Impacts of Climate Change on National and Regional Productivity and Profitability: Forestry

Pont, D., White, D. A., Dunningham, A., Villamor, G. B., and Salekin, S.

REPORT INFORMATION SHEET

Report title	Impacts of Climate Change on National and Regional Productivity and Profitability: Forestry
Authors	Pont, D., White, D. A., Dunningham, A., Villamor, G. B., and Salekin, S.
Client	MBIE
PAD output number	98203242
Date	April 2025
Intellectual property	
Disclaimer	The information and opinions provided in the Report have been prepared for the Client and its specified purposes. Accordingly, any person other than the Client uses the information and opinions in this report entirely at its own risk. The Report has been provided in good faith and on the basis that reasonable endeavours have been made to be accurate and not misleading and to exercise reasonable care, skill, and judgment in providing such information and opinions. Neither Scion, nor any of its employees, officers, contractors, agents or other persons acting on its behalf or under its control accepts any responsibility or liability in respect of any information or opinions provided in this Report.

Published by: Scion, Private Bag 3020, Rotorua 3046, New Zealand. www.scionresearch.com

Executive summary

Introduction

This report is part of the project, "Impacts of Climate Change on Regional Economies", commissioned by MBIE to understand the economic impacts of a changing climate on regional economies, with a focus on land-based primary industry. This report covers forest productivity and profitability results from simulations with best-available models for three tree species using nine management regimes across future climate change and time-period scenarios.

Methods

Productivity (wood volume per hectare) and growth rates (wood volume per hectare per year - MAI) were modelled using the physiological process-based model CABALA-W. Profitability was modelled using Forestscape2, a spatial forest economic model. Productivity and profitability were calculated for 5×5 km grid cells across New Zealand. Modelled species were *Pinus radiata* D. Don (Radiata), *Sequoia sempervirens* (Lamb. ex D. Don) Endl. (Redwood), and *Eucalyptus fastigata* H. Deane & Maiden (Fastigata). The range of management regimes included Sawlog, Pulpwood, and Carbon, under varying rotation lengths.

Species and Regimes

Species	Regime	Rotation length (years)
Radiata	Sawlog	25
	Carbon	50
Fastigata	Pulpwood	15
	Sawlog	25
	Sawlog	50
	Carbon	50
Redwood	Sawlog thinned	40
	Sawlog not thinned	40
	Sawlog thinned	50

The climate scenarios modelled were Baseline (Current climate), Mild (Representative Concentration Pathway (RCP 4.5)), Moderate (RCP 6.0), and Extreme (RCP 8.5) climates. The baseline productivity was simulated for the current period, and productivity for each RCP was simulated for Mid and Late periods.

Climates and Period combinations

Climate	Period	Mid points (year)
Baseline	Baseline	1995
RCP 4.5	Mid	2055
	Late	2089
RCP 6.0	Mid	2055
	Late	2089
RCP 8.5	Mid	2055
	Late	2089

Results - National Productivity (Volume and MAI) Trends under Climate Scenarios and Regimes

CABALA-W predicted increased productivity from the Baseline to the Mid and Late periods for all species and regimes. Increased productivity was associated with increases in atmospheric CO_2 levels (from RCP 4.5 to 6.0, and 8.5), indicating that higher atmospheric CO_2 concentrations, and associated temperature increases, enhance tree growth. The Late period RCP 8.5 consistently exhibited the highest productivity gains, suggesting that moderate-to-high climate change scenarios may be beneficial for tree growth in New Zealand. Radiata Carbon is predicted to be the most productive regime in volume over 50 years. The 40- and 50-year Redwood regimes follow as the next most productive. The Fastigata regimes demonstrate substantially lower productivity than the other species, regardless of rotation length.

Results - Regional Productivity Variation

There is intra- and inter-regional variation in productivity for volume (amount) and mean annual increment (rate). The Radiata Sawlog 25-year regime demonstrates the highest MAI productivity and stability across all regions and RCPs. The Redwood Sawlog Thin 40-year regime exhibits the greatest productivity increases in response to RCPs in South Island regions by the Late period. The Fastigata Pulpwood 15-year regime shows lower productivity across regions than other regimes, particularly under baseline and RCP 4.5 conditions. Additionally, Redwood regimes experience decreased productivity in certain regions under RCP 8.5.

Results - Profitability

The profitability assessment of Radiata, Redwood, and Fastigata regimes reveals varied responses to climate scenarios. The Radiata Sawlog 25-year regime shows consistent earnings, especially under RCP 8.5. Redwood regimes see slight profit increases during warmer climates, particularly in no-thinning scenarios. Fastigata regimes offer higher returns over longer rotations despite constraints, though Fastigata Pulpwood 15-year remains unprofitable. The analysis underscores the need to choose the appropriate forestry regime and adapt practices to enhance profitability amid climate change.

Considerations

The following qualifications must be considered when interpreting these results:

- Despite being the product of extensive research and modelling efforts internationally, the climate data used are projections of the future rather than predictions. The accuracy and precision of these climate data projections diminish over time, particularly affecting Late period productivity projections. The values from the RCP 8.5 projections should be treated with particular caution.
- The national soil data used for parameterising and running the model were developed for agricultural systems and lack critical inputs for forest growth models, introducing uncertainty about the simulated values of forest productivity.
- Short term climate extremes are not well represented in the climate data used for this project. Abiotic and biotic stressors, such as heat waves, pest outbreaks, or diseases, and their negative effects on productivity and profitability, were not able to be considered in the modelling. We also note the incidence of pests and diseases is expected to increase under climate change.
- While CABALA-W simulates productivity using the best available representation of a chain of underlying processes, our understanding of the effect of climate change on these processes is incomplete. Important uncertainties and limitations of the model are described in section 2.4 (CABALA-W physiological growth model).
- The revenue and costs used are largely based on current knowledge and data from mainstream operational forestry growing Radiata. There is a need for better information on revenues and costs for species other than Radiata. Additionally, there is uncertainty about future revenues and costs.

Conclusions

Under the modelled climate change scenarios and future periods, productivity is projected to increase for all three species. Radiata exhibits the strongest performance in terms of productivity and profitability under future climatic conditions. Redwood shows potential as a viable option for diversifying species selection and enhancing forest resilience. To further refine productivity and profitability estimates, there are future research opportunities to improve parameterisation of the growth and economic models, for Radiata, and particularly for alternative species. Additionally, consideration should be given to incorporating the effects of abiotic and biotic risks such as heat waves, pest outbreaks, and diseases, which can lead to decreases in productivity.

Table of contents

Table of Figures

Table of Tables

1 Introduction

1.1 Climate change opportunities and risks to forestry

Forests are affected by various direct and indirect effects of average and extreme weather conditions, which influence productivity and the risk of mortality over rotation lengths. Increasing carbon dioxide (CO_2) and temperatures, and changes to humidity and precipitation amounts, frequency, and seasonality affect the physiological processes driving plantation productivity. Indirect or secondary impacts can be caused by increasing droughts, extreme weather events, increased fire risk, damage from pathogens and insects, and increased competition from weed species (Dunningham et al., 2012).

Amid these challenges, there is a growing interest in enhancing forest resilience and sustainability in the face of climate change by planting a range of different forest types, including appropriate choices of single- and mixed-species forests (Messier, 2022). Tree diversification helps spread risks to bolster resilience while mitigating climate impacts (Villamor et al., 2023). However, to reduce these adverse effects in the future, understanding how tree species respond to climate change is key to future-proofing our forests.

This research project, funded by the Ministry for Business, Innovation and Employment (MBIE), provides insights into the direct impacts of climate change on forestry productivity and is complementary to a report on selected horticultural and arable crops completed by Plant & Food Research.

The requirements of the project were to assess productivity and profitability of a range of candidate species and management regimes under future climate scenarios, for the New Zealand local government regions. Productivity was modelled on a 5 km grid over New Zealand to generate fine-grained results comprehensively representing site and climate variations within each region.

To model the effects of a changing climate on tree growth, across diverse sites, a process-based modelling approach was essential. The process-based approach used environmental inputs including local climate and soil data to model the physiological growth responses for each species and regime.

The approach generated productivity data at an unprecedented spatial resolution, across national scale, for a range of species, climate scenarios, and future time-periods. Productivity data were then able to be used in predicting profitability. The high resolution 5 km results were used to derive regional results that usefully represented the underlying fine-scale detail and variability. The results generated represent the best-available national and regional information on productivity and profitability of key species under climate change. The three species modelled were *Pinus radiata* D. Don (Radiata), *Sequoia sempervirens* (Lamb. ex D. Don) Endl. (Redwood), and *Eucalyptus fastigata* H. Deane & Maiden (Fastigata).

This report is structured as follows. The Methods section (2) describes the assumptions and modelling methodologies used for productivity and profitability modelling. This includes details of the regions (2.1), climate scenarios (2.2), species, and regimes selected (2.3), the process-based model and its limitations (2.4), and the key management, climate, site, and species inputs used (2.5), as well as the key assumptions and inputs used for the profitability modelling (2.6).

Results section 3 presents and summarises the large amount of productivity modelling results and has three main sections. Section 3.1 begins with a brief summary of the key findings, followed by presentation of national average productivity by regime, climate scenario, and time-period, followed by summaries for each species (3.1.1, 3.1.2, and 3.1.3), and then for all regimes (3.1.4). Section 3.2 begins with a summary of key findings, followed by productivity results for a representative regime for each of the 3 species (3.2.1, 3.2.2, and 3.2.3), and then for the full set of nine regimes (3.2.4) and sixteen regions (3.2.5).

Results section 4 presents a summary of profitability results for regimes. These begin with a summary of key findings, followed by results for Fastigata (4.1), Radiata (4.2), and Redwood (4.3).

In section 5.1 the key findings of the report are summarised. Those findings include a summary of limitations, which inform future research topics presented in section 5.2.

2 Methods

This project estimated the changes in the productivity and profitability of selected tree species under different climate change scenarios. A forestry expert evaluated the approaches, reviewing the assumptions and estimates of forest productivity and profitability. This provided input for defining the costs associated with the regimes used, including adjusted harvesting costs reflecting current operational values.

Productivity was modelled using the CABALA-W process-based growth model (Battaglia et al. 2004). Radiata and two commercially prospective alternative species, Redwood, and Fastigata, were modelled using management regimes to produce different timber or carbon products.

Forest productivity was quantified using volume and mean annual increment (MAI). Volume is the total standing stem wood volume per hectare and represents the cumulative amount of wood production over the whole growing period. It does not include wood volume removed in thinnings. MAI is the mean volume increment per year (total volume divided by total growing period in years) and represents the average annual production rate over the whole growing period. MAI does include wood volume removed in thinnings. The total volume depends on the rotation length, allowing for the same regime to be compared across regions, whereas MAI is rotation length independent, allowing for comparisons of regimes. Interpreting total volume requires care, for example, if an area is planted in a Redwood 50-year regime, the equivalent 50-year total volume from a Radiata 25-year regime would be from two rotations, and approximately three rotations from a 15-year Pulpwood regime.

Modelling was conducted on a 3 arc-minute (approximately 5 km) grid across New Zealand. Grid locations defined climate and soil inputs for the modelling. Each grid location, species, regime, period, and climate (RCP) combination defined all the necessary inputs for a single run of CABALA-W.

Profitability was modelled using Forestscape2, using the productivity estimates from CABALA-W and costs and revenues from a variety of sources for each species and regime.

2.1 Regions

New Zealand is divided into sixteen local government regions[1]. These regions were used for analyses and reporting of results at regional level. The names and details of the regions are presented in Table 1 and a map of the region boundaries[2] are presented in Figure 1 .

[1] "Local Government Act 2002 No 84 - Interpretation". Retrieved 14 April 2025.

[2] By Korakys - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=56957024

Table 1: List of regions.

Region	Island	Regional council	Total land area (km²)
Auckland	North	Auckland Council	4,941
Bay of Plenty	North	Bay of Plenty Regional Council	12,072
Canterbury	South	Environment Canterbury	44,504
Gisborne	North	Gisborne District Council	8,385
Hawke’s Bay	North	Hawke's Bay Regional Council	14,138
Manawatū-Whanganui	North	Horizons Regional Council	22,221
Marlborough	South	Marlborough District Council	10,458
Nelson	South	Nelson City Council	422
Northland	North	Northland Regional Council	12,504
Otago	South	Otago Regional Council	31,186
Southland	South	Southland Regional Council	31,196
Taranaki	North	Taranaki Regional Council	7,254
Tasman	South	Tasman District Council	9,616
Waikato	North	Waikato Regional Council	23,900
Wellington	North	Greater Wellington Regional Council	8,049
West Coast	South	West Coast Regional Council	23,245

Figure 1: The local government regions (indicated by colour) displayed over territorial authorities.

2.2 Climate scenarios

An RCP is a climate-modelling-based scenario representing a specific trajectory of greenhouse gas concentrations (particularly CO_2) in the atmosphere. Each RCP corresponds to a specific pathway of radiative forcing (the difference between sunlight energy absorbed by the Earth and energy radiated back into space) by the year 2100, measured in watts per square meter (W/m^2). The Intergovernmental Panel on Climate Change (IPCC) defined five future climate scenarios which are widely used for research. The use of these benchmark scenarios ensured results will be consistent and comparable with other national and international research findings. After consultation with stakeholders, three of the five scenarios were selected to represent the range of relevant future conditions.

The three RCP scenarios used were:

- RCP 4.5. A moderate scenario with substantial emissions reductions later in the period allows for radiative forcing to stabilise at 4.5 W/m^2.
- RCP 6.0. An intermediate scenario with slower mitigation strategies that stabilise radiative forcing at about 6.0 W/m^2.
- RCP 8.5. A high-emissions scenario without substantial global mitigation measures, leading to radiative forcing around 8.5 W/m^2 by 2100.

2.3 Species and regime selection

Radiata, Fastigata, and Redwood were selected for this project after proposed species and regimes were discussed with MBIE and MPI and subsequently reviewed by a forest management expert. The criteria for species and regime selection were:

- flexibility and options for producing a viable range of products
- bioclimatic suitability for a wide range of locations in New Zealand
- a degree of industry knowledge and existing systems and infrastructure for species selection, management, and processing (Ministry for Primary Industries, 2023)
- the ability to parameterise the CABALA-W model

Regimes are the collective set of silvicultural operations managers apply to individual forest stands to produce specific products (e.g., structural timber, carbon). Typical management operations include varying planting density (stems per hectare), optional thinning and pruning, and rotation length, all of which impact productivity and profitability. Operational regimes are explicitly defined for species, sites, and desired product mixes.

The regimes used were derived from MPI (Ministry for Primary Industries, 2023), and it was assumed that any trees removed through thinning were not extracted (thinning to waste). The decision to model thinning to waste was made because extraction of thinned trees would not be realistic under low-yield productivity conditions such as marginal sites and unfavourable climate scenarios. Thinning to waste therefore enabled more meaningful comparisons of regimes, climate scenarios, and time-periods. Table 2 summarises the species and management regimes modelled.

Table 2: List of species and regimes modelled.

Species	Regime	Rotation length (years)	Regime label
Radiata	**Sawlog**	**25**	Radiata Sawlog 25
	Carbon	**50**	Radiata Carbon 50
Fastigata	**Pulpwood**	**15**	Fastigata Pulpwood 15
	Sawlog	**25**	Fastigata Sawlog 25
	Sawlog	**50**	Fastigata Sawlog 50
	Carbon	**50**	Fastigata Carbon 50
Redwood	**Sawlog thinned**	**40**	Redwood Sawlog Thin 40
	Sawlog not thinned	**40**	Redwood Sawlog NoThin 40
	Sawlog thinned	**50**	Redwood Sawlog Thin 50

The climate and period combinations modelled are shown in Table 3. Baseline corresponds to the current climate conditions and period, representing one modelling run. The three other climates (RCP 4.5, RCP 6.0, and RCP 8.5) and two other time-periods (Mid and Late) create an additional six modelling runs, making seven distinct climate and period combinations for modelling.

Table 3: List of climates and periods modelled with time-period mid points.

Climate	Period	Mid points (year)	Climate – Period label
Baseline	**Baseline**	1995	Baseline
RCP 4.5	**Mid**	2055	4.5 Mid
	Late	2089	4.5 Late
RCP 6.0	**Mid**	2055	6.0 Mid
	Late	2089	6.0 Late
RCP 8.5	**Mid**	2055	8.5 Mid
	Late	2089	8.5 Late

2.3.1 Radiata

Radiata is the dominant species used in commercial forestry in New Zealand. The key indicators of its economic and social importance are given in Table 4, and the regimes modelled are in Table 5.

Table 4: Radiata economic indicators.

Indicator	Value
Area	1.8 M ha
GDP	$6.7 B
Employment	41,000 people

Table 5: Management details for Radiata regimes.

Species	Regime label	Operation	Age (years)	Parameter Value
Radiata	**Radiata Sawlog 25**	Planting	0	1000 sph[1]
		Thinning	7	600 sph
		Harvest	25	
	Radiata Carbon 50	Planting	0	1000 sph

[1] sph: stems per hectare

2.3.2 Fastigata

Fastigata is a fast-growing species that grows well on various sites. It produces non-durable wood and can be managed to produce pulpwood, veneer logs, sawlogs, or long-term carbon storage. It has been evaluated and performs well across the full range of climates of the existing national forest estate. The Fastigata regimes modelled are in Table 6.

Table 6: Management details for Fastigata regimes.

Species	Regime label	Operation	Age (years)	Parameter Value
Fastigata	**Fastigata Pulpwood 15**	Planting	0	1111 sph
		Harvest	15	
	Fastigata Sawlog 25	Planting	0	1111 sph
		Thinning	7	700 sph
		Pruning	10	6 m
		Thinning	12	300 sph
		Harvest	25	
	Fastigata Sawlog 50	Planting	0	1111 sph
		Thinning	7	700 sph
		Pruning	10	6 m
		Thinning	15	300 sph
		Thinning	25	100 sph
		Harvest	50	
	Fastigata Carbon 50	Planting	0	1111 sph

2.3.3 Redwood

Redwood is well suited to the warm, humid climate of the North Island of New Zealand. Redwood lacks the frost tolerance of Radiata, but bioclimatic modelling suggests the range will increase with climate change. Redwood is relatively shade tolerant and resprouts from cut stumps, making it suited to a range of alternative management regimes and a prospect for continuous cover forestry. The Redwood regimes modelled are in Table 7.

Table 7: Management details for Redwood regimes.

Species	Regime label	Operation	Age (years)	Value
Redwood	**Redwood Sawlog Thin 40[1]**	Planting	0	800 sph
		Thinning	10	600 sph
		Pruning	11	6 m
		Harvest	40	
	Redwood Sawlog NoThin 40[1]	Planting	0	625 sph
		Pruning	11	6 m
		Harvest	40	
	Redwood Sawlog Thin 50	Planting	0	833 sph
		Thinning	11	450 sph
		Pruning	11	6.5 m
		Harvest	50	

[1]The two redwood sawlog regimes simulated follow recommended silviculture (Forest Owners Association, 2023) for seedlings (higher initial stocking followed by a thinning to reduce to 600 sph) and clonal material (lower initial stocking and no thinning).

2.4 CABALA-W physiological growth model

CABALA (CArbon BALAnce), (Battaglia et al., 2004), is a physiological process-based model developed for silvicultural decision support and has several features that aid in the simulation of tree species and their responses to management under future climates:

- A ray-tracing light interception model that realistically simulates the growth of complex stand structures immediately after thinning.
- A biochemically based leaf photosynthesis model (von Caemmerer et al., 2009) that simulates the effect of elevated CO_2 and interactions with water and temperature.
- A hydraulically based model of canopy conductance that simulates the effects of increased mortality on productivity under climate change.

CABALA-Water (CABALA-W) (White et al., 2025) is the latest version of CABALA, incorporating modified sub-models for water balance, photosynthesis, and canopy conductance. CABALA-W was used in this project to model the growth of Radiata, Fastigata, and Redwood.

CABALA-W simulates plantation productivity as an outcome of a sequence of processes calculated at a daily time step. While CABALA-W incorporates our current understanding of the effects of site, climate, and management on these processes, this knowledge is far from complete, and CABALA-W has limitations that are important considerations for interpreting the results in this report.

2.4.1 Considerations

The following considerations highlight limitations in the model that should be considered when interpreting the simulation results:

- Our understanding of the effects of elevated CO_2 on forest productivity and underlying plant and soil processes is limited due to the inherently difficult and costly nature of experiments at elevated CO_2. In CABALA-W, CO_2 affects productivity via parameters that describe the shape of the response of leaf photosynthesis to atmospheric CO_2. These parameters are usually measured on plants with optimal nutritional status. CABALA-W does not account for the co-limiting effects of nitrogen or phosphorus on leaf photosynthesis and therefore probably overestimates the benefits of increased CO_2 for photosynthesis.
- In process-based models, construction and maintenance respiration are either a constant proportion of gross production or a function of biomass nitrogen concentration. Neither approach accounts for the probable increase in construction and maintenance respiration under climate change due to increased mean temperature.
- Temperature extremes have important residual effects on canopy production, and normal data for the simulations almost certainly underestimates the negative effects of extreme, high, or low temperatures on canopy production.
- The effects of climate change on underlying (self-thinning) and event-driven (drought, heatwave) tree mortality are not well understood and are probably under-estimated by existing forestry models including CABALA-W, noting that stocking has a strong influence on total volume at harvest. Climate change is also predicted to increase the occurrence and impact of pests and diseases on forest productivity (Dunningham et al., 2012), with potential for negative impacts on plantation productivity that are not captured by the modelling.
- The accuracy and precision of CABALA-W predictions rely on quality soil and climate data availability. The Fundamental Soil Layer (FSL) data does not provide reliable estimates of soil depth or the Carbon to Nitrogen (C:N) ratio, both of which are critical for predicting plantation productivity. The projection accuracy and precision of the climate data reduce over time, so Late period results are highly uncertain. The values from the RCP 8.5 projections should be treated with caution, especially in the Late period.

2.4.2 CABALA-W model parameterisation

Parameterisation of CABALA-W for new species is crucial to the accuracy of results. CABALA-W parameterisation has previously been completed for plantation species, including Radiata, *Eucalyptus globulus* Labill*, Eucalyptus nitens* (H. Deane & Maiden) Maiden*,* and *Eucalyptus grandis* W. Hill ex Maiden. As a starting point, existing parameter sets from analogue species were used to develop new parameter sets, using *E. nitens* for Fastigata (*E. fastigata*) and Radiata for Redwood.

For the new species, parameters associated with the most important limits to key processes in the target environments were modified one at a time based on information from the literature, unpublished studies at Scion, and expert knowledge. Predicted wood volume was compared with observed wood volume for selected permanent sample plots (PSPs) that covered the growth rate range of the set of plots for that species. This process required information on forest management in each PSP and a description of the soil for the PSP site to initialise the water and nitrogen cycle in the model. As there is no soil data in the PSP database, the soil description was created from a combination of the FSL (Newsome et al., 2008) for a polygon associated with the PSP and an available C:N layer.

