Modelling carbon stocks in transition forests

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NATIVE FORESTS FOR OUR FUTURE

Hereherea te Wao-nui-a-Tāne

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Abstract:

Radiata pine dominates New Zealand's planted forests, often on erosion-prone hill country. However, harvesting these stands can expose major risks, with slash causing destructive debris flows and undermining social licence, while steep-land economics and regulations further erode viability. There is growing support for transitioning such plantations to resilient native forests, though practical management pathways remain uncertain and the ecological and carbon storage benefits of restoring native forest are well recognised.

We present a model that simulates carbon sequestration in transition forests. It draws on existing empirical growth and carbon models for radiata pine, the predominantly native understory, and the native species expected to eventually replace the pine. While various scenarios are presented for a range of timeframes allowing for natural thinning or managing the pine canopy, the model incorporates an assumption about radiata pine longevity, set at an upper limit of approximately 170 years.

The model was used to simulate the likely carbon profile of a radiata pine stand left unmanaged. Four distinct phases were identified by this simulation:

1. Phase 1, 0-50 years: Rapid sequestration by the radiata pine averaging 31 tonnes of CO_2 per hectare per year. Native understory develops but stores minimal carbon. Total stock at the end of this phase is 1570 tonnes of CO_2 per hectare.
2. Phase 2, 50-100 years: Slowing sequestration by the radiata pine and increasing sequestration by the native understory averaging 31 tonnes and 2.3 tonnes of CO_2 per hectare per year respectively. Total carbon stock peaks at the end of this phase at 2050 tonnes of CO_2 per hectare.
3. Phase 3, 100-200 years: Gradual death of the radiata pine releases 19 tonnes of CO_2 per hectare per year partly offset by sequestration from the developing native forest which averages 1.3 to 10.4 tonnes of CO_2 per hectare per year, depending on forest type. Total carbon stock at the end of this phase is reduced to between 260 and 835 tonnes of CO_2 per hectare depending on the native forest type.
4. Phase 4, 200-250 years: Steady sequestration by the replacement native forest averaging between 0 and 8 tonnes of CO_2 per hectare per year depending on forest type. Total carbon stock averages between 260 and 1160 tonnes of CO_2 per hectare depending on forest type.

The modelling also indicates likely carbon trajectories with disturbance events factored in that can affect the timing of the growth/senescence phases. These disturbances could either be planned management intervention or unplanned natural mortality events (such as storm wind throw). Various scenarios including natural or managed early radiata pine mortality, and a range of radiata pine stand densities were also modelled.

1 Introduction

New Zealand is situated in the cool temperate moist zone, a region where carbon-dense forests are typically found (Lal & Lorenz, 2012). Before human settlement, forests covered up to 85% of the land area (McGlone, 1989). However, extensive burning and clearance following human arrival around 800 years ago (Beaglehole, 2012) greatly reduced this coverage. Today, natural forests occupy roughly 29% of the country's land area (Paul et al., 2021). These are predominantly primary or old-growth forests, though they also include areas of secondary regenerating forest and shrubland.

Alongside the native forest, large areas of production forest have been established over the past century. These forests typically consist of single-species, single-aged stands of fast-growing exotic trees. Radiata pine (*Pinus radiata*) dominates, making up around 90% of the planted forest resource, and is generally managed using a clearfell regime with a rotation length of 25–30 years. This is the case for forest established on erosion-prone hill country of the East Coast, where it was promoted to stabilise fragile soils and provide timber. However, on many sites, harvesting plantation forests has revealed major risks. Clearfelling leaves the land vulnerable to large storm events, removing the protective intercepting vegetation cover. It also leaves large amounts of logging debris on steep slopes, which storm events can mobilise into destructive debris flows, damaging rivers, farmland, infrastructure, and downstream communities (Ministerial Inquiry into Land Use, 2023; Cave, 2018; Phillips et al., 2024). The severe impacts during Cyclone Gabrielle in 2023 further illustrated these vulnerabilities and have contributed to undermining the social licence of pine forestry in high-risk landscapes.

