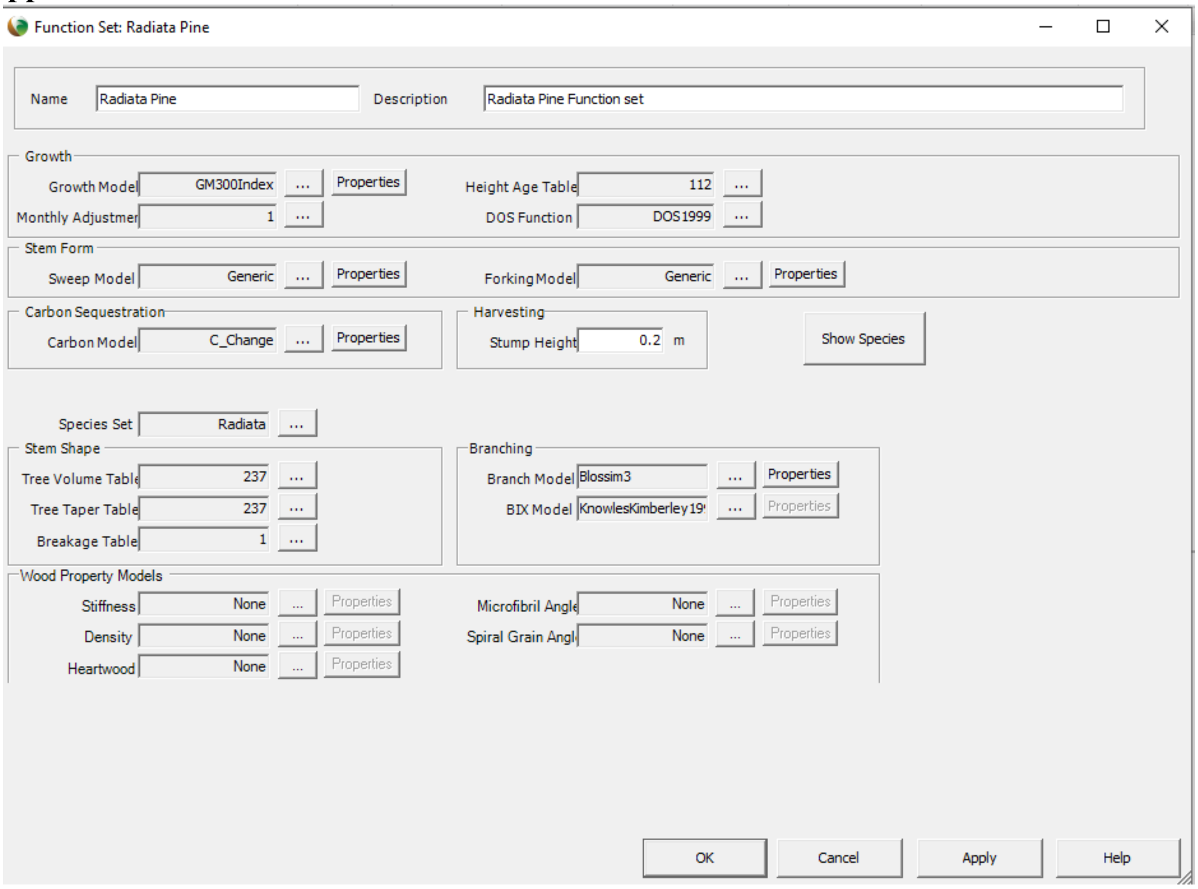
8. Appendices

Appendix 1: Function set used in Forecaster.



Appendix 2: Log grades and prices used in financial cash flow analysis ($/tonne).

PR1	PR2	PR3	S1S2	S3L3	L1L2	PULP
185	169	100	135	119	120	55

Appendix 3: LEV with timber only (no carbon revenue).

		Thin and Harvest	No thin and Harvest	Plant and Leave
	625 stems/ha	$ 227.37	$227.37	$-2272.35
Weed Control	1250 stems/ha	$-1485.90	$-1295.07	$-2918.01
	2500 stems/ha	$-3242.06	$-2659.14	$-4180.25
No Weed Control	625 stems/ha	$302.30	$302.30	$-1829.08
	1250 stems/ha	$-1021.25	$-858.93	$-2446.68
	2500 stems/ha	$-2722.10	$-2145.27	$-3680.87

Appendix 4: LEV with a carbon price of $98/t

		Thin and Harvest	No thin and Harvest	Plant and Leave
	625 stems/ha	$ 31,017.33	$ 31,017.33	$ 28,597.64
Weed Control	1250 stems/ha	$ 30,547.60	$ 35,576.01	$ 33,537.99
	2500 stems/ha	$ 29,684.71	$ 39,121.46	$ 36,979.75
No Weed Control	625 stems/ha	$ 27,944.79	$ 27,944.79	$ 25,904.91
	1250 stems/ha	$ 28,673.59	$ 33,239.36	$ 31,265.31
	2500 stems/ha	$ 30,101.88	$ 39,622.06	$ 37,283.12

Appendix 5: Northern-Central South Island: Marlborough, Nelson, Canterbury.

	Land Value $/ha
Class 2 hill country	$6,000
Class 6 Finishing Breeding	$19,000
Class 8 Mixed Finishing	$34,600