2.4.3 Parameterisation results

CABALA-W underestimated observed productivity at the selected plots for *E. fastigata*, and while modifying parameters improved fit, the fit was still relatively poor (Figure 2).

Closer examination of the soil information in these simulations revealed that the "potential rooting depth" for many plots was 0.5m or less. Soil depth information to bedrock or local groundwater is critical for modelling forest productivity because *Eucalyptus* and *Pinus* species can root to depths of more than 20 metres within a single rotation (Dye, 1996; White et al., 2009), especially when evaporation exceeds rainfall for extended periods. The soil data from the FSL were universally and unrealistically shallow, preventing realistic water balance prediction and resulting in model predictions of complete water depletion early in the rotation. Using this soil data, the model underestimated observed productivity, and this was not improved by modifications to species parameters, making it impossible to evaluate the effect of changes to model parameters using the FSL soil data.

Increasing the soil depth to 1m for all the test sites improved the fit of the model results ($R^2 > 0.7$), indicating that the species parameter file for *E. fastigata* 2 was suitable and that the underestimation of observed productivity in Figure 2 was due to a lack of reliable information on soil depth. A soil depth of 1 m was subsequently used for all the simulations.

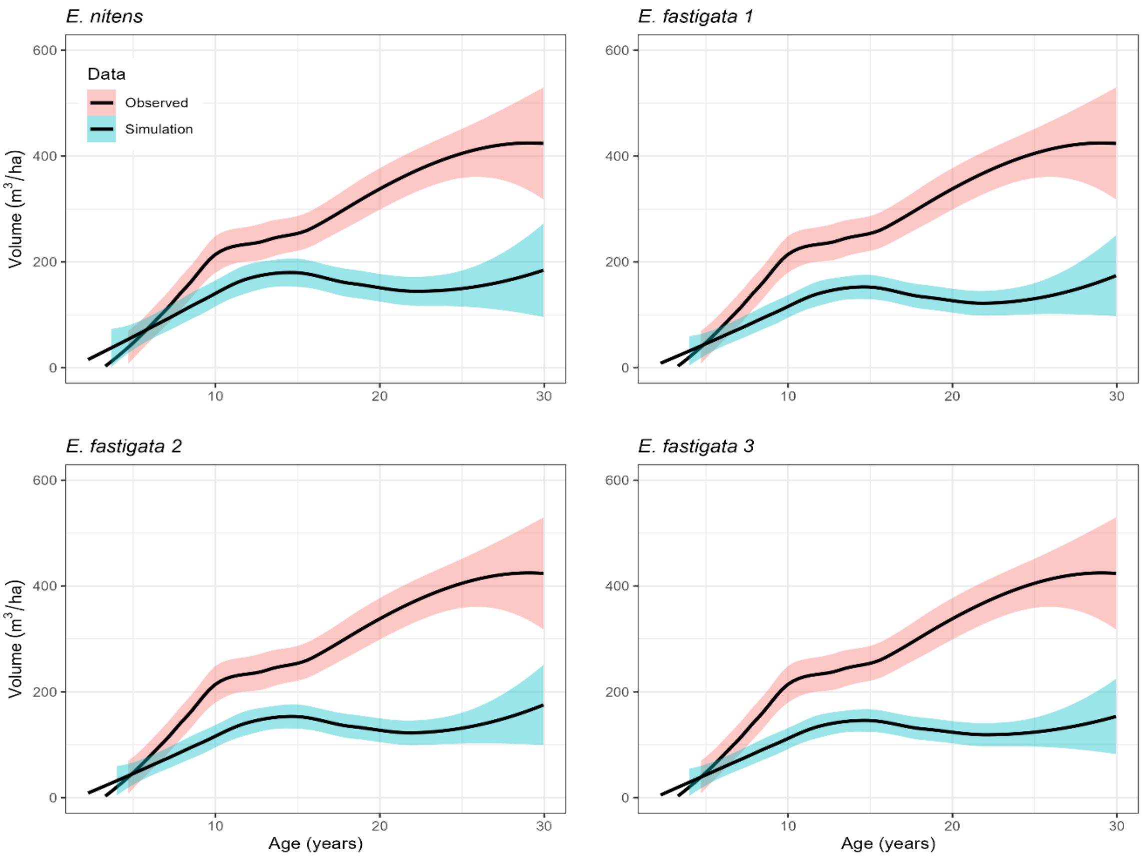


Figure 2: The observed (red) and predicted (blue) volume (m^3/ha) for a selection of *E. fastigata* permanent sample plots with the 95% confidence intervals (shaded area). The top left panel uses an unmodified *E. nitens* parameter set. *E. fastigata* 1 is the *E. nitens* parameters set with modified wood density and specific leaf area. *E. fastigata* 2 has a modified maximum rate of photosynthesis and temperature response of photosynthesis after Lin et al. (2012). *E. fastigata* 3 also has a modified initial and final slope of the photosynthetic response to elevated CO_2.

The initial parameterisation for Redwood was more successful than for Fastigata. CABALA-W overestimated productivity early in the rotation, but simulations of standing volume and basal area later in the rotation more closely approximated observed values (Figure 3).

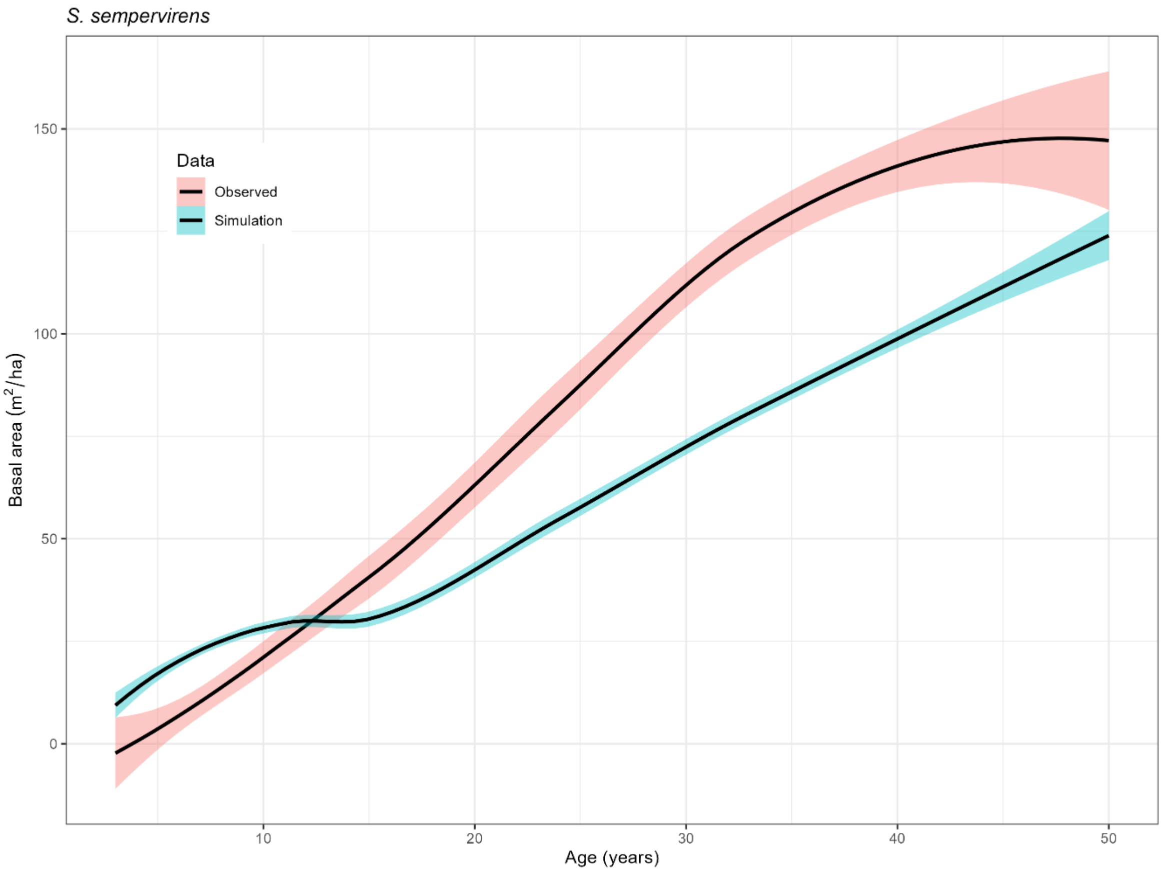


Figure 3. The observed and predicted basal area (m^2/ha) for Redwood permanent sample plots.

2.5 Data sets used in CABALA-W

Four sets of input files are used to control CABALA-W, containing all the key parameters describing the regime, climate, site, and species.

2.5.1 Regime

The regime file details the planting and harvest dates, the date of silvicultural actions, the initial CO_2 concentration, and any subsequent increases in CO_2.

2.5.2 Climate data

NIWA's Coupled Model Intercomparison Project Phase 5 (CMIP5) dataset was used (Sood, 2014; Tait et al., 2016). That dataset consists of five General Circulation Models (GCMs) projecting values for ten climate change parameters (such as temperature, humidity, and precipitation) for every day from 1970 to 2120[3], for four Representative Concentration Pathways RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 as scenarios of the increasing impact of climate change.

[3] Some of the GCM's only project results to 2100.

These data are downscaled to the Virtual Climate Station Network 3 arc-minute resolution (approximately 5 km) grid over New Zealand. The grid defines centres of 25 km^2 cells used as the basis for simulation (Mason et al. 2017 and Tait et al. 2006).

The climate data was further processed to an ensemble mean of the 5 GCMs and then normalised over 20 years every 5 years. The analysis modelled RCP 4.5, 6.0, and 8.5, using daily climate inputs of total solar radiation (MJ), maximum and minimum temperature (C), and rainfall (mm).

2.5.2.1 CO_2 levels

Based on the planting date, the starting and finishing CO_2 levels for the Baseline, Mid, and Late periods were obtained from the International Institute for Applied Systems Analysis (IIASA) database[4] and incremented each year, assuming a straight-line increase in CO_2 concentrations.

2.5.3 Site information

The site file initialises the soil water, carbon (C), and nitrogen (N) status and provides information on location and initial CO_2 concentration.

CABALA-W needs soil chemistry information to model nitrogen mineralisation at three soil depth ranges: 0-10, 10-20, and 20-50 cm. Information on pH and organic C was sourced from the FSL (Newsome et al., 2008), while the C:N ratio was derived from a spatial layer published by Watt and Palmer (2012). The FSL only provided soil information for a 0-10 cm depth. Values for the successive downward soil layers were assumed to be half that of the layer above.

CABALA-W requires soil physical properties information on:

- The type of material in the layer (soil, saprolite, hardpan).
- The soil texture class (15 classes are recognised).
- The thickness of each layer.
- The saturated hydraulic conductivity (K_{sat} in mm day^{-1}).
- The capillary length (λ, mm).

Soil data not provided by FSL were defined as follows:

- Each soil type in the FSL was assigned a CABALA-W texture class for which K_{sat} and λ were calculated as a function of mean particle size after White and Sully (1987).
- Maximum soil water storage is determined by soil texture and soil depth. The FSL does not provide useful information on soil depth. For the simulations, a uniform soil depth of 1 m was assumed.

2.5.4 Species information

The species file includes species-specific parameters for important relationships in the model that affect light interception, leaf and canopy scale photosynthesis and conductance, carbon allocation,

[4] https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=download

and the growth and development of the main tree organs. The water and nitrogen cycle are also described, and parameters in the species file control interactions with the key growth processes.

2.5.5 Productivity processing – CABALA-W

CABALA-W is a daily timestep model; one run is required for each combination of regime, climate (RCP), period, site, and soil depth (collectively referred to as a Scenario in CABALA-W). CABALA-W was installed on Scion's high-performance computing (HPC) facility, and the processing was enabled using GNU Parallel (Tange, 2018), utilising between 70 and 100 CPUs. The indicative time for running CABALA-W on a typical computer was 10 seconds per run. The time per run with 100 concurrent CPUs on the HPC varied from 0.2 to 0.5 seconds, depending on regime operations and rotation length.

For each of the three modelling periods (Baseline, Mid, and Late), regime start dates were set to provide a common mid-point of projections. Therefore, longer rotation regimes started earlier and finished later than shorter rotations.

2.6 Profitability modelling

2.6.1 Forestscape2

The Forestscape2 is a spatial economic model developed to calculate the profitability of forest crops at local, regional, and national scales. Forestscape2 applies an agent-based modelling approach using the NetLogo (version 6.3) modelling platform (Wilensky, 1999).

Forestscape2 calculated economic outputs using the productivity estimates from CABALA-W. Profitability was determined by the total volume produced in the rotation, the length of the rotation, and estimates of revenue and costs. The operational costs of the regimes used in the model included labour for silvicultural operations from establishment to harvesting (see Villamor (2024)). The value of the crop was estimated after harvesting at the end of the rotation period, and road costs were accounted for. The model calculates harvesting costs by considering slope, as higher slopes substantially increase harvest costs. The price assumptions used in profitability modelling are presented in Table 8, and costs are presented in Table 9.

Table 8: Assumptions for the prices (at stumpage) for estimating NPV and EAI.

Species (Regime)	Assumed/estimated prices
Radiata (Sawlog)	$ 145 per tonne[1]
Redwood (Sawlog)	$145 per tonne[1]
Fastigata (Sawlog)	$145 per tonne[1]
Fastigata (Pulpwood)	$45 per tonne[1]

[1]Source: Villamor (2024) and *Historic indicative New Zealand radiata pine log prices | NZ Government (mpi.govt.nz))

Table 9. Assumed costs (at stumpage) for estimating NPV and EAI (Note: roading and transportation costs to mill or wharf point are not included in the calculations). Where values were not available (NA) Radiata costs were assumed.

Costs ($/ha)	Radiata	Redwood	Fastigata Sawlog	Fastigata Pulpwood
Establishment	$2600	$3100	$2700	$3000
Releasing	$620	$620	NA	NA
Thinning	$825	$800	$800	None
Pruning	$1300	$1900	$400	None
Other	$100	$100	$100	$80
Harvesting (depending on slope)	$32 – $60	$32 – $75	$32 – $50	$35 – $45

Two economic indices were applied to assess the profitability:

- Net Present Value (NPV) provides the potential financial returns of each regime. NPV is the present value of all revenues minus the present value of all costs. The present values of revenues and costs are discounted using the discount rate of 6.4% (Manley, 2024). NPV is calculated at the regime start dates.
- Equivalent Annual Income (EAI) compares investments with different lifespans (rotation lengths) by annualising their cash flows, allowing comparison between regimes with different rotation lengths, where *n* = rotation length and *i* = interest rate.

$$EAI = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

3 Results: National and regional productivity (volume and MAI) by climate scenario

Two measures of productivity are used to present the results, end of rotation wood volume per hectare and MAI, the average annual wood volume produced per hectare per year. While for a given scenario these are comparable, end of rotation wood volume gives a measure of harvested volume or final carbon stored and is strongly influenced by rotation length (time between planting and harvest). The MAI productivity per year allows for direct comparison of regimes with different rotation lengths.

The results are presented in two sub-sections that describe the effect of species, regime (management), RCP, and time-period on productivity. Section 3.1 presents end of rotation wood volume and MAI for all of New Zealand. Section 3.2 presents MAI results for selected regimes summarised by region.

Although the results described below were derived using a leading process-based model designed for simulating the effects of silviculture and climate change on the productivity of species, they should be interpreted with caution considering the model and data limitations outlined in section 2.4.

3.1 National average MAI and volume productivity – effects of species, regime, RCP, and time-period

At the top of this results section is a brief summary of the key findings from the results on national productivity which follow.

Summary of regime-specific national trends in volume and MAI

MAI

- Radiata Sawlog 25 is predicted to be the most productive regime in terms of MAI.
- Radiata Carbon 50 and all the Redwood regimes have similar moderate-high predicted MAI.
- Fastigata Pulpwood 15 and Fastigata Sawlog 25 regimes have similar intermediate predicted MAI, and Fastigata Sawlog 50 is lower.
- Fastigata Carbon 50 has the lowest predicted MAI.

Volume

- Radiata Carbon 50 has the highest predicted volume production over 50 years.
- The next best volume production regimes are predicted for Redwood Carbon 50 followed by Redwood Sawlog NoThin and Thin 40-year regimes.
- Fastigata regimes have much lower predicted volume production than Radiata and Redwood.
- Fastigata Carbon 50 has slightly higher predicted productivity than the Pulpwood and Sawlog regimes, which are similar.

Mean national volume and MAI productivity are presented in Figure 4 and Figure 5 respectively, each comparing baseline with the six combinations of RCP (4.5, 6.0, and 8.5) and time-period (Mid and Late) for each regime.

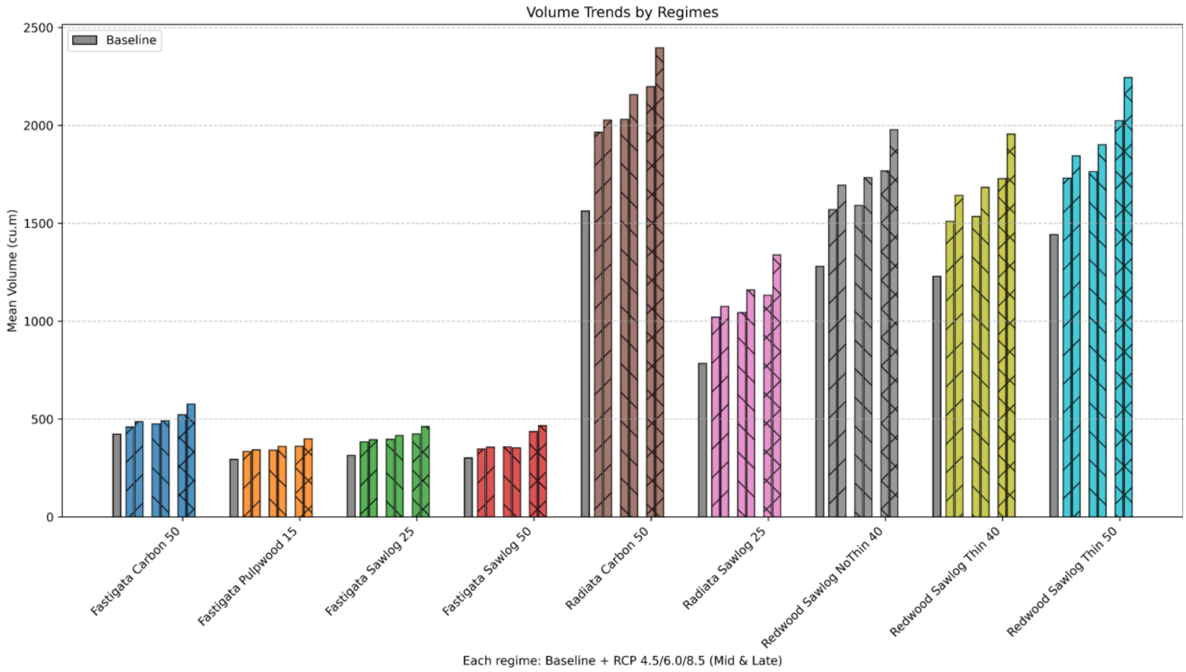


Figure 4: Mean Volume trends by regime, climate (RCP) and time-period. For each regime the seven columns represent the baseline (grey) and then three RCPs (4.5, 6.0, and 8.5) by two time-periods (Mid and Late).

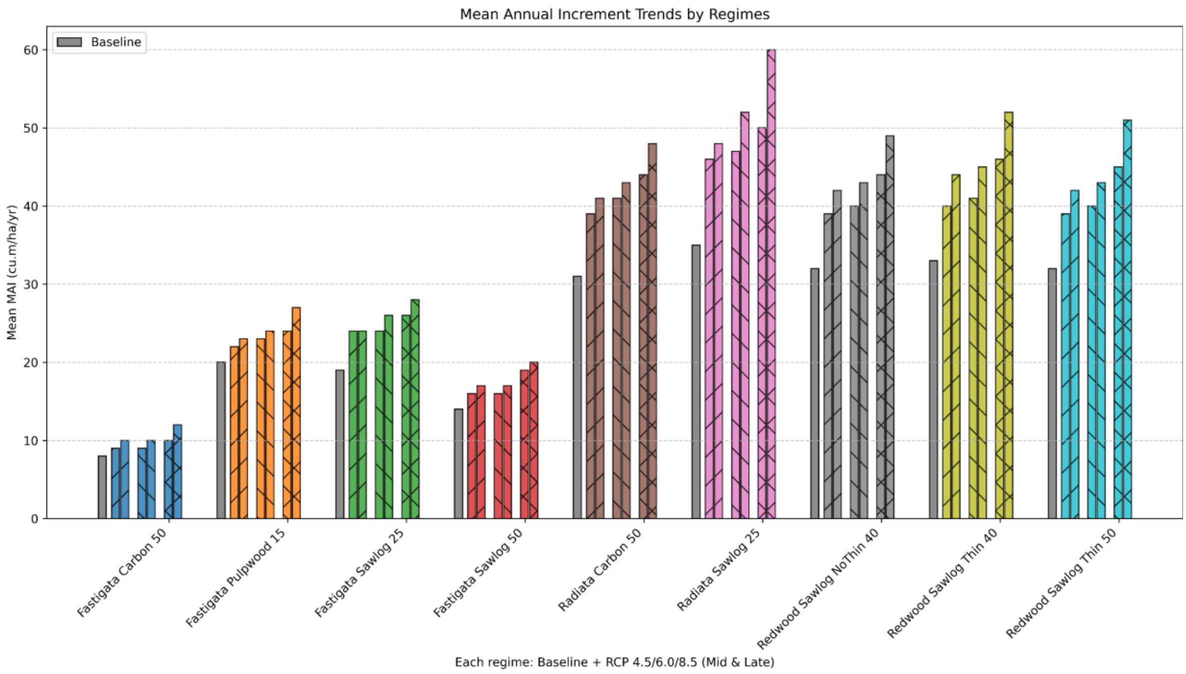


Figure 5: Mean Annual Increment (MAI) for regimes, climates (RCP) and time-periods. For each regime the seven columns represent the baseline (grey) and then three RCPs (4.5, 6.0, and 8.5) by two time-periods (Mid and Late).

The following sub-sections (3.1.1 to 3.1.3) describe how MAI changes with climate scenario and time period for each species, followed by section 3.1.4, which presents graphs showing these trends for each regime (Figure 6 to Figure 14).

3.1.1 Fastigata regimes

Predicted MAI was substantially lower for Fastigata than for either Radiata or Redwood. Predicted MAI was greatest for the Fastigata Pulpwood 15 and Fastigata Sawlog 25 regimes, intermediate for Fastigata Sawlog 50 regime, and lowest for the Fastigata Carbon 50 regime.