At the same time, the economics of steep-land pine forestry are increasingly marginal. Harvest engineering and road construction on unstable terrain are costly, while new National Environmental Standards for Commercial Forestry impose tighter requirements on slash management and erosion control (MfE, 2023; MPI, 2024). When downstream damage and reputational risks are considered, the viability of continuing radiata pine production forestry on such country is doubtful (Ministerial Inquiry into Land Use, 2023).

Native species account for only a small fraction of new planted forests, largely due to their higher establishment costs and slower growth compared with exotics such as radiata pine. Nonetheless, the ecological and carbon storage benefits of restoring native forest are well recognised, and there is broad support for expanding native forest cover at scale. There is growing interest in practical pathways for transitioning existing exotic plantation forests on uneconomic, erosion-prone steeplands into native cover (Te Uru Rākau, 2021; Envirolink/HBRC, 2019; Parliamentary Commissioner for the Environment, 2025). However, uncertainty remains over how such plantations can be effectively managed to transition to diverse, resilient native forest.

There are various well-tested and reliable empirical growth models that can be used to predict carbon sequestration in planted exotic forests along with various models for predicting carbon in native forests. However, there is an almost total lack of quantitative, empirical data from transition forests and no empirical growth models have therefore been developed for predicting carbon sequestration in such forests.

Forest growth models can be broadly classified into two main types: empirical models, and process-based models. Empirical models are built from statistical relationships between measured growth data and variables like age, site quality, and climate. They predict growth based on observed trends rather than underlying biological processes. Empirical models are very reliable when applied to forests comparable to those used to derive them. In contrast, process-based models simulate growth from first principles, using physiological and environmental processes such as photosynthesis, respiration, and water/nutrient cycling. They are more complex and require calibration for each species using measurements of fundamental parameters. An advantage of process-based models is that they can be used to predict growth for conditions (e.g., climate) outside the range for which forest measurement data exists. Some models fall between these two types and are sometimes referred to as hybrid models or simplified process-based models.

Given the lack of empirical data and models, process-based or hybrid models may provide a means of predicting carbon stocks over time in transition forests, and there have been at least two attempts to do this. Meurk and Hall (2006) used an ecosystem process model, LINKNZ, to predict likely long-term responses of New Zealand forests to the impacts of introduced plants and imposition of harvesting. More recently, Mason et al. (2025) used hybrid models to predict carbon sequestration in transition forests. To predict carbon in the exotic component, they used the 3-PG model (Landsberg et al., 2003) which is often referred to as a simplified process-based model. They used a version of the model parameterised to predict growth of radiata pine in New Zealand (Salekin et al., 2024). To predict growth, recruitment and mortality of native species, they used the PPA hybrid model (Purves et al., 2008). The PPA model uses Canopy Area Index (the total canopy area of trees within a stand taller than the target tree's height) to predict growth, recruitment and mortality. Mason et al. (2025) calibrated the model for individual native species using repeated measurements, and records of recruitment and mortality from plots measured as part of the Land Use and Carbon Analysis System (LUCAS). In the remainder of this report, we refer to the Mason et al. (2025) model as the MJMDS model.

Results of applying process-based or hybrid models to transition forests are shown in Figures 1 and 2. Figure 1 shows very long-term predictions from Meurk and Hall (2006) of above-ground biomass in (A) radiata pine, and (B) Douglas-fir stands which are gradually thinned out over time and replaced with native trees. Figure 2 shows predictions to 100 years from the MJMDS model of carbon in the exotic and native components of radiata pine transition forests. This figure shows the following three of the various scenarios considered by Mason et al. (2025): (A) Pines removed between ages 9-19 years allowing natives to regenerate; (B) Pines removed between ages 9-65 years allowing natives to regenerate; (C) Pines left undisturbed with natives developing under the pine canopy.