Compared to the baseline, the effect of RCP and time-period was consistent across all Fastigata regimes and can be summarised as a moderate increase from baseline to RCP 4.5, a small to negligible difference between RCP 4.5 and RCP 6.0, and a further moderate increase from RCP 6.0 to RCP 8.5. For all RCPs, a larger change is predicted between Baseline and Mid time-period than between Mid and Late period.

3.1.2 Radiata regimes

Predicted MAI was higher for the Radiata Sawlog 25 regime than for all other combinations of management and species. The predicted MAI was a little lower for Radiata Carbon 50 than the Radiata Sawlog 25 but was still comparable with all Redwood regimes and more productive than all Fastigata regimes.

For the two Radiata regimes modelled, productivity was predicted to increase substantially from baseline to RCP 4.5, with a further less marked increase from RCP 4.6 to RCP 6.0, and another substantial increase from RCP 6.0 to RCP 8.5. For all RCPs, a larger change is predicted between Baseline and Mid time-period than between Mid and Late time-period.

3.1.3 Redwood regimes

The predicted MAI is similarly high for all three Redwood regimes, only exceeded by Radiata Sawlog 25. The pattern of variation in MAI with RCP and time-period is similar for all Redwood regimes and parallels that observed for Radiata. Productivity was predicted to increase substantially from baseline to RCP 4.5, with a further less marked increase from RCP 4.6 to RCP 6.0, and another large increases from RCP 6.0 to RCP 8.5. For all RCPs, a larger change is predicted between Baseline and Mid time-period than between Mid and Late time-period.

3.1.4 Productivity for all regimes

This section presents productivity for each of the nine regimes. For each regime there are a set of four line charts showing volume, percentage volume change from baseline, MAI, and percentage MAI change from baseline. Each chart includes baseline, and the six combinations of three RCPs and two time-periods.

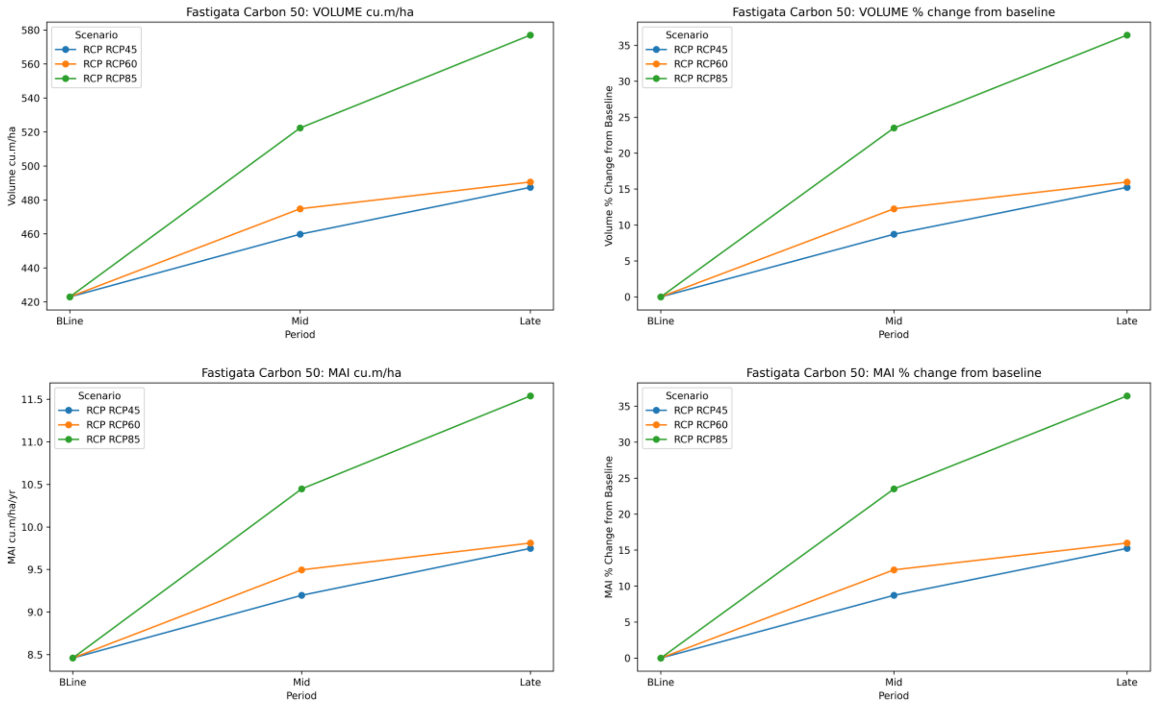


Figure 6: National Volume and MAI Productivity for Fastigata Carbon 50 and percentage change from baseline.

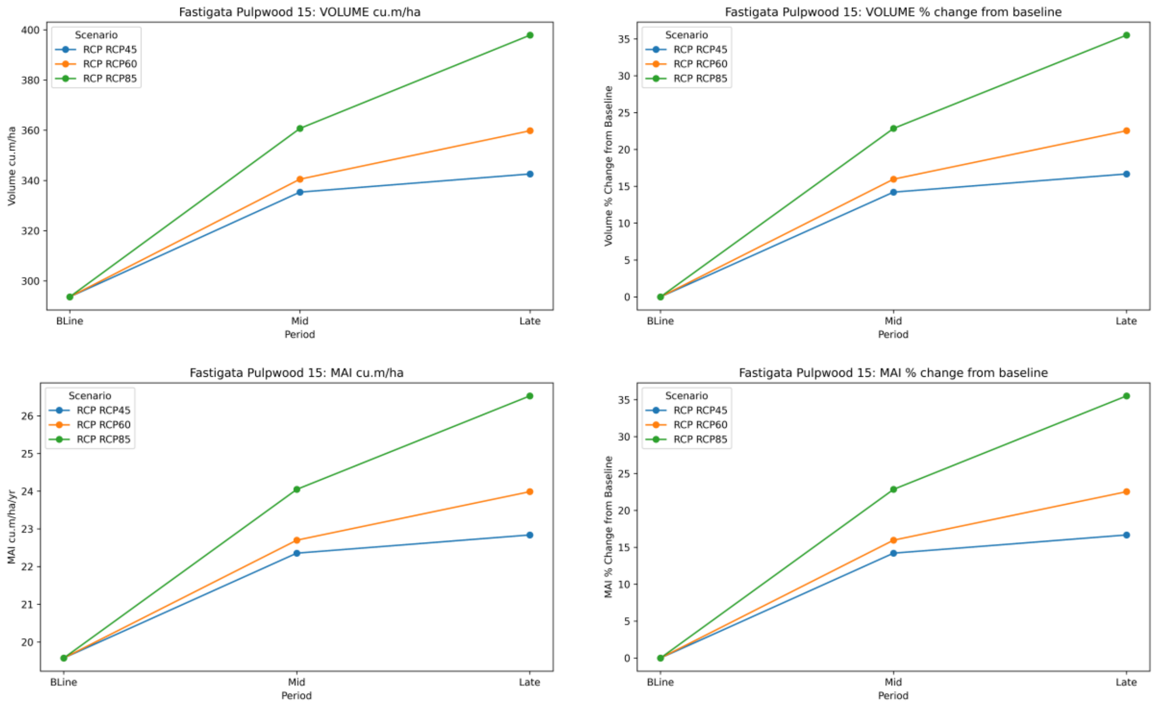


Figure 7: National Volume and MAI Productivity for Fastigata Pulpwood 15 and percentage change from baseline.

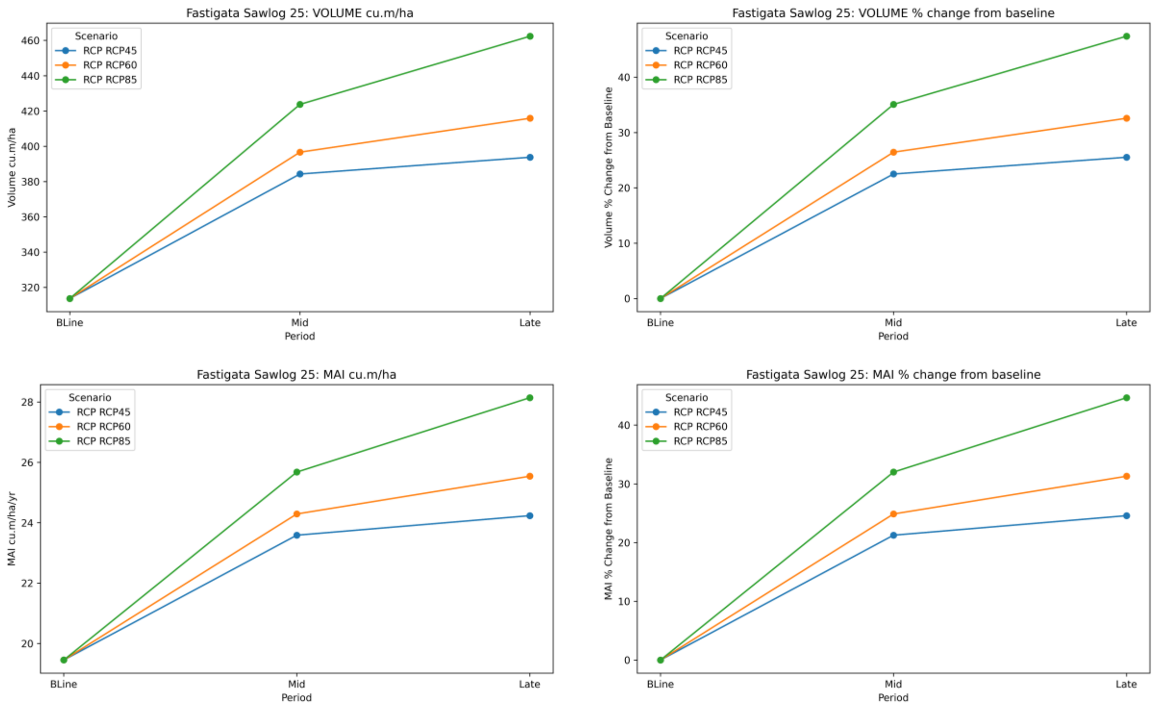


Figure 8: National Volume and MAI Productivity for Fastigata Sawlog 25 and percentage change from baseline.

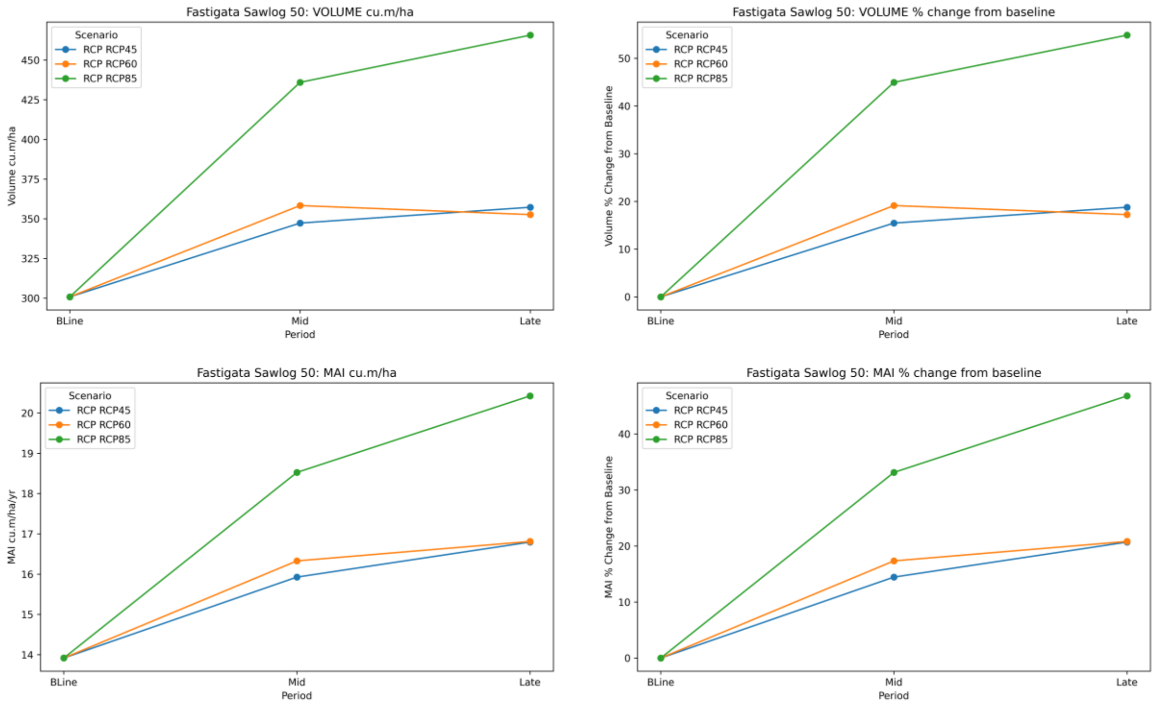


Figure 9: National Volume and MAI Productivity for Fastigata Sawlog 50 and percentage change from baseline.

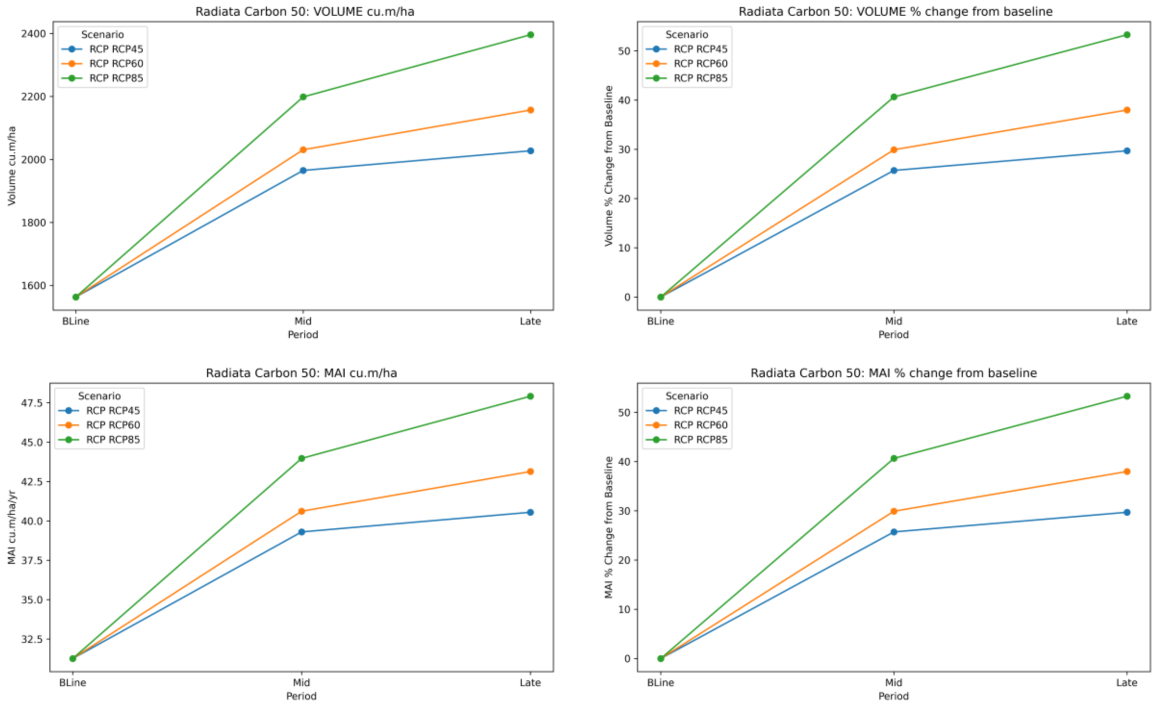


Figure 10: National Volume and MAI Productivity for Radiata Carbon 50 and percentage change from baseline.

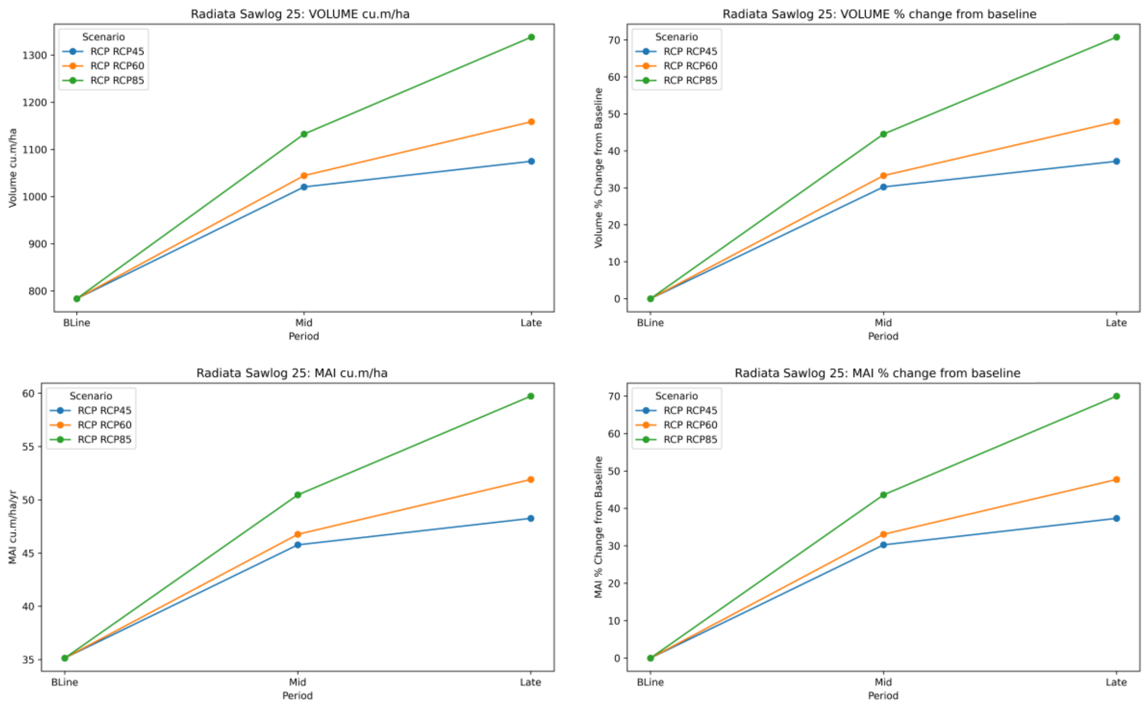


Figure 11: National Volume and MAI Productivity for Radiata Sawlog 25 and percentage change from baseline.

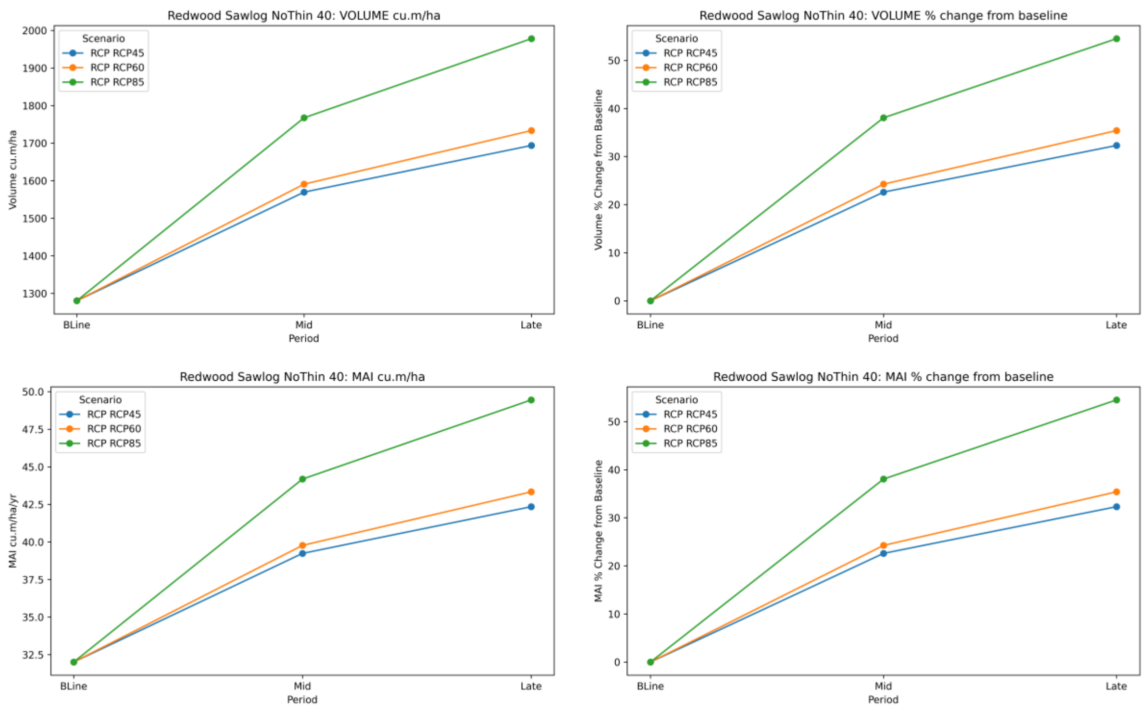


Figure 12: National Volume and MAI Productivity for Redwood Sawlog NoThin 40 and percentage change from baseline.

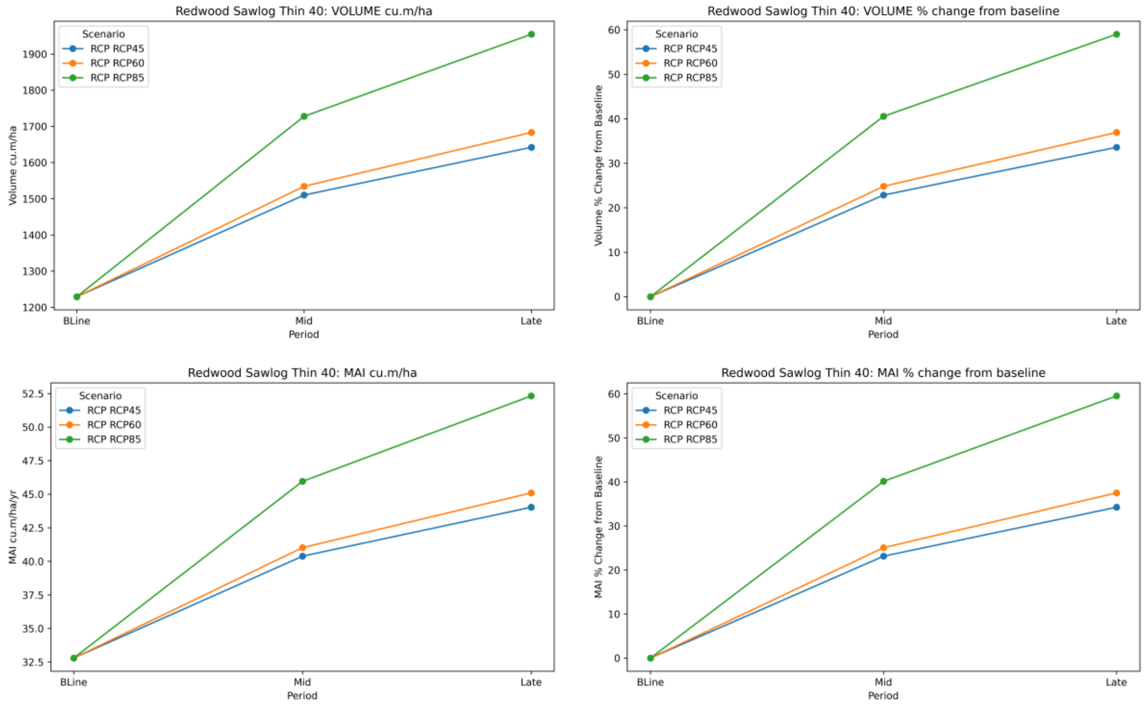


Figure 13: National Volume and MAI Productivity for Redwood Sawlog Thin 40 and percentage change from baseline.

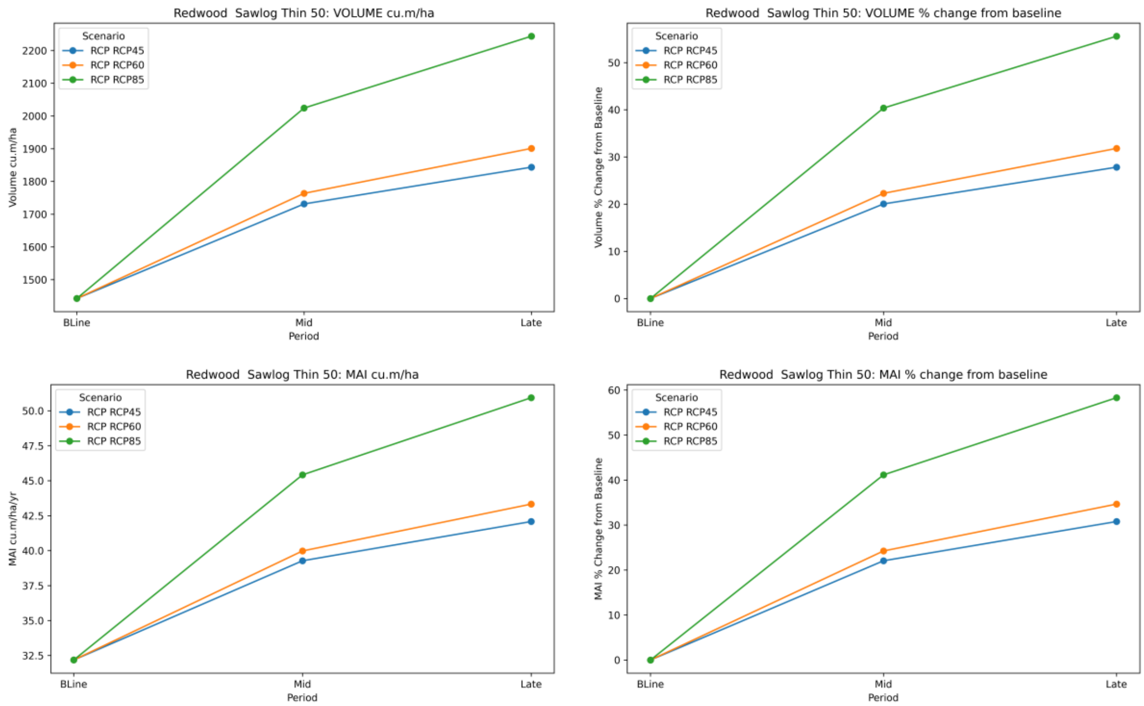


Figure 14: National Volume and MAI Productivity for Redwood Sawlog Thin 50 and percentage change from baseline.

3.2 Regional productivity analysis

This section begins with a brief summary of the key regional productivity findings, followed by detailed results.

Summary of regional productivity analysis (MAI)

Overall

- CABALA-W predicts that Radiata Sawlog 25 will have the highest MAI productivity of all tested regimes across all regions and RCPs.
- The predicted MAI productivity of Redwood Sawlog Thin 40 increases under higher RCPs and shows the largest increases in South Island regions by the Late period.
- The predicted MAI productivity of Fastigata Pulpwood 15 regime is lower than that of alternatives across all regions, especially under baseline and RCP 4.5.
- The predicted MAI productivity of Redwood decreased in some regions under RCP 8.5.

By regime

- Radiata Sawlog 25 is predicted to be the most productive regime in every region, regardless of RCP or period.
- The predicted productivity of Redwood regimes improves under climate changes but remains lower than Radiata and higher than Fastigata.
- Fastigata Pulpwood and Carbon regimes show strong increases in predicted productivity in response to climate changes, especially in the North Island.
- For each simulated regime, the pattern of variation in predicted productivity among the seven combinations of RCP and time-period is consistent in all regions.
- Predicted productivity in Southland, West Coast, and parts of Canterbury consistently rank lowest across all regimes.
- Most regimes have the same regional rankings of predicted productivity.

The pattern of variation in productivity among species, regime, RCP, and time-period is similar across the sixteen regions and repeats patterns reported at the national level in Section 3.1. We have therefore selected one regime for each species as representative case studies. Three sections describe the effect of climate change on mean productivity of these regimes (3.2.1 Fastigata Sawlog 25, 3.2.2 Radiata Sawlog 25, and 3.2.3 Redwood Sawlog Thin 40), using the change from baseline to RCP 6.0 as representative of broader climate change patterns across New Zealand.

Following the sections on representative regimes (3.2.1, 3.2.2, and 3.2.3) is section 3.2.4 containing a series of figures (Figure 21 to Figure 29) used to present the MAI productivity for regimes by region. Following that is section 3.2.5 containing a series of figures (Figure 30 to Figure 43) used to present the MAI productivity for regions by regime. The figures are box-and-whisker plots where the circle represents the mean, the box represents the 1st and 3rd quartiles, and the whiskers represent the range of the data excluding outliers (being the respective quartile value multiplied by 1.5 times the range between quartiles 1 and 3). These plots therefore describe the underlying distribution of productivity values modelled at high resolution on the 5 km grid within each region. This information provides useful insights into variations between and among regimes and regions, revealing that some regimes and regions are more and less variable than others.

3.2.1 Fastigata Sawlog 25 regime

The effect of RCP and time-period on mean productivity (MAI) of the Fastigata Sawlog 25 regime is summarised by region in Figure 15. The predicted baseline productivity was lowest in Tasman and around 20 cu.m/ha/yr in all other local government regions. In many regions, particularly Bay of Plenty, Waikato, Otago, and Wellington, predicted productivity under all RCP's is highly variable and negatively skewed indicating some locations or soil types with extremely low productivity.

The forecast MAI of this regime increased uniformly across the sixteen regions by about 15% from the baseline to mid time-period under RCP 6.0. The forecast increase in productivity was lowest in Tasman at about 8% of baseline (Figure 16).

Figure 15: Productivity (MAI) of Fastigata Sawlog 25 regime by region.

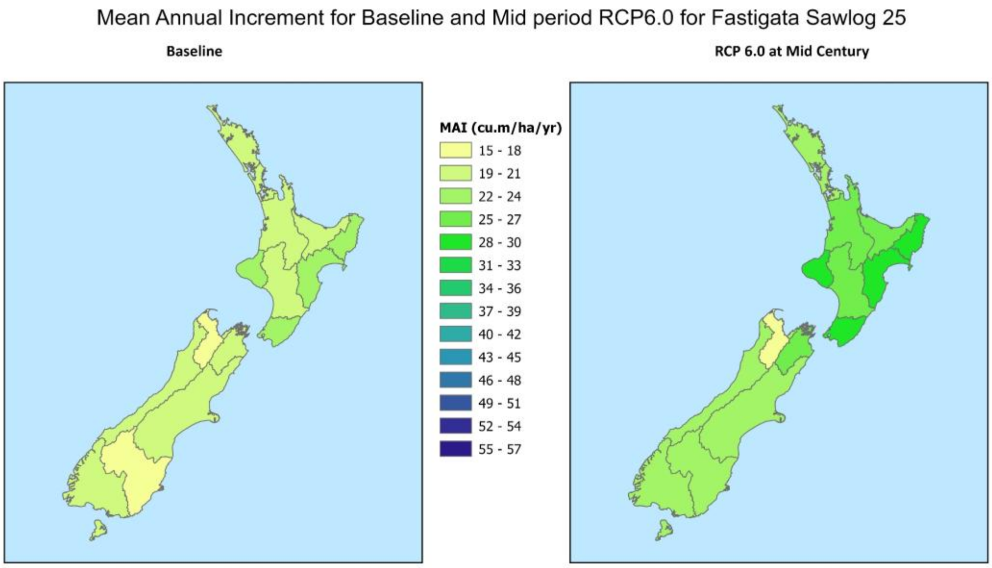


Figure 16: Map showing mean productivity (MAI) of Fastigata Sawlog 25 for each of sixteen regions and comparing the baseline scenario and RCP 6.0.

3.2.2 Radiata Sawlog 25 regime

The effect of RCP and time-period on mean productivity (MAI) of the Radiata Sawlog 25 regime is summarised by region in Figure 17. This regime is the most productive of all those modelled in all regions. For most regions productivity was more uniform, and the distribution was less skewed for Radiata Sawlog 25 (Figure 17) than for Fastigata Sawlog 25 (Figure 15). For both these regimes predicted productivity was most variable in Bay of Plenty and Waikato regions.

Under RCP 6.0, a large proportional increase in productivity was predicted for Radiata Sawlog 25 across all sixteen local government regions by the mid time-period. An increase of about 30% occurred uniformly across the regions, including cooler regions like Otago and Southand (Figure 18).

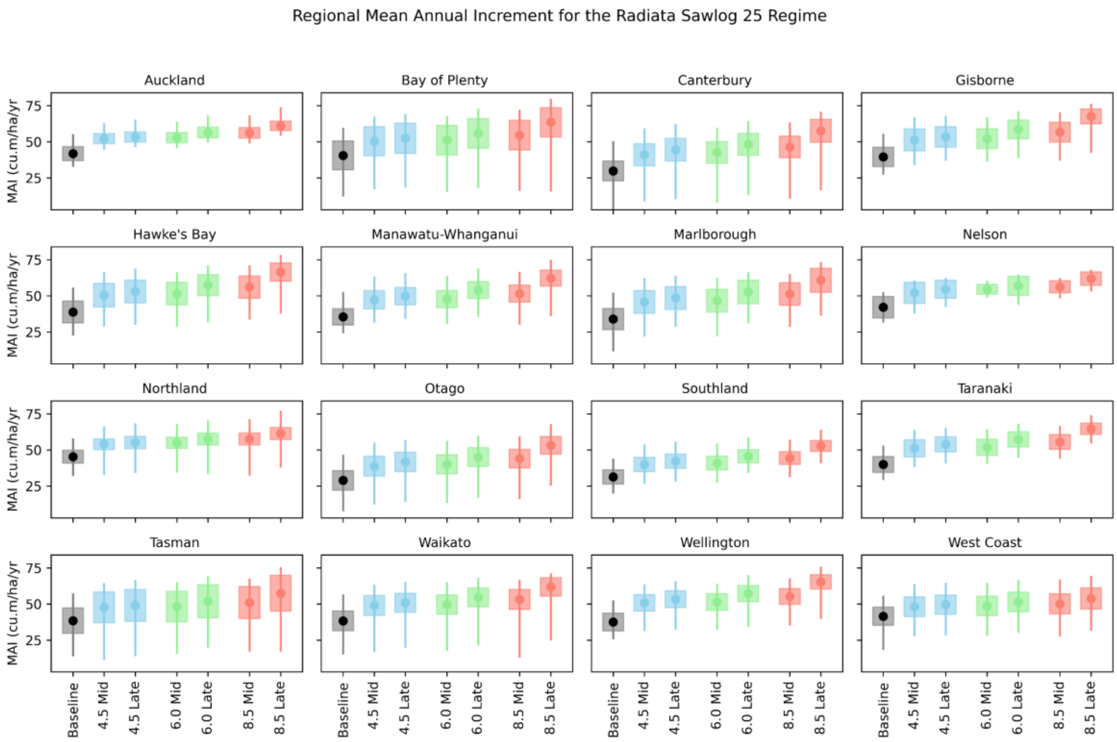


Figure 17: Productivity (MAI) of Radiata Sawlog 25 regime by region.

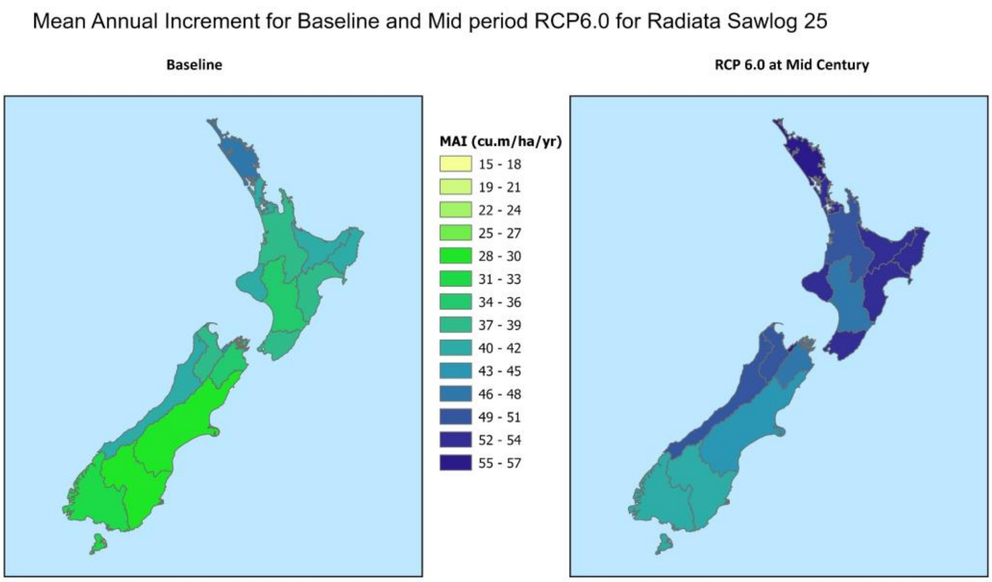


Figure 18: Map showing mean productivity (MAI) of Radiata Sawlog 25 for each of sixteen regions and comparing the baseline scenario and RCP 6.0.

3.2.3 Redwood Sawlog Thin 40 regime

The effect of RCP and time-period on mean productivity (MAI) of the Redwood Sawlog Thin 40 regime is summarised by region in Figure 19. The regime performs strongly in all regions. Although it is less productive in the south, it benefits from the warming conditions in all local government regions with a predicted increase by the mid time-period of 23% under RCP 6.0 (Figure 20).

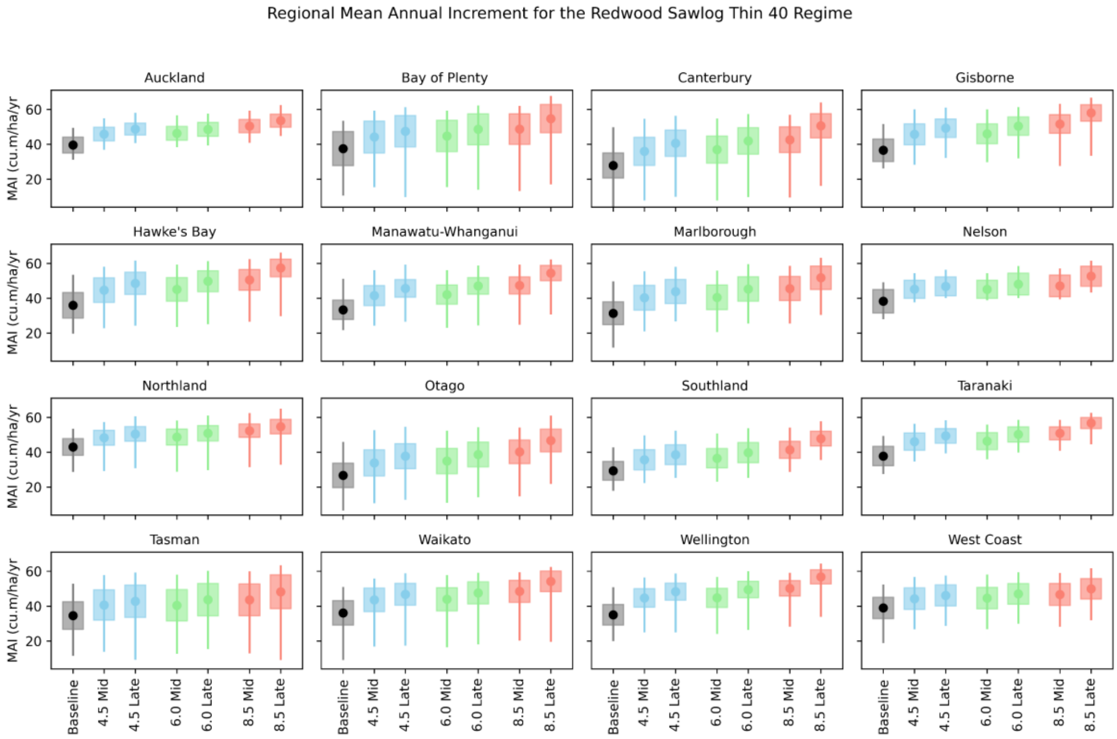


Figure 19: Productivity (MAI) of Redwood Sawlog Thin 40 regime by region.

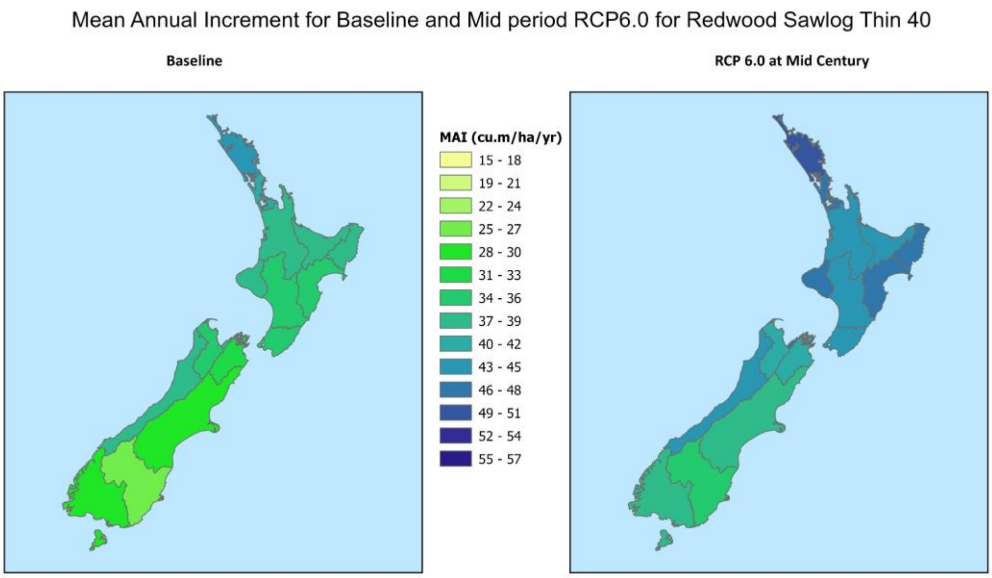


Figure 20: Map showing mean productivity (MAI) of Redwood Sawlog Thin 40 for each of sixteen regions and comparing the baseline scenario and RCP 6.0.

3.2.4 MAI productivity for all regimes

This section presents MAI productivity for each of the nine regimes. Mean annual increment is used because it allows comparisons across regimes having different rotation lengths. For each regime there is a chart showing MAI for each of the sixteen regions. Each chart includes baseline, and the six combinations of three RCPs and two time-periods.

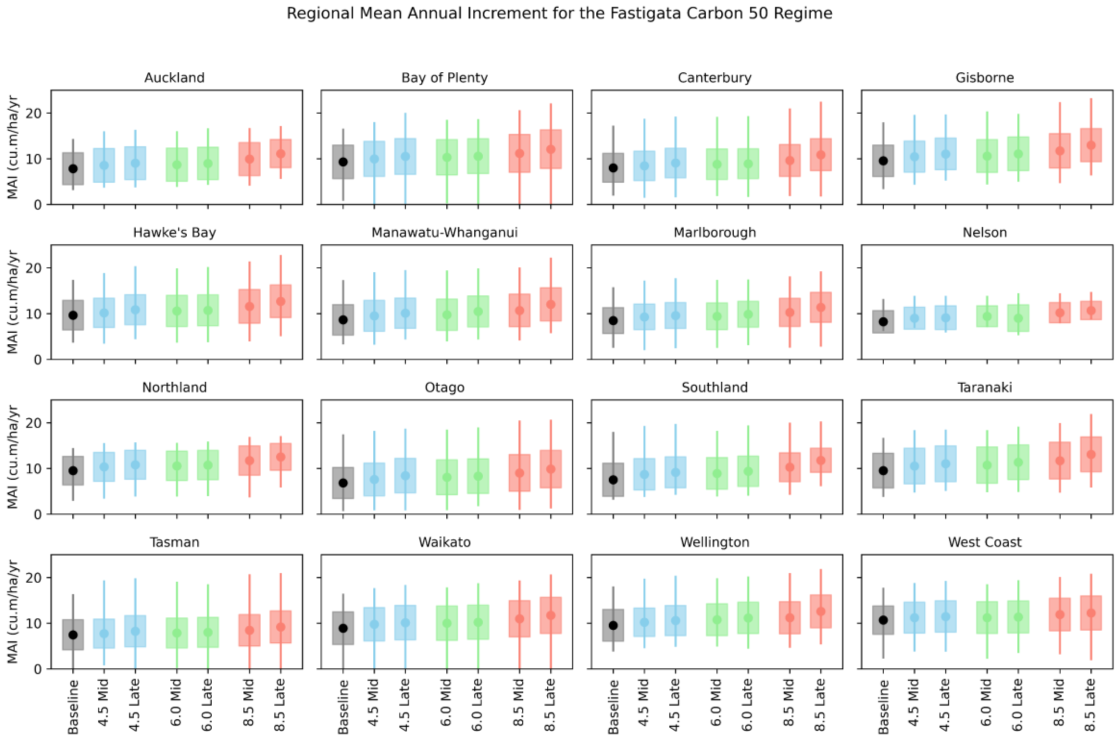


Figure 21: Productivity (MAI) of Fastigata Carbon 50 regime by region.

Figure 22: Productivity (MAI) of Fastigata Pulpwood 15 regime by region.