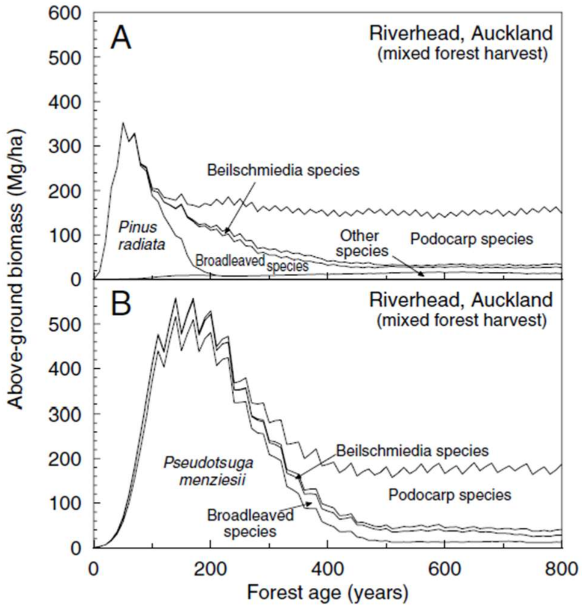


Figure 1. Charts reproduced from Meurk and Hall (2006) showing modelled above-ground biomass in exotic forest transitioning to native forest in the Auckland region. This shows (A) a radiata pine plantation with 20% of stems removed every 20 years from age 15 years and indigenous species gradually introduced, and (B) a Douglas-fir plantation with 20% of stems removed every 30 years from age 20 years and indigenous species gradually introduced.

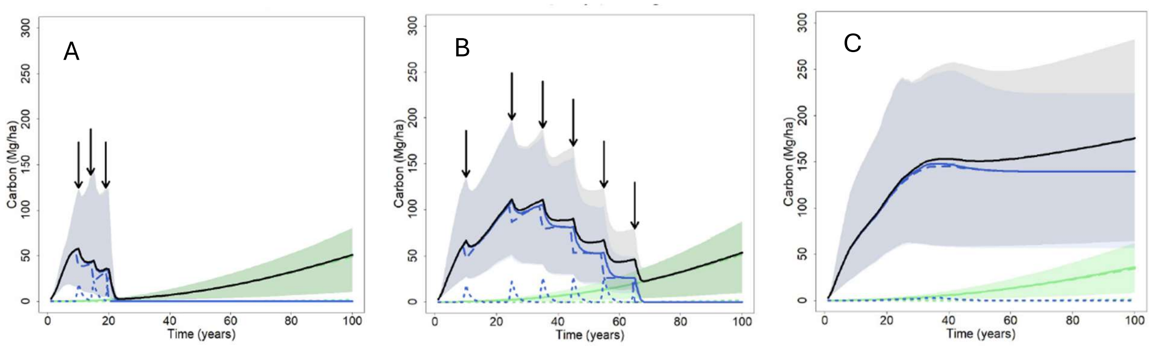


Figure 2. Charts reproduced from Mason et al. (2025) showing modelled carbon in radiata pine forest transitioning to native forest in New Zealand. Each chart shows radiata pine carbon (blue line), native carbon (green line) and combined carbon (black line) with interventions (thinning or killing of pines) indicated by arrows, for three scenarios: (A) Pines removed between ages 9-19 years followed by natural regeneration; (B) Pines removed between ages 9-65 years followed by natural regeneration; (C) Pine planted and left with no further intervention.

Applying process-based or hybrid growth models to transition forests yields intriguing results. However, the absence of measurement data from these forests has hindered validation of the predictions against actual observations. Such a validation would be highly valuable, as it is debatable, for example, whether hybrid models developed using data from old-growth indigenous forests can reliably predict the processes occurring in the understory of a pine forest. This highlights the importance of collecting real measurement data from transition forests.