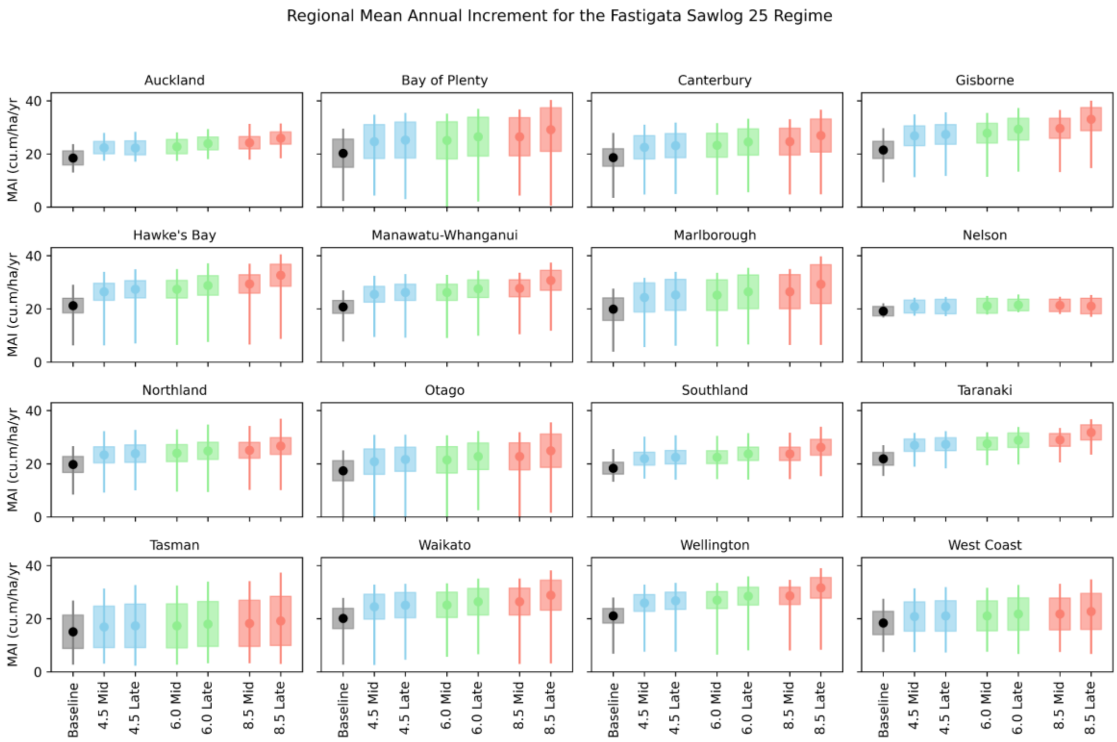


Figure 23: Productivity (MAI) of Fastigata Sawlog 25 regime by region.

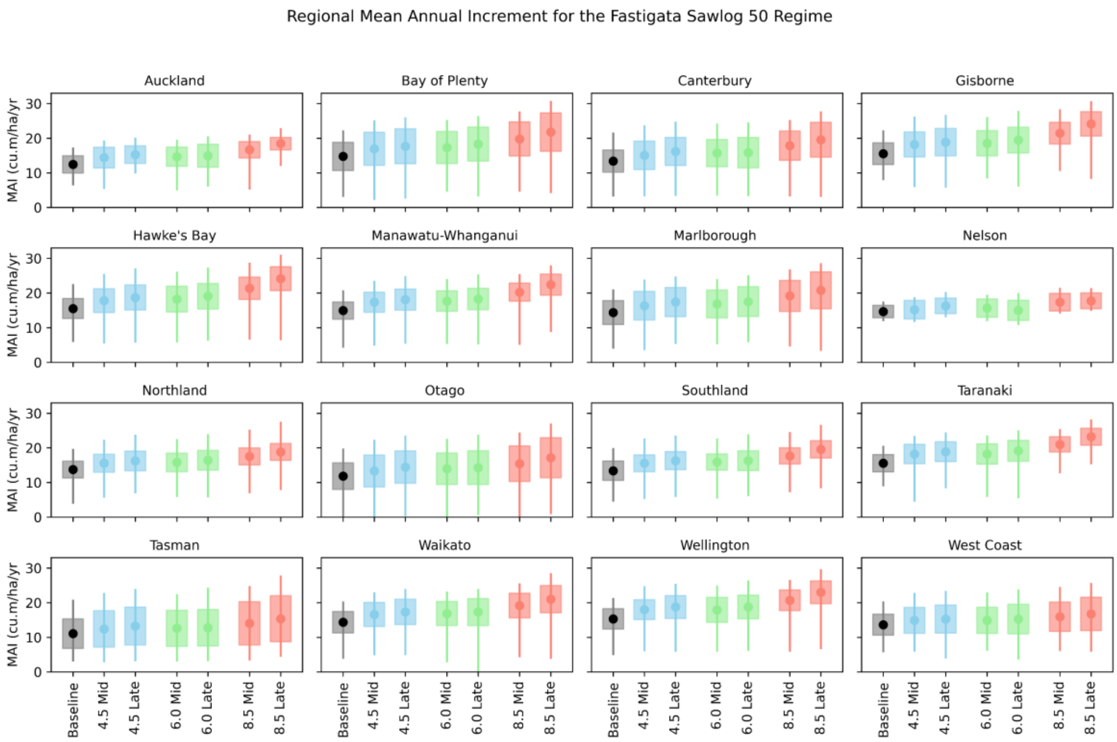


Figure 24: Productivity (MAI) of Fastigata Sawlog 50 regime by region.

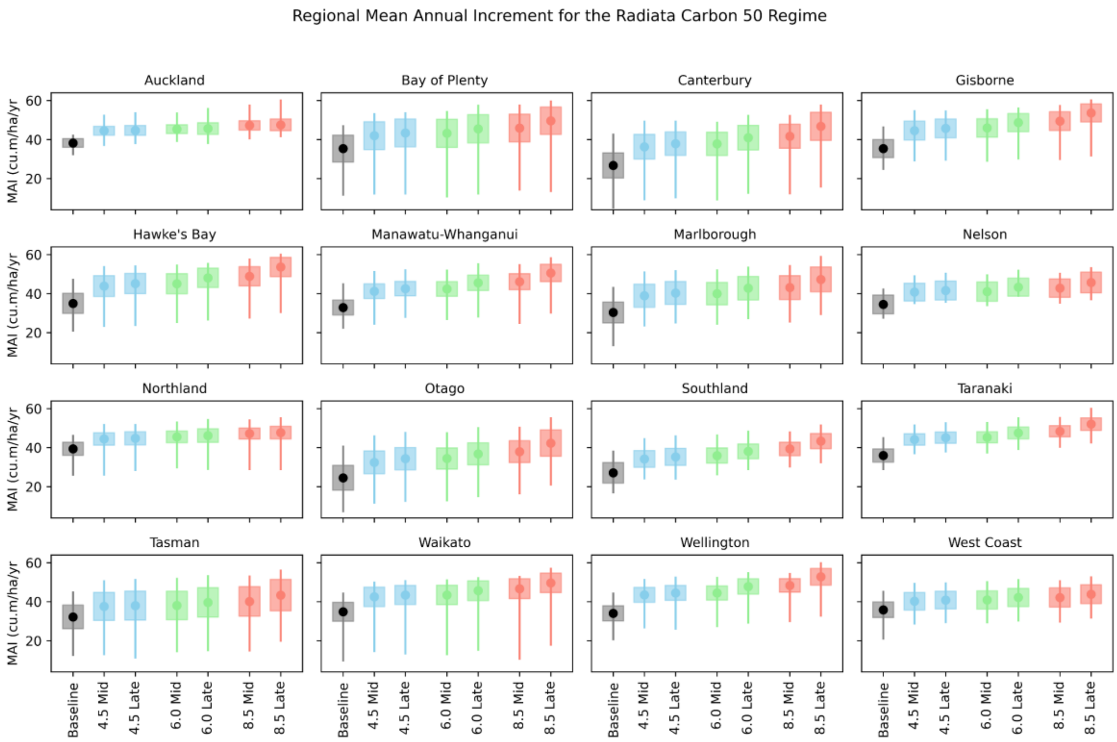


Figure 25: Productivity (MAI) of Radiata Carbon 50 regime by region.

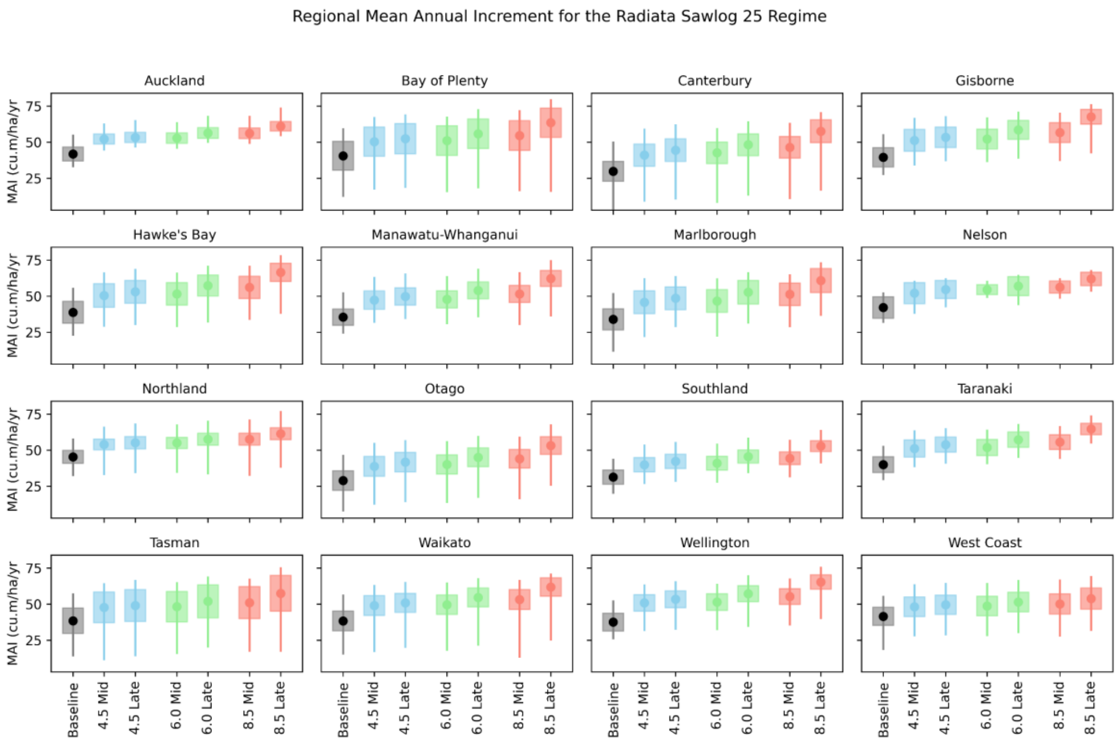


Figure 26: Productivity (MAI) of Radiata Sawlog 25 regime by region.

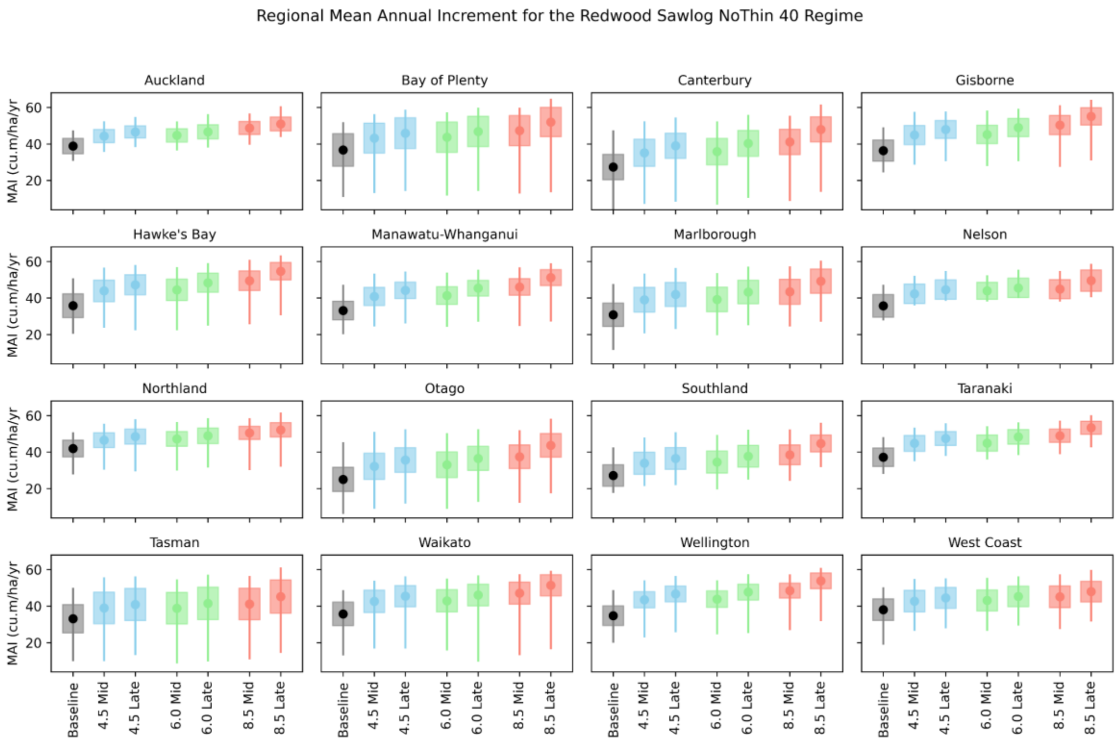


Figure 27: Productivity (MAI) of Redwood Sawlog NoThin 40 regime by region.

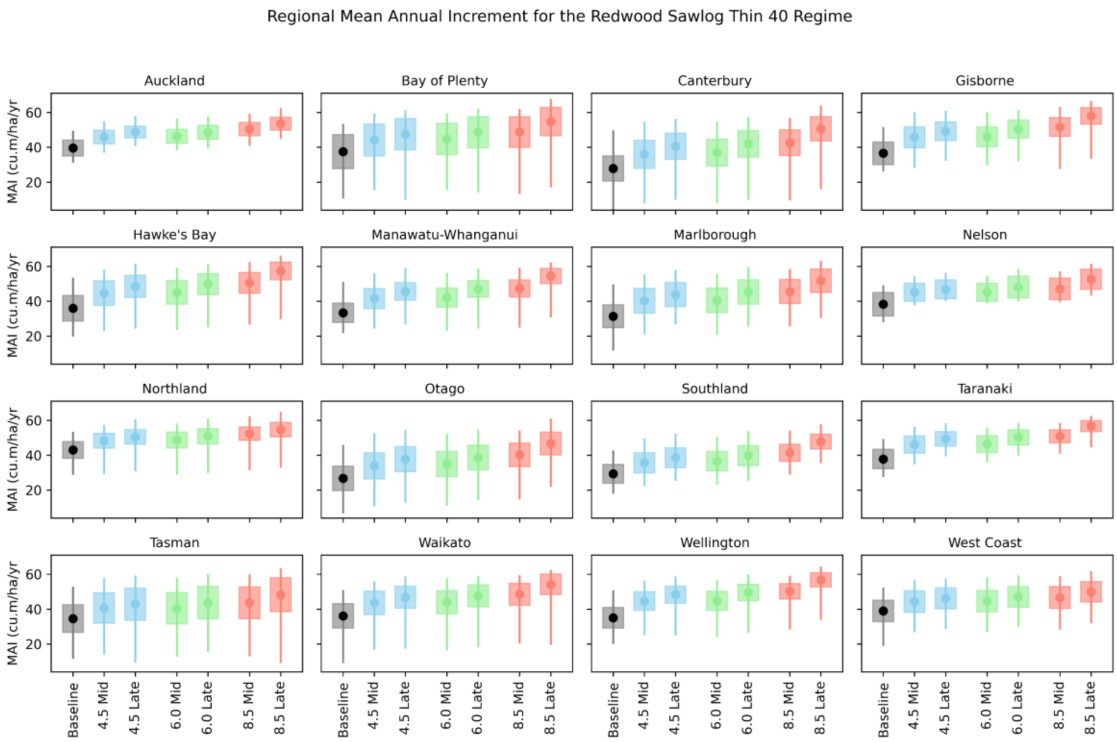


Figure 28: Productivity (MAI) of Redwood Sawlog Thin 40 regime by region.

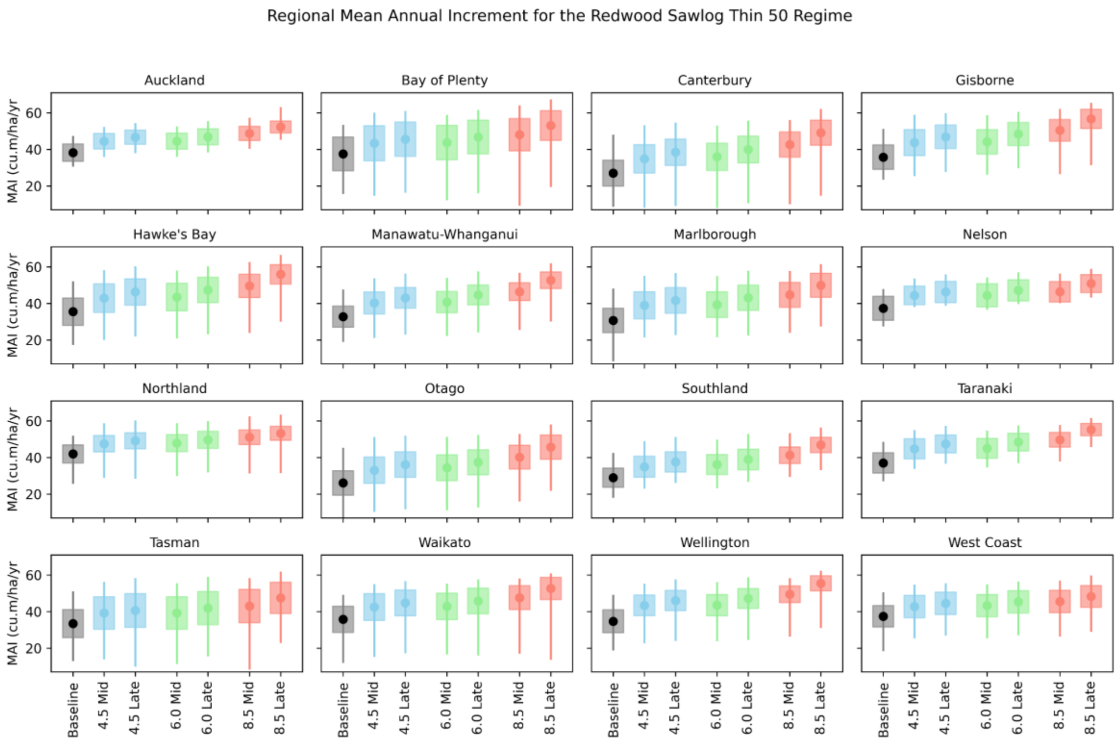


Figure 29: Productivity (MAI) of Redwood Sawlog Thin 50 regime by region.

3.2.5 MAI productivity for all regions

This section presents MAI productivity for each of the sixteen regions. Mean annual increment is used because it allows comparisons across regimes having different rotation lengths. For each region there is a chart showing MAI for each of the nine regimes. Each chart includes baseline, and the six combinations of three RCPs and two time-periods.

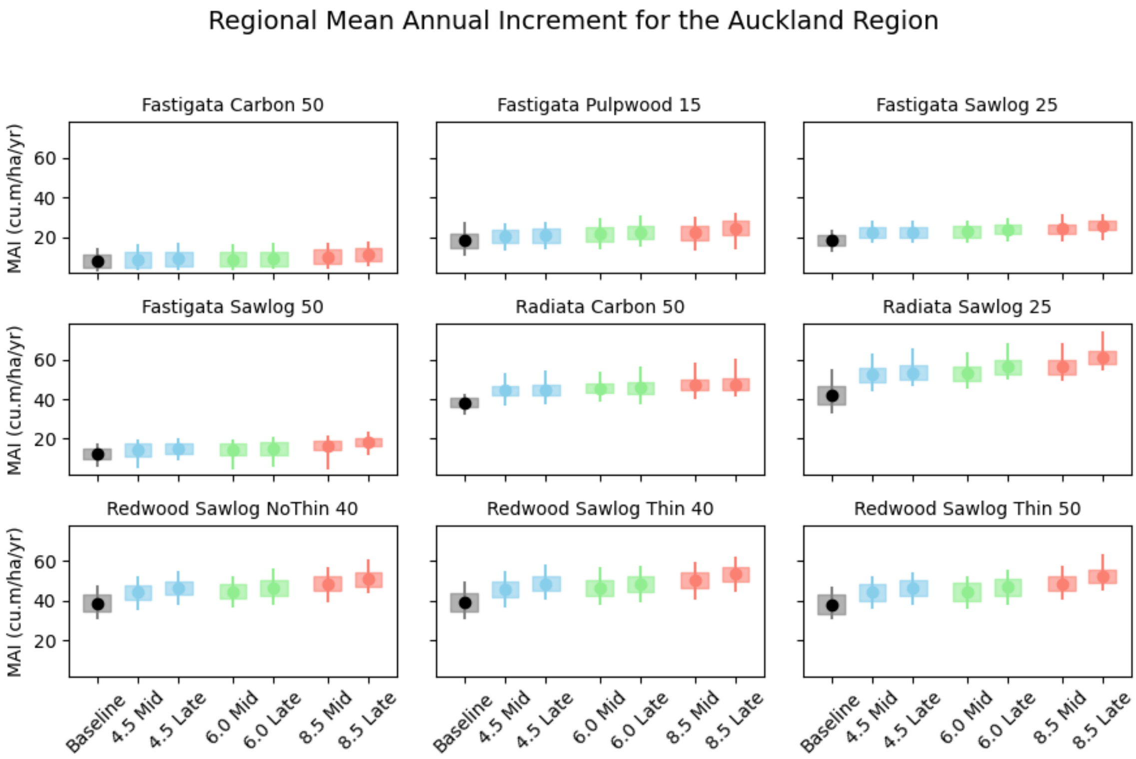


Figure 30: Productivity (MAI) of Auckland region by regime.

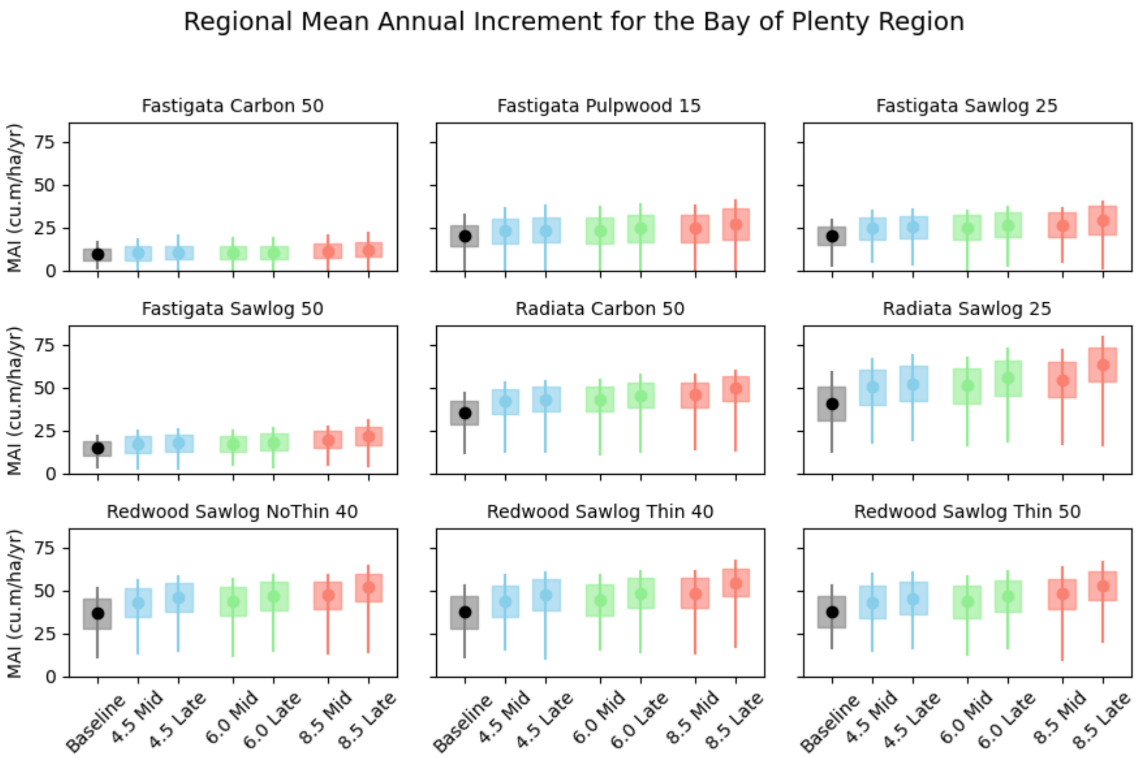


Figure 31: Productivity (MAI) of Bay of Plenty region by regime.

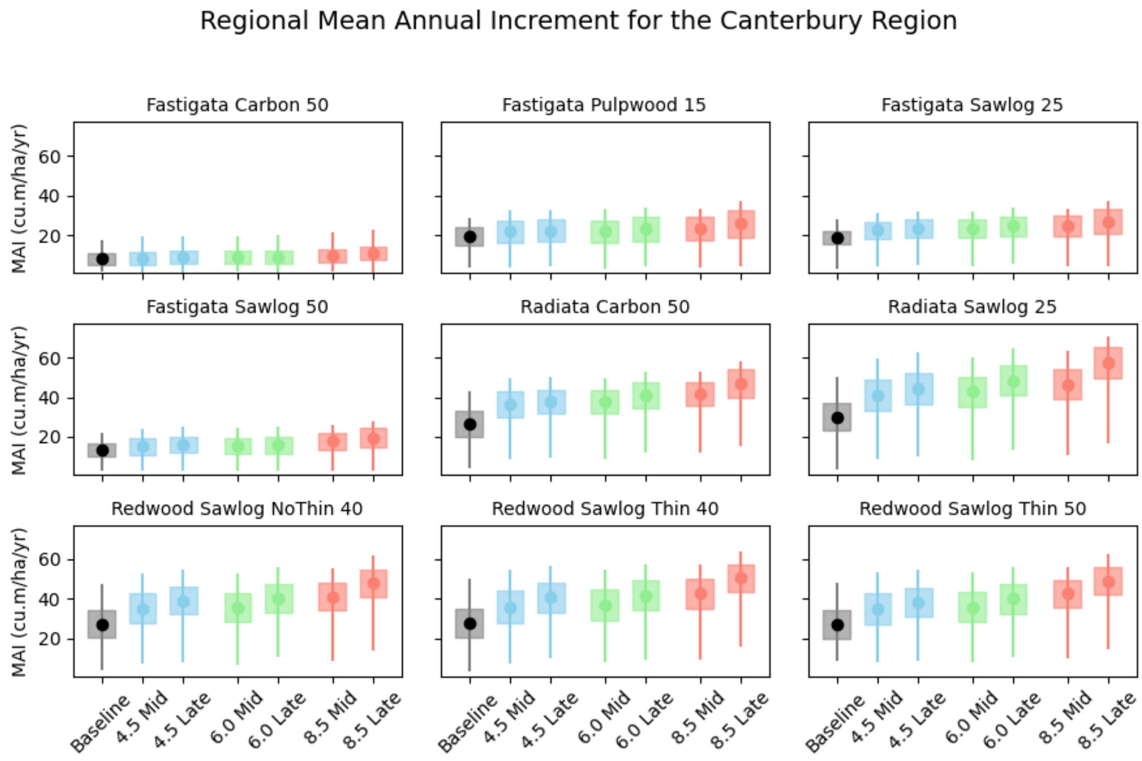


Figure 32: Productivity (MAI) of Canterbury region by regime.

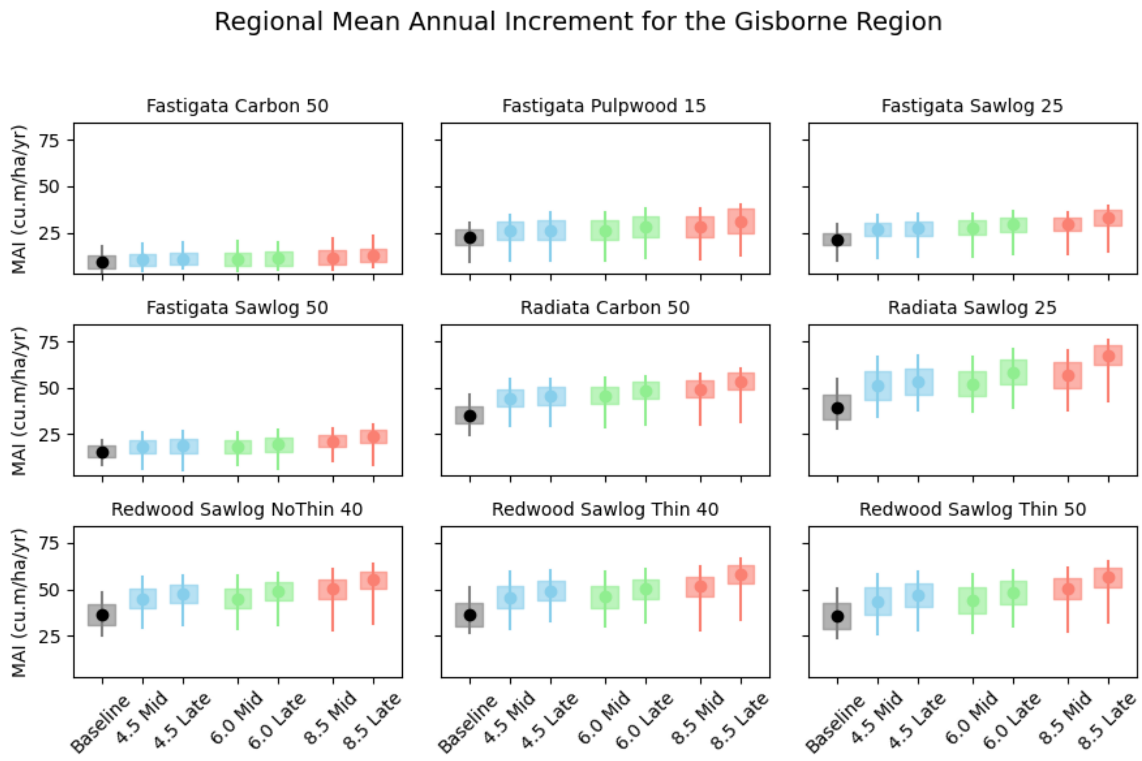


Figure 33: Productivity (MAI) of Gisborne region by regime.

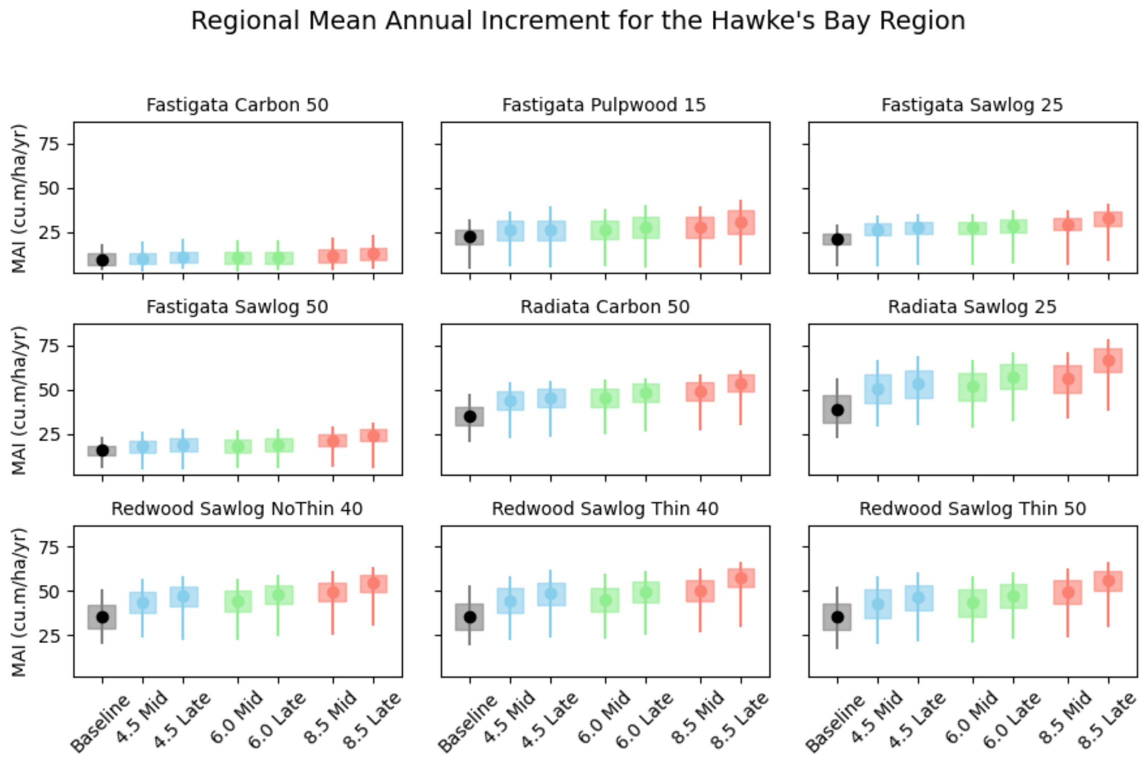


Figure 34: Productivity (MAI) of Hawke's Bay region by regime.

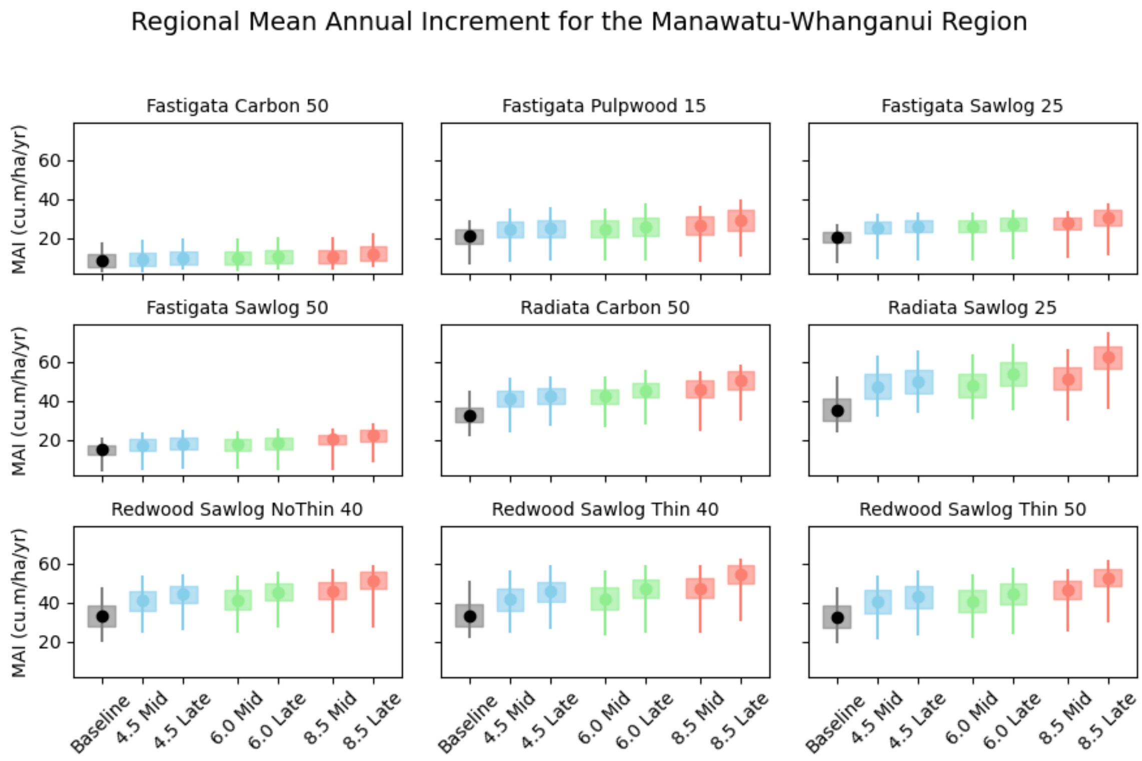


Figure 35: Productivity (MAI) of Manawatu-Whanganui region by regime.

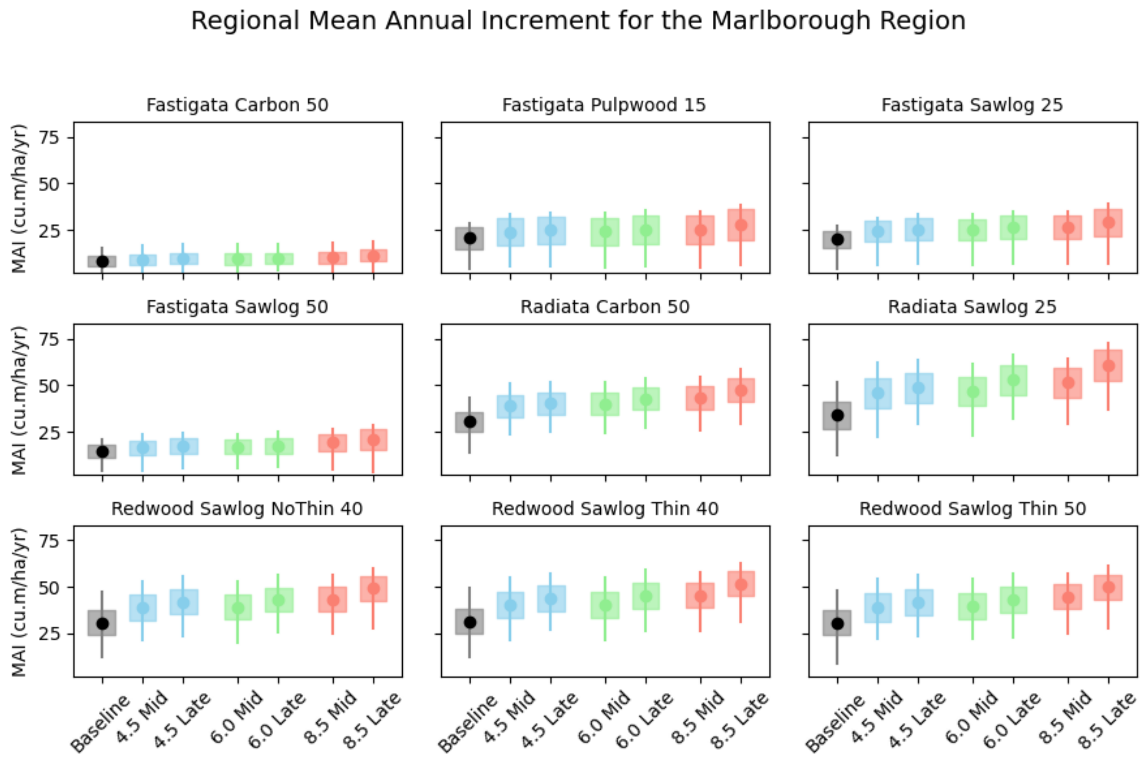


Figure 36: Productivity (MAI) of Marlborough region by regime.

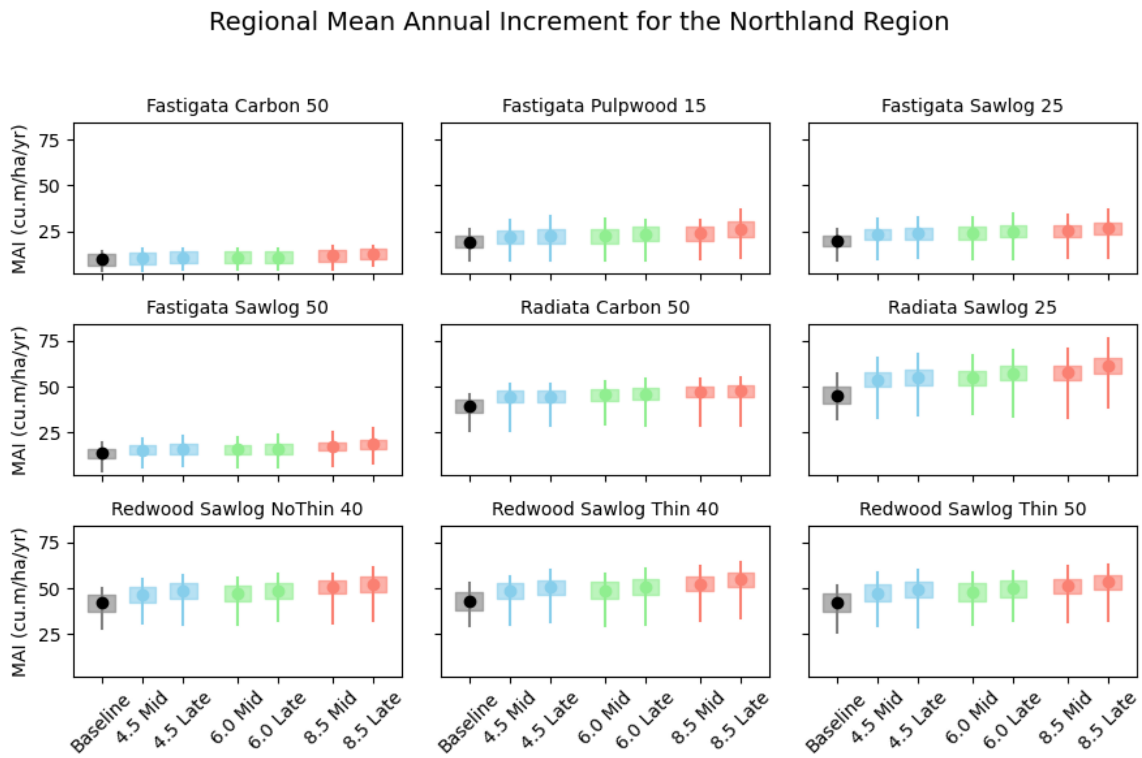


Figure 37: Productivity (MAI) of Northland regime by region.

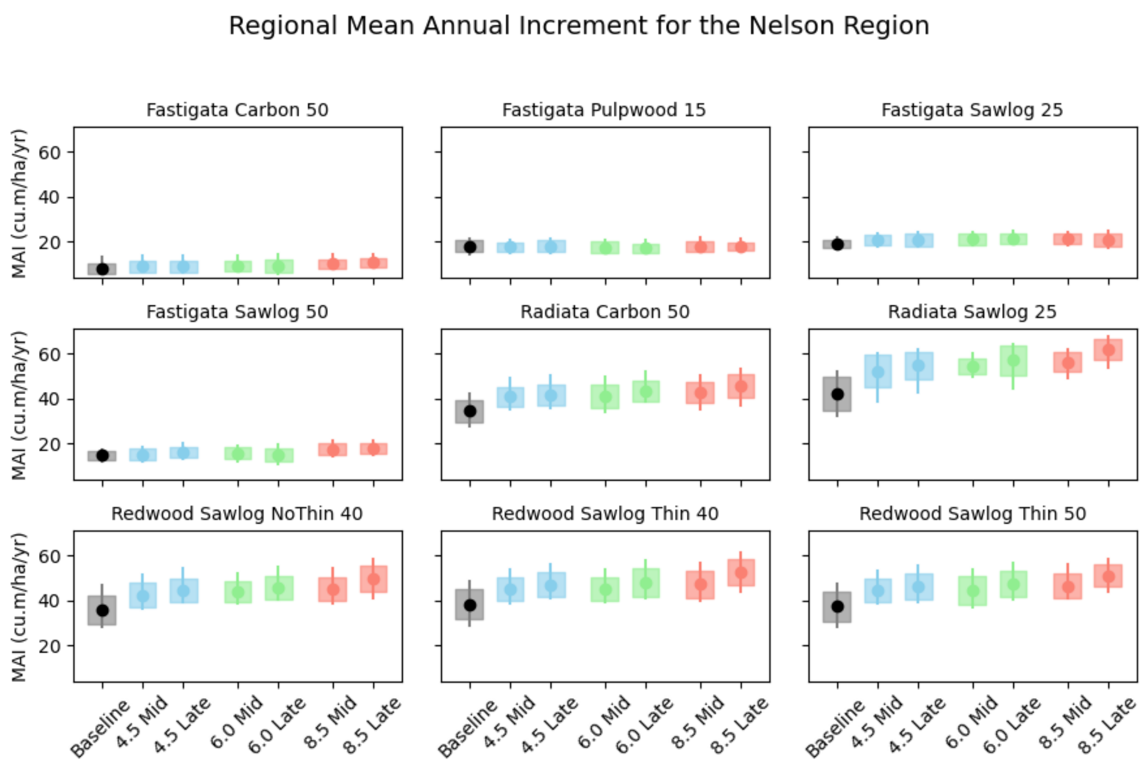


Figure 38: Productivity (MAI) of Nelson region by regime.