Although we still lack data covering the entire span over time of a forest transitioning from radiata pine to native forest, we do now have extensive measurements of carbon stocks in the native understory of existing radiata pine forests covering a broad range of ages and stand densities. Using such data, an empirical model has been developed for predicting the carbon in the understory of a transition forest while the radiata pine canopy remains relatively intact (Graeme et al. 2025). Secondly, we have measurements of carbon stocks and growth equations derived from regenerating native stands of various forest types, and these could be used to represent what happens in a transition forest once the radiata pine trees are removed, either through natural mortality or through thinning, poisoning or ring barking of trees. And thirdly there are very good empirical growth models predicting carbon sequestration in radiata pine trees. By coupling together these three types of empirical models, we can therefore produce an empirical modelling system for predicting carbon sequestration in transition forests.

In this report, we present an empirical model for carbon sequestration in transition forests developed using this approach. We apply this model to estimate carbon stocks under the three scenarios described above as modelled by Mason et al. (2025). We then use our empirical approach to project the likely carbon dynamics of a radiata pine stand originally planted for commercial purposes but left unmanaged until it dies and is gradually replaced by native forest. Finally, we model a comparable radiata pine stand subject to higher early mortality, representing either the effects of an increased frequency of storm events or of deliberate management actions such as tree removal through poisoning.

2 Methods

2.1 Broad outline of the model

The empirical transition forest model used in this study consists of three sub-models. The first predicts carbon sequestration of the radiata pine component. The second predicts carbon sequestration in the native understory of the forest while the radiata pine trees are still present. And the third predicts sequestration in the native component after the radiata pine has been removed either through natural mortality or management intervention. The inputs required to run the model are as follows:

- Site productivity indices controlling the radiata pine growth model:
    - Site Index – The mean top height (MTH, m) of the radiata pine trees at age 20 years
    - 300 Index – Volume mean annual increment at age 30 years for radiata pine trees growing at 300 stems/ha
- Mean annual temperature (ºC)
- Radiata pine stand density at establishment
- Age and radiata pine stand density following interventions such as thinning or mortality events
- Forest type of the regenerating native forest replacing the radiata pine – four modelled types are available: coastal broadleaf; kānuka/red beech succession; mānuka/kānuka secession; tōtara.

Note that the radiata pine growth model predicts radiata pine stand density through time from its initial value accounting for natural mortality. However, the user can enter a series of stand densities at subsequent ages to represent managed removal of radiata pine (e.g., through conventional thinning, coupe felling, poisoning or ring barking trees), or the effects of catastrophic events such as storm damage. The model discriminates between two types of thinning:

- Conventional Thinning method. This assumes that scattered trees are killed or thinned leaving an intact radiata pine canopy. The reduced stand density is fed into the radiata pine growth model to predict subsequent radiata pine carbon sequestration whilst also modelling how the killed trees, which are assumed left on site, lose their carbon gradually through decay. Carbon in the native tree component is predicted using the native understory model.
- Coupe Thinning method. This assumes that relatively large areas of pine trees are killed or felled, leaving open gaps in the forest. To model this, the portion of the forest that is unaffected continues to be predicted for both the radiata pine and native understory carbon components as before using the original stand density. However, in the portion of the forest where pine trees have been removed, the system models the gradual loss in carbon in the killed trees through decay, which are assumed to be left on site along with the carbon in the replacement native trees which is predicted using the appropriate regenerating native model rather than the native understory model.

2.2 Radiata pine carbon model

Carbon sequestration by the radiata pine component of the forest is predicted using a stand-level modelling system that integrates the radiata pine 300 Index growth model, a stem wood density model, and the C-Change model (see Beets et al., 2011 for a detailed description). The 300 Index growth model is used to generate MTH and basal area from the productivity indices, which are then used to predict under-bark stem volume using a national stand-level radiata pine volume function (Kimberley & Beets, 2007). Annual variation in radiata pine basic wood density is predicted using a wood density model from growth predictions and site mean annual air temperature (Kimberley et al., 2015). Stem volume and basic density are then used by C-Change to estimate stemwood dry matter, which is used in turn to predict biomass in other components using growth partitioning functions (Beets et al., 1999). Biomass is converted into carbon using a range of conversion factors specific to each biomass component. Carbon flows to dead organic matter are estimated and decay functions used to predict losses of carbon from these pools (Garrett et al., 2010). The inputs required to run this model are the two productivity indices, 300 Index and Site Index (we used 300 Index=25 and Site Index=30 for all runs in this study), mean annual temperature (we used 12°C for all runs), initial stand density, and age and stand density following any subsequent thinning or removal of trees.