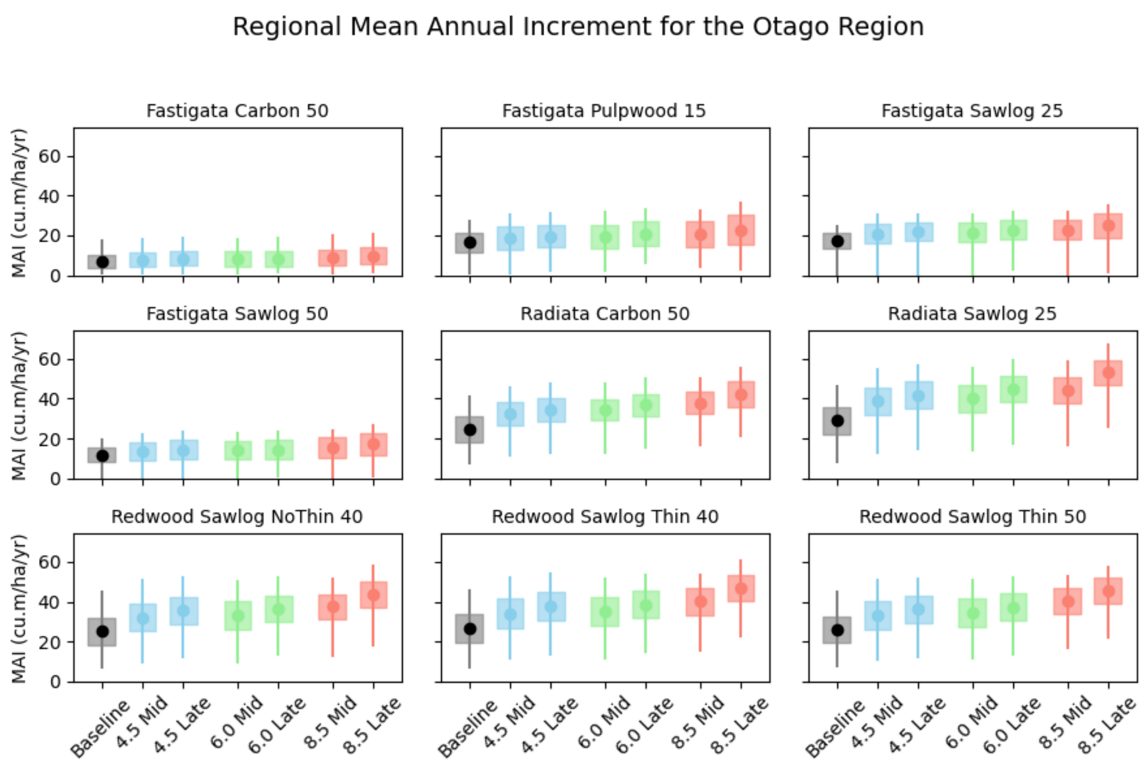


Figure 39: Productivity (MAI) of Otago region by regime.

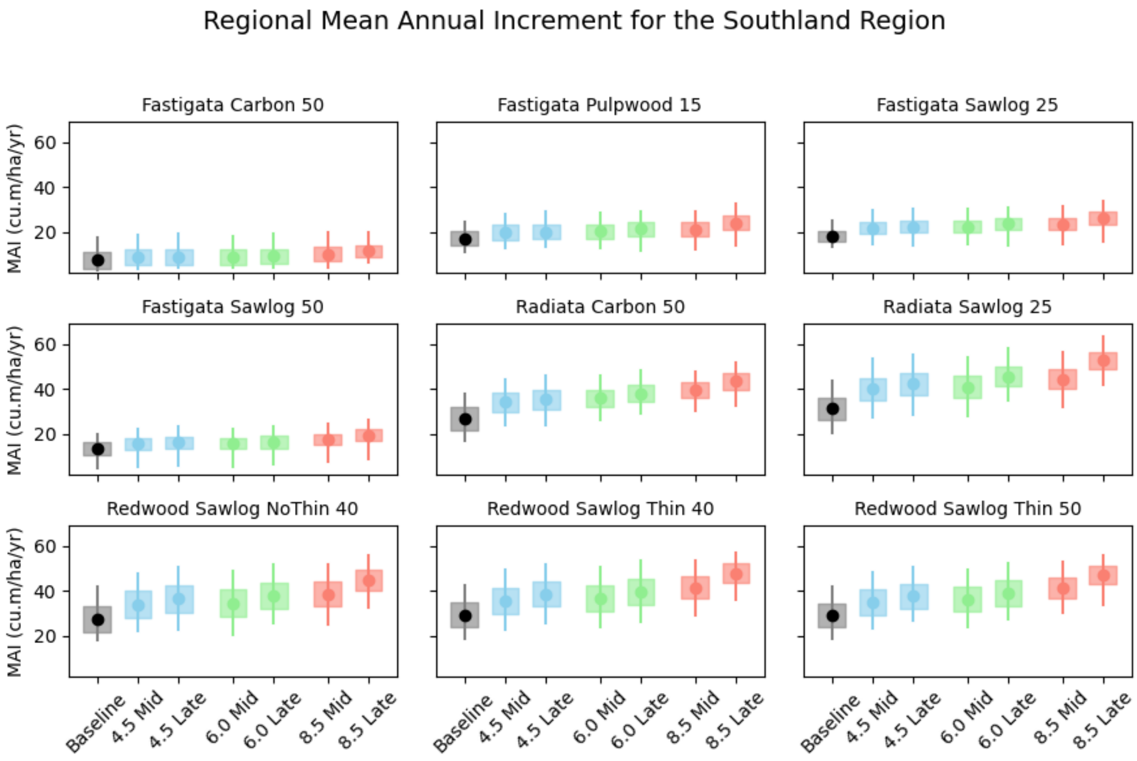


Figure 40: Productivity (MAI) of Southland region by regime.

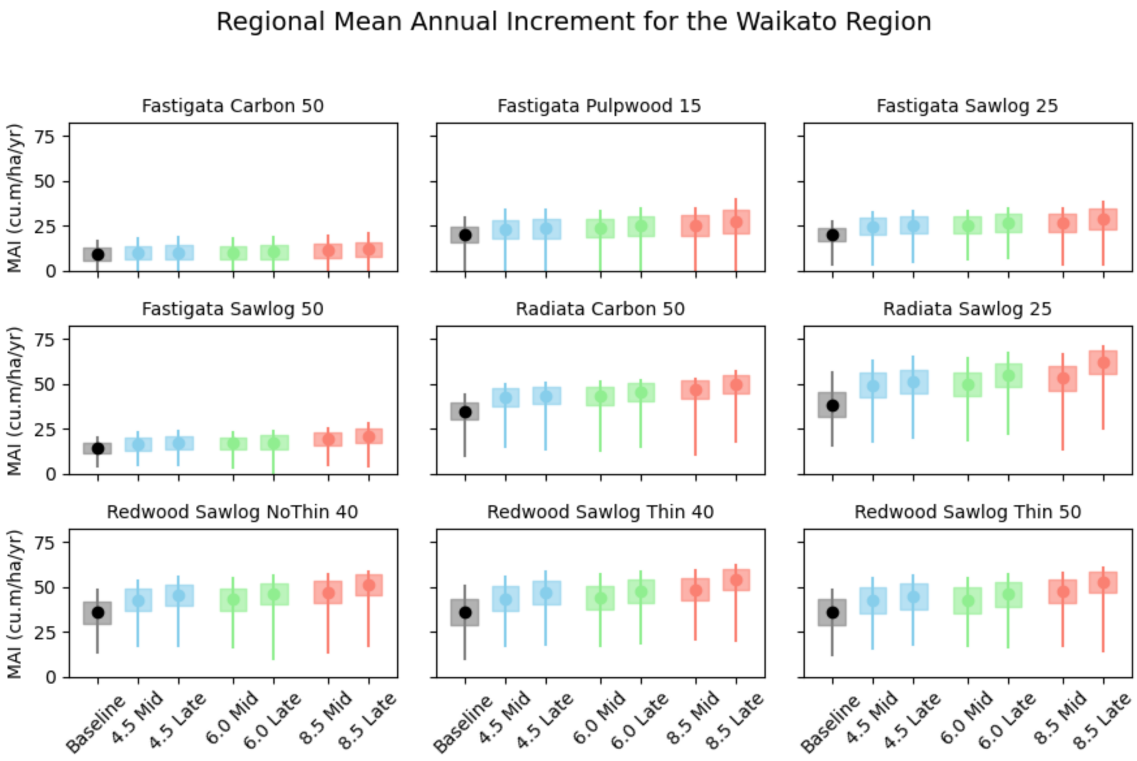


Figure 41: Productivity (MAI) of Waikato region by regime.

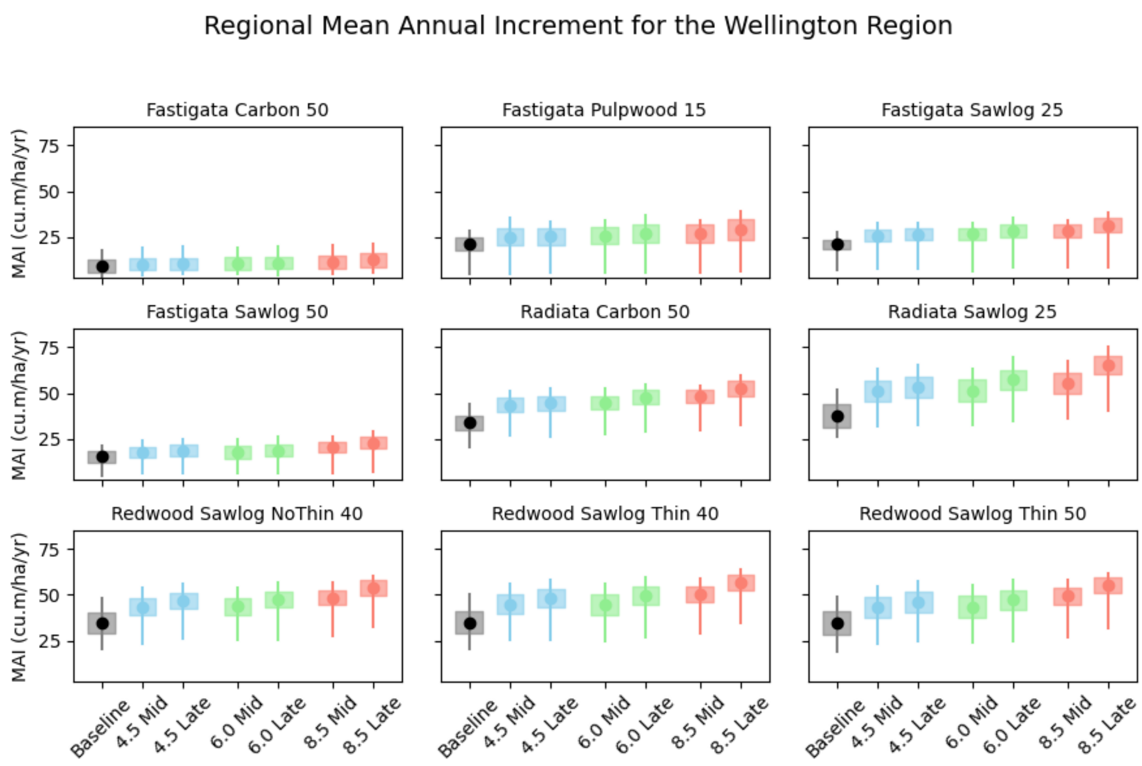


Figure 42: Productivity (MAI) of Wellington region by regime.

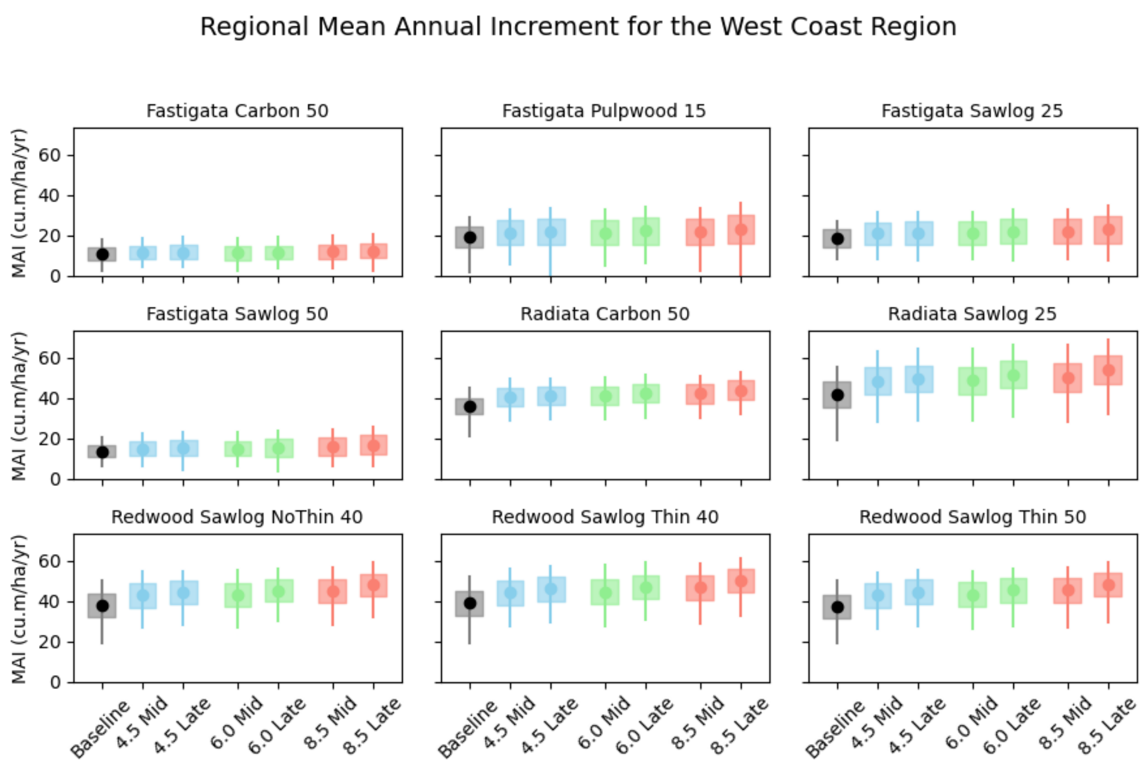


Figure 43: Productivity (MAI) of West Coast region by regime.

4 Results: National profitability by climate scenario for selected regimes

This section begins with a brief summary of the key national profitability findings, followed by detailed results.

Summary of national profitability by climate scenario for selected regimes

- Radiata shows consistent profitability across all climate scenarios, with highest performance under RCP 8.5.
- Redwood regimes (with or without thinning) slightly outperform the baseline, with no-thinning being more profitable in warmer climates.
- Fastigata regimes face profitability challenges at Baseline and Mid time-periods, particularly with the Pulpwood regime. The 25- and 50-year sawlog rotations show potential, though with high variability and risk.
- Fastigata Pulpwood production is generally unprofitable under current cost estimates.
- Strategic regime selection, improved cost estimates, and integration of carbon credits could enhance economic sustainability and reduce climate-related risks.

4.1 Fastigata regimes

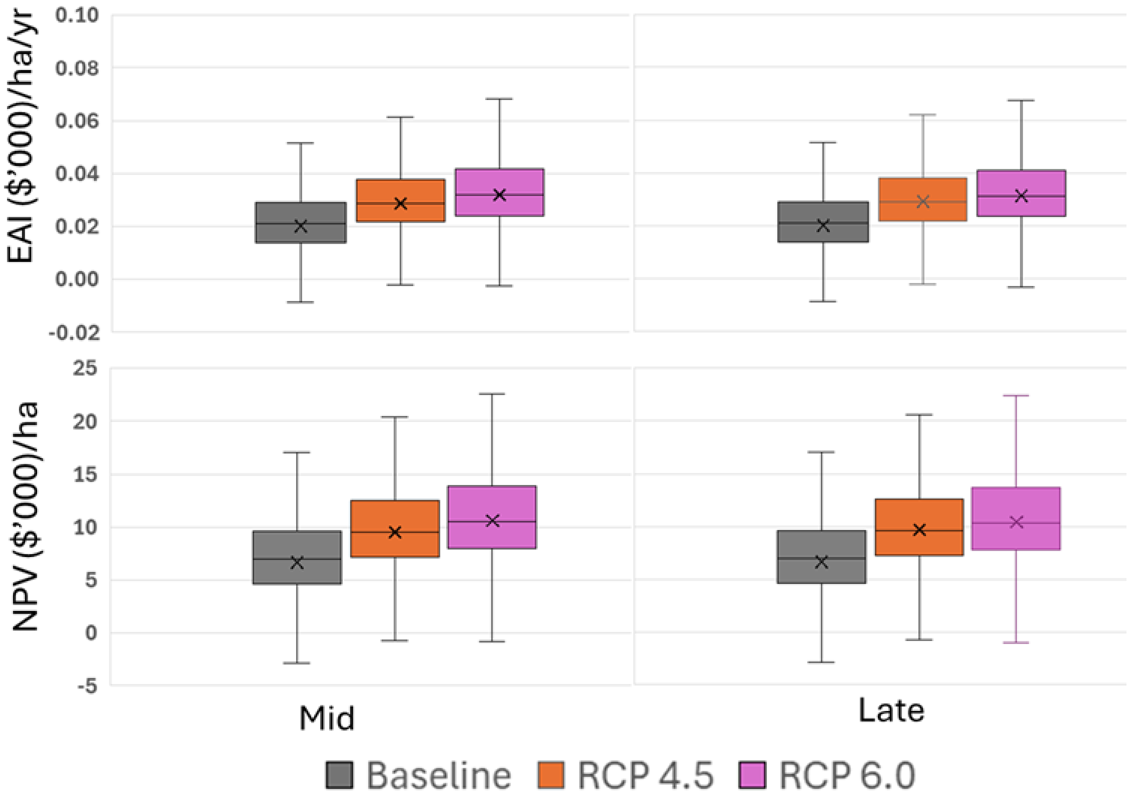
The profitability of the three Fastigata regimes was estimated: Fastigata Sawlog 25, Fastigata Sawlog 50, and Fastigata Pulpwood 15 (Figure 44). RCPs 4.5 and 6.0 were compared with the baseline estimations. Because of the limited cost information for Fastigata, most of the operational cost values were based on Radiata. Overall, there is no considerable difference in the average EAI and NPV in RCP scenarios between a 25-year and a 50-year sawlog regime. Pulpwood production was estimated to be unprofitable, likely due to the use of costs based on Radiata. Incorporating carbon production (for the emissions trading scheme) could potentially enhance the profitability between the two rotations. The detailed EAI and NPVs for each regime are presented below.

For the Fastigata Sawlog 25 regime, the average EAI and NPV for the two RCPs are higher than the baseline, with RCP 6.0 projected to be the highest. The average EAI of all scenarios is above $20 per year, while the average NPV exceeds $5000. Like Redwood, NPVs for each scenario show high variability, ranging from negative values to over $15,000, indicating that certain locations may consider this regime risky.

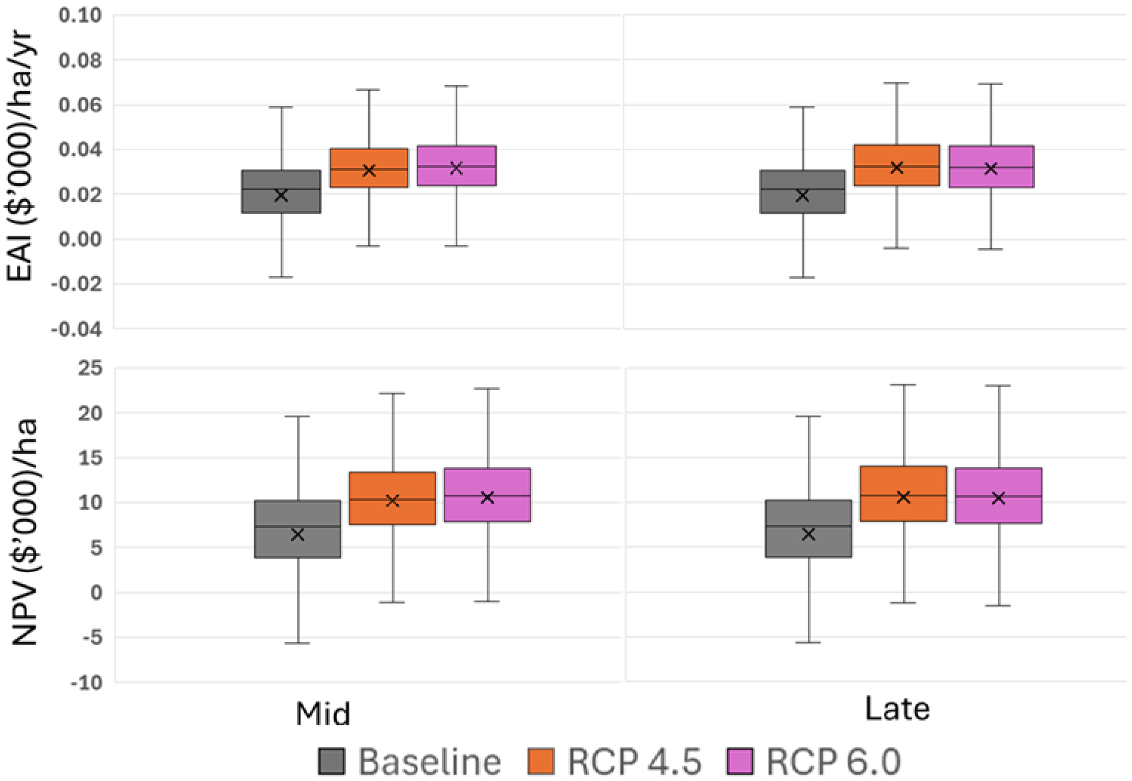
For the Fastigata Sawlog 50 regime, similar to the Fastigata Sawlog 25 regime, the average EAI and NPV for the two RCPs are higher than the baseline. The average EAI and NPV for both RCPs and periods are quite comparable. The average EAI for both RCPs is approximately $30, while the average NPVs are slightly above $10,000 for both periods, which is slightly higher than those in the Fastigata Sawlog 25 regime. Like the Fastigata Sawlog 25 regime, NPVs for each scenario exhibit high variability, ranging from negative values to over $15,000, indicating that certain locations may view this regime as risky.

For Fastigata Pulpwood 15 (low-grade wood for chips, energy, pellets, and engineered products), the average EAI in both periods is below 0, suggesting that the forestry practice is unprofitable. This low profitability is mainly due to the operational cost values derived from Radiata, and the much higher productivity of Radiata, with more than 20 years rotation compared to the 15 years rotation for Pulpwood. Nevertheless, the upper range of the NPV for RCP4.5 shows positive values reaching $1000 and above $1500 in the Mid and Late periods, respectively, indicating that some locations may find this regime profitable. A similar trend is also observed in RCP 6.0, although the simulated NPV is slightly lower than that of RCP 4.5 during the Mid period.

(a) Fastigata Sawlog 25



(b) Fastigata Sawlog 50



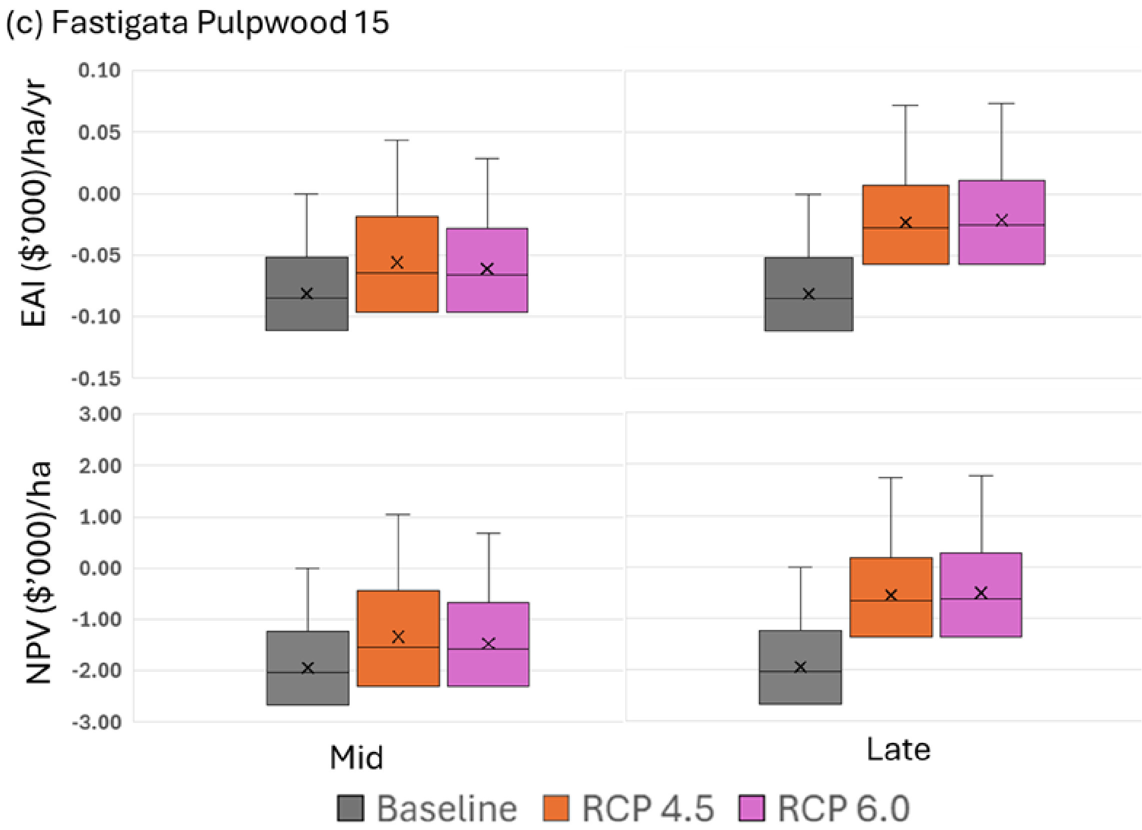


Figure 44: Fastigata Sawlog 25 (a) Fastigata Sawlog 50 (b) and Fastigata Pulpwood 15 (c) profitability (NPV and EAI).

4.2 Radiata Sawlog 25 regime

The Radiata Sawlog 25 regime is projected to respond well to future climate scenarios (Figure 45). All RCP scenarios have an average EAI above $700 per ha annually, with some areas exceeding $1,000 annually. The average EAI for all RCPs exceeds the baseline, with RCP 8.5 having the highest average in both periods, which is the same pattern for the NPV. The NPV ranges from as low as $10,000 to more than $100,000, depending on the productivity per ha and RCP. For RCPs 4.5 and 6.0, there is a slight increase from the Mid to the Late period, indicating moderate growth in profitability. RCP 8.5 shows a notable growth trajectory from the Mid to Late periods, suggesting enhanced profitability in warmer climates.

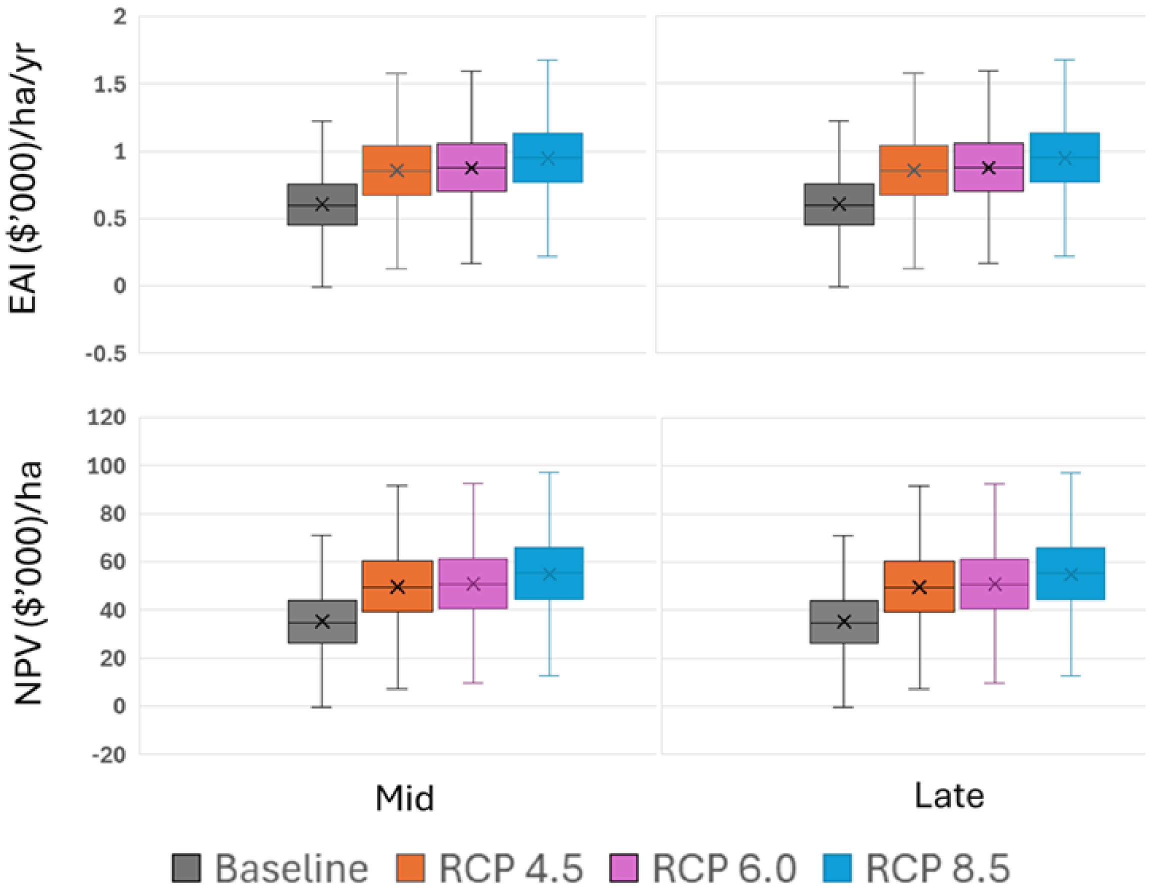


Figure 45: Radiata Sawlog 25 profitability (NPV and EAI).

4.3 Redwood regimes

Two Redwood regimes were projected to estimate profitability – Redwood Sawlog Thin 40 and Redwood Sawlog NoThin 40, both having a 40-year rotation, differing only in thinning (Figure 46). Like Radiata, the average EAI is slightly higher than the baseline under future climates. Comparing the NoThin and Thin regimes, the average EAI and NPV are slightly lower with thinning, due to the thinning costs. It was assumed that produce from thinning was not accounted for as profit but as waste. In addition, the largest expense for the operation is the establishment costs for both regimes.

Under the Redwood Thin 40 regime, the EAI and NPV for each RCP scenario are presented. The average EAI and NPV are slightly higher than the baseline in both periods. Regarding the RCPs, the average EAI and NPV for RCPs 4.5 and 6.0 are slightly lower than that for RCP 8.5. The average EAI exceeds $400 across all RCPs, but there is high variability between negative values and those above $800.

Under the Redwood NoThin 40 regime, the average EAI for all RCPs is slightly higher than the baseline, especially RCP 8.5. Under the Redwood NoThin 40 regime, the average EAI for all RCPs is slightly higher than the baseline, especially RCP 8.5. Regarding periods, the Late period is slightly higher in average EAIs and NPVs for all RCPs. The average EAI for a 40-year rotation with no thinning is above $400 for RCP 4.5 and RCP 6.0 across the two periods, whereas the average EAI for RCP 8.5 is around $500. Like the Redwood Thin 40 regime, the EAI and NPV are highly variable, from negative values to above $800, except for those under RCP 8.5.

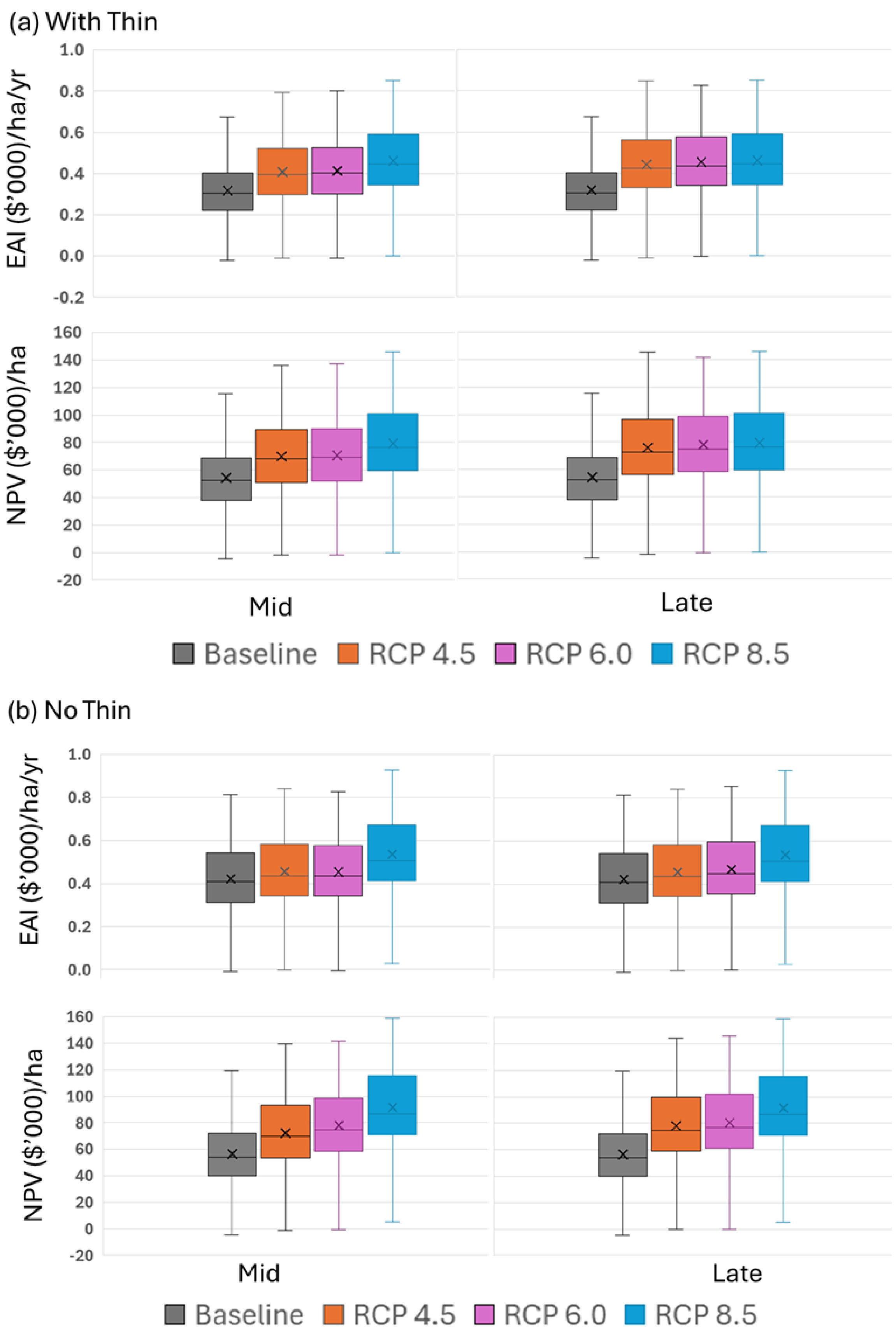


Figure 46: Redwood Sawlog Thin 40 (a) and Redwood Sawlog No Thin 40 (b) regimes profitability (NPV and EAI).

5 Conclusions

There is strong and growing interest, nationally and internationally, in **planting and managing forests using a broadening range of tree species, for increasingly diverse outcomes**. The longevity of forest stands places extra emphasis on the need to accurately predict growth under changing current and future climatic conditions. The process-based model CABALA-W provides a suitable approach to address these modelling challenges. In this project, CABALA-W was parametrised for three key species, and a modelling platform was developed to allow predictions at the national scale for multiple regimes, future periods, and climate scenarios.

The modelling platform and data sets created in this study represent a valuable resource and have generated useful insights into forest productivity and profitability under future climate scenarios. Future development of the CABALA-W model and the modelling platform will further enhance the ability to evaluate future forestry management options.

5.1 Key conclusions

The following key conclusions summarise the main insights from the project:

- Modelling results project **increased forest productivity** across all modelled species and management regimes under the three climate change scenarios. The productivity growth is most strongly associated with rising atmospheric CO_2 concentrations, with the **Late period RCP 8.5 scenario consistently showing the greatest productivity gains**. These trends suggest that climate change may enhance the biophysical potential for tree growth in New Zealand. However, the extent and reliability of these gains vary by species, regime, and region.
- There is an indication that land with low productivity will become more suitable for forest crops in the Late period under RCP 6.0 and 8.5.
- Among the species analysed, **Radiata exhibited the highest productivity and profitability** under all future climate scenarios. Radiata planted under a carbon sequestration regime performs particularly well, producing the largest total volumes over 50-year rotations. Radiata also maintains high productivity under shorter sawlog rotations, with consistent profitability across regions and scenarios. This makes it the most robust and economically viable option across a wide range of climatic conditions.
- **Redwood shows good potential as an alternative or complementary species**, especially under longer rotation lengths. While its productivity is generally lower than Radiata, Redwood performs well in warmer climates, particularly in no-thinning regimes. Increased productivity is projected in several regions, with marked productivity increases in the South Island by the Late period. These results suggest that Redwood could play a valuable role in diversifying forest portfolios and improving resilience to climate change.
- **Fastigata, by contrast, consistently demonstrates lower productivity and more variable profitability**, particularly under shorter pulpwood regimes, which remain unprofitable across all climate scenarios. Fastigata does show improved returns under longer rotations, indicating that its economic viability could be improved with regime adjustments. Its

limited adaptability and performance under future climate conditions make it a less attractive option relative to Radiata and Redwood.

- Regionally, productivity gains are not uniform. There are **intra- and inter-regional differences** in species performance, reflecting influences such as local climate, soil, and topography. Under the 25-year sawlog regime, Radiata demonstrates the most stable productivity across all regions. In contrast, the performance of Redwood is more sensitive to climate variation, and Fastigata remains consistently lower, particularly under milder climate scenarios.
- The profitability analysis shows that economic outcomes are strongly influenced by **rotation length, species choice, and the underlying volume produced**. The profitability estimates rely on current forestry costs and revenue data based on Radiata practices, better data for the other species would improve the economic analysis. These economic parameters are expected to shift under future climate and market conditions, adding further uncertainty to long-term projections.
- Despite the clear potential for increased productivity, several **key limitations** must be acknowledged. Climate projections become less reliable over time, particularly under RCP 8.5 in the Late period. The physiological model used (CABALA-W) offers detailed process-based projections but does not account of **abiotic and biotic stressors**, such as heat waves, pest outbreaks, or disease, which limit productivity and are expected to become more frequent and severe under climate change. Additionally, the national soil data used in modelling lacks specificity for forest systems, introducing uncertainty in regional outputs.

In conclusion, of the species modelled, **Radiata remains the most dependable and profitable species choice under future climate conditions**, but **Redwood offers strategic value** in diversifying plantation forests. **Fastigata requires cautious consideration** due to its lower performance and profitability, especially under short rotations. Proactive planning and adaptive management strategies will be essential to maximise the potential benefits and minimise the risks of climate change for New Zealand's forestry sector.

5.2 Future research topics

The following key areas for future research activities are identified:

- **Future work should prioritise refining model parameterisation**, improving forest-specific soil data, and incorporating risk factors such as tree mortality, extreme weather, and pest and disease dynamics to provide more comprehensive assessments. This also includes improving costing data for other alternative species, particularly Fastigata.
- **There is a need for fundamental physiological studies** to quantify the limiting effects of Nitrogen and Phosphorus on growth under elevated CO_2, and the responses of construction and maintenance respiration under a range of CO_2 and temperature conditions.
- New Zealand soil data sets lack information on basic characteristics needed to model the growth of tree species. This limits the ability to predict growth accurately under current and future climate scenarios. **A national data set characterising soil depth and texture is needed**, at the increased depths essential for forest species.

- Physiological parameterisation was adequate for Radiata, but the lack of suitable soil data for permanent sample plots also limited the utility of available growth validation data. This prevented accurate parameterisation of CABALA-W for simulation tests against validation data. Physiological parameters and validation data sets were limited or absent for Redwood and Fastigata, restricting the ability to parameterise and validate CABALA-W for those species. **Research is recommended to quantify the essential CABALA-W physiological parameters for a broader set of species**, which are suitable for future forestry.

Acknowledgements

Forest Growers Research Limited and Scion have made important contributions to this project through the Resilient Forests Programme and aligned Scion SSIF funding. This provided co-funding of the CABALA-W and Forestscape2 development and parameterisation, and of the productivity and profitability modelling conducted for this report.

Dr. Suzie Greenhalgh, Manaaki Whenua Landcare Research, contract manager, provided significant guidance and support during the project. The contributions of Scion employees: Andrew Cridge as project sponsor, Peter Clinton as Resilient Forests Programme leader, Kim Murrell for project management, Tim Payn for publication review, and Sumedha Amarasena for automation scripting of CABALA-W input files are recognised. Simon Papps, Resource Manager at Manulife Investment Management (NZ) Ltd, reviewed methodologies and provided valuable guidance on operational forestry regimes and costs.

Glossary

Baseline	Refers to present-day conditions, for climate and time-period.
CABALA-W	A physiological process-based model able to simulate growth of tree species and their responses to management under current and future climate scenarios.
EAI	Equivalent Annual Income is a financial metric taking the net present value of the selected regime and dividing it by the rotation length in years. It is often used to compare forestry returns with other land uses such as agricultural crops.
Forestscape2	A spatial economic model for modelling profitability of New Zealand plantation forests at local to national scales.
FSL	The Fundamental Soil Layer is a dataset that provides spatial information about key soil attributes for New Zealand.
GCM	A General Circulation Model is used to simulate the circulation of the Earth's atmosphere and ocean, considering factors like greenhouse gases, landforms, ocean currents, and their interactions. GCMs are used to understand climate, forecast weather, and project climate change.
MAI	Mean Annual Increment is the mean volume increment per year (total volume divided by total growing period in years) and represents the average annual production rate over the whole growing period.
NPV	Net Present Value is the present value of all revenues minus the present value of all costs.
Period	A time interval used for modelling productivity and profitability. Baseline (current), Mid, and Late periods were used. Regimes of different rotation lengths were modelled using common time mid-points, longer rotations starting earlier and finishing later than shorter rotations.
RCP	Representative Concentration Pathway, representing a specific trajectory of increased greenhouse gas concentrations (particularly CO_2) in the atmosphere, with associated expected temperature increase. RCPs 4.5, 6.0, and 8.5 were modelled in this project.
Regime	A set of operational forestry tending operations applied to manage a stand of trees for species-specific production outcomes.
Rotation	The duration of tree growth in years until harvest, or until assessment of value in the case of permanent cover regimes.
Volume	The total stem wood volume per hectare, representing the cumulative amount of production over the whole growing period.

Bibliography

Battaglia, M., Sands, P., White, D. A., & Mummery, D. (2004). CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management, 193, 251-282.

Dunningham, A., Kirschbaum, M. U. F., Payn, T., & Meason, D. (2012). Chapter 7. Forestry Long-term adaptation of productive forests in a changing climatic environment. In Impacts of climate change on land-based sectors and adaptation options. MPI.

Dye, P. J. (1996). Response of Eucalyptus grandis trees to soil water deficit. Tree Physiology 16, 233-238.

Forest Owners Association. (2023). Facts and Figures 2022/23 New Zealand Plantation Forest Industry. Forest Owners Association. https://www.nzfoa.org.nz/images/Facts_and_Figures_2022-2023_-_WEB.pdf

Lin, Y. S., Medlyn, B. E., & Ellsworth, D. S. (2012). Temperature responses of leaf net photosynthesis: the role of component processes. Tree Physiology, 32 (2), 219-231.

Manley, B. (2024). Discount rates used for forest valuation – results of 2023 survey New Zealand Journal of Forestry, 69(4), 31-38.

Messier, C. (2022). For the sake of resilience and multifunctionality, let's diversify planted forests! Conservation Letters, 15(e12829).

Ministry for Primary Industries. (2023). A New Zealand Guide to growing Alternative Exotic Forest Species. Ministry for Primary Industries.

Newsome, P., Wilde, R., & Willoughby, E. (2008). Land Resource Information System Spatial: Data Layers. L. R. N. Zealand.

Sood, A. (2014). Improved bias corrected and downscaled regional climate model data for climate impact studies: Validation and assessment for New Zealand. NIWA. https://www.researchgate.net/publication/265510643_Improved_Bias_Corrected_and_Downscaled_Regional_Climate_Model_Data.

Tait, A., Sood, A., Mullan, B., Stuart, S., Bodeker, G., Kremser, S., & Lewis, J. (2016). Updated climate change projections for New Zealand for use in impact studies. Synthesis Report RA1. NIWA.

Tange, O. (2018). GNU Parallel 2018. In http://ole.tange.dk

Villamor, G. B. (2024). Operational costs of growing selected alternative tree species.

Villamor, G. B., Wakelin, S. J., Dunningham, A., & Clinton, P. W. (2023). Climate change adaptation behaviour of forest growers in New Zealand: An application of protection motivation theory. Climatic Change, 176(3).

von Caemmerer, S., Farquhar, G., & Berry, J. (2009). Biochemical Model of C3 Photosynthesis. In Photosynthesis in silico (pp. 209-230). https://doi.org/10.1007/978-1-4020-9237-4_9

Watt, M. S., & Palmer, D. J. (2012). Use of regression kriging to develop a Carbon:Nitrogen ratio surface for New Zealand. Geoderma 183-184, 49-57.

White, D. A., Crombie, D. S., & Kinal, J. (2009). Managing productivity and drought risk in Eucalyptus globulus plantations in south-western Australia. Forest Ecology and Management 259(1), 33-44.

White, D. A., Palma, J. N., Salekin, S., Meason, D. F., Battaglia, M., Dawes, W., Yang, J., Dudley, B. D., Dempster, A., Griffiths, J., Contreras-Balocchi, F., Tomás, A., & Ramirez, P. (2024). Capturing complex carbon and water dynamics in radiata pine using CABALA with an improved water balance. DOI: 10.2139/ssrn.4994401.

White, I., & Sully, M. (1987). Macroscopic and microscopic capillary length and time scales from field infiltration. Water Resources Research 23(8), 1514-1522.

Wilensky, U. (1999). NetLogo. In Center for Connected Learning and Computer-Based Modeling, Northwestern University,. http://ccl.northwestern.edu/netlogo/