2.3 Native understory carbon model

Carbon sequestration in the mainly native understory of was predicted using a model recently developed from measurements of understory in production stands in Tairāwhiti (Graeme et al., 2025). The study used 45 sample plots with radiata pine age ranging from 21 to 63 years and stand density ranging from 133 – 467 stems/ha. The model developed predicts above and below ground carbon in the native understory (C, t $CO2_2$/ha) as a function of stand age (T, years) and stand density (N, stems/ha):

$$C = -31.72 + 1.47T + 0.200 \times (N - 300) - 0.00836 \times T \times (N - 300),$$

$$\text{where } N > 475.8 \text{ and } T > (31.72 - 0.200 \times (N - 300) / (1.47 - 0.00836 \times (N - 300))$$

$$C = 0, \text{ otherwise}$$

Because stand density can vary over time, this model and the regenerating native models described in the following section, were converted into difference equations, which predict C_2, carbon ΔT years into the future, from its current level C_1:

$$C_2 = C_1 + 1.47 - 0.00836 \times (N - 300) \times \Delta T,$$

$$\text{where } N > 475.8 \text{ and } T > (31.72 - 0.200 \times (N - 300) / (1.47 - 0.00836 \times (N - 300))$$

$$C_2 = 0, \text{ otherwise}$$

2.4 Regenerating native forest carbon models

To predict carbon sequestration in regenerating native forest in the absence of a radiata pine canopy, we used four models representing four different forest types, two described by Carswell et al. (2012), and two developed for this study using unpublished Tanes Tree Trust data. All four models were developed using similar methods. Sample plots were used to collect stem height and diameter measurements which were converted into carbon using published allometric equations. These were summed and converted into per hectare carbon stocks. Ages were obtained using growth ring analysis of a sample of stems in each plot. Regression models were then derived predicting per hectare carbon as a function of age. We converted all these models into difference equations to predict carbon ΔT years in the future, C_2, from its current level C_1. The original models and their difference equation forms are as presented in the following sections:

2.4.1 Coastal broadleaf, Marlborough Sounds.

This model is described by Carswell et al. (2012) and was developed using measurement plots in coastal broadleaved forests in the outer Marlborough Sounds ranging in age from approximately 5-180 years. The equation predicts above ground carbon (tC/ha) and we have converted this into total above and below ground carbon by multiplying by 1.234 (based on a root/shoot ratio of 0.234 which has been found appropriate for native broadleaves) and converted into CO_2 equivalents by multiplying by 3.667. The resulting equation is:

$$C = 1.234 \times 3.667 \times \exp(-0.01) \times T^{1.1}$$

The difference equation derived from this model is:

$$C_2 = 4.525 \times \exp(-0.01) \times (\Delta T + (C_1 / 4.525 \times \exp(-0.01))^{1/1.1})^{1.1}$$

2.4.2 Kānuka-red beech succession, Banks Peninsula.

This model is described by Carswell et al. (2012) and was developed using measurement plots in kānuka–red beech succession was investigated at Hinewai Reserve, near Akaroa on Banks Peninsula ranging in age from approximately 15-230 years. The equation predicts above ground carbon (tC/ha) and we have converted this into total above and below ground carbon by multiplying by 1.234 and converted into CO_2 equivalents by multiplying by 3.667. The resulting equation is:

$$C = 1.234 \times 3.667 \times \exp(3.1) \times T^{0.40}$$

The difference equation derived from this model is:

$$C_2 = 4.525 \times \exp(3.1) \times (\Delta T + (C_1/4.525 \times \exp(3.1))^{1/3.1})^{3.1}$$

2.4.3 Regenerating mānuka/kānuka, Tairāwhiti.

This model was developed using a Tāne's Tree Trust dataset of measurement plots in Tairāwhiti regenerating mānuka/kānuka shrubland ranging in age from 6 to 63 years. The growth model is:

$$C = 250.71 \times (1 - \exp(-0.303 \times T))^{11.49}$$

The difference equation derived from this model is:

$$C_2 = 250.71 \times (1 - \exp(0.303 \times \Delta T) \times (1 - (C_1 / 250.71)^{1/11.49}))^{11.49}$$

2.4.4 Regenerating tōtara, Northland.

This model was developed using a Tāne's Tree Trust dataset of measurement plots in Northland regenerating tōtara-dominated stands ranging in age from 28 to 126 years. The growth model is:

$$C = 2000 \times (1 - \exp(-0.00684 \times T))^{1.085}$$

The difference equation derived from this model is:

$$C_2 = 2000 \times (1 - \exp(0.00684 \times \Delta T) \times (1 - (C_1 / 2000)^{1/1.085}))^{1.085}$$

2.5 Scenarios modelled

Using our empirical modelling system, we simulated 12 different scenarios representing different levels of management and external intervention in radiata pine forests transitioning to native forests. In all simulations, we used Site Index = 30 m, 300 Index = 25 m^3/ha/year, and mean annual temperature = 12°C. These values are representative of commercial radiata pine forests growing in the North Island. We applied all four native regeneration forest types for each scenario to show how the composition of the native forest might influence carbon sequestration. Thus, in total we ran 48 different simulations.

Firstly, scenarios A-C represent the three scenarios simulated using the MJMDS model as described earlier in this report. Following Mason et al. (2025), predictions for these three scenarios were produced to age 100 years. Table 1 shows the settings used to model these three scenarios.

Table 1. The settings we used for our empirical model to reproduce the three scenarios modelled by Mason et al. (2025).

Scenario	Initial pine stand density	Interventions applied to pine trees					
		1	2	3	4	5	6
A	1000 stems/ha	Conventional thin to 667 stems/ha at age 9 years	Conventional thin to 333 stems/ha, age 14 years	Kill remaining pine trees, age 19 years			
B	833 stems/ha	Conventional thin to 500 stems/ha at age 9 years	Coupe thin to 400 stems/ha, age 25 years	Coupe thin to 300 stems/ha, age 35 years	Coupe thin to 200 stems/ha, age 45 years	Coupe thin to 100 stems/ha, age 55 years	Kill remaining pine trees, age 65 years
C	833 stems/ha						

We next modelled scenarios D - L representing, what we believe is the likely carbon profile for commercial radiata pine stand either left unfelled and undisturbed or managed to reduce stand density over time. The settings used for these scenarios are in Table 2. To simulate these scenarios, it was necessary to incorporate mortality events to represent the end-of-life of the radiata pine trees. While the radiata pine growth model includes a mortality function, this does not impose an explicit age limit on the trees. In reality, however, radiata pine has a finite lifespan. For example, according to Sudworth (1908), in its natural range the species rarely exceeds 150 years. In New Zealand, the first radiata pine trees were planted around 1860 and a few specimens of these early plantings which are currently about 160 years old still survive (Mead and Mason, 2025) suggesting that a simulation which removes all trees by age 170 years would be appropriate. Predictions for all these scenarios were then extended to cover 250 years from the time of pine establishment.

Scenarios D – F represent commercial radiata pine stands that receive the early thinning which is the standard silvicultural treatment for such stands. To approximate most likely end-of-life mortality, we modelled scenario D which includes ‘coupe thinnings’ applied starting at age 90 and repeated every 20 years until all pine trees were eliminated at age 170 years. We also modelled scenario E, which is like scenario D, but includes an accelerated mortality from age 40 years with all trees eliminated by age 80 years. Scenario F is similar but removes the radiata pine between ages 20-40 years. Scenarios E and F could represent radiata pine forests seriously damaged by extreme weather events which are likely to become more common with climate change, but could also represent stands subject to a managed gradual reduction in radiata pine carried out using poisoning for example.

We next modelled scenarios G - I which are similar to scenarios D – F except that they don’t include an early thinning at age 9 years. These would represent radiata pine stands established and then left with no further intervention, including the early thinning that is standard forestry practice.

Finally, scenarios J – L were modelled which include an extreme early thinning to 150 stems/ha at age 9 years, to test the effect of using radiata pine at a low stand density as an early nurse crop.

Table 2. The nine new scenarios modelled using our empirical transition forest model showing initial pine stand density and subsequent interventions applied to the pine crop.

Scenario	Initial pine stand density	Interventions applied to pine trees					
		1	**2**	**3**	**4**	**5**	**6**
D	833 stems/ha	Conventional thin to 500 stems/ha at age 9	Coupe thin 1/5th forest area at age 90 years	Coupe thin 1/5th forest area at age 110 years	Coupe thin 1/5th forest area at age 130 years	Coupe thin 1/5th forest area at age 150 years	Kill remaining pine trees at age 170 years
E	833 stems/ha	Conventional thin to 500 stems/ha at age 9	Coupe thin 1/5th forest area at age 40 years	Coupe thin 1/5th forest area at age 50 years	Coupe thin 1/5th forest area at age 60 years	Coupe thin 1/5th forest area at age 70 years	Kill remaining pine trees at age 80 years
F	833 stems/ha	Conventional thin to 500 stems/ha at age 9	Coupe thin 1/5th forest area at age 20 years	Coupe thin 1/5th forest area at age 25 years	Coupe thin 1/5th forest area at age 30 years	Coupe thin 1/5th forest area at age 35 years	Kill remaining pine trees at age 40 years
G	833 stems/ha	Coupe thin 1/5th forest area at age 90 years	Coupe thin 1/5th forest area at age 110 years	Coupe thin 1/5th forest area at age 130 years	Coupe thin t1/5th forest area at age 150 years	Kill remaining pine trees at age 170 years	
H	833 stems/ha	Coupe thin 1/5th forest area at age 40 years	Coupe thin 1/5th forest area at age 50 years	Coupe thin 1/5th forest area at age 60 years	Coupe thin 1/5th forest area at age 70 years	Kill remaining pine trees at age 80 years	
I	833 stems/ha	Coupe thin 1/5th forest area at age 20 years	Coupe thin 1/5th forest area at age 25 years	Coupe thin 1/5th forest area at age 30 years	Coupe thin 1/5th forest area at age 35 years	Kill remaining pine trees at age 40 years	
J	833 stems/ha	Conventional thin to 150 stems/ha at age 9	Coupe thin 1/5th forest area at age 90 years	Coupe thin 1/5th forest area at age 110 years	Coupe thin 1/5th forest area at age 130 years	Coupe thin 1/5th forest area at age 150 years	Kill remaining pine trees at age 170 years
K	833 stems/ha	Conventional thin to 150 stems/ha at age 9	Coupe thin 1/5th forest area at age 40 years	Coupe thin 1/5th forest area at age 50 years	Coupe thin 1/5th forest area at age 60 years	Coupe thin 1/5th forest area at age 70 years	Kill remaining pine trees at age 80 years
L	833 stems/ha	Conventional thin to 150 stems/ha at age 9	Coupe thin 1/5th forest area at age 20 years	Coupe thin 1/5th forest area at age 25 years	Coupe thin 1/5th forest area at age 30 years	Coupe thin 1/5th forest area at age 35 years	Kill remaining pine trees at age 40 years

3 Results

3.1 Predictions of carbon sequestration in transition forests for scenarios A-C

In this report, all carbon sequestration predictions are presented as total above- and below-ground carbon, expressed in tonnes of CO_2 equivalents per hectare. Figure 3 shows predictions of carbon sequestration produced by our model for scenarios A-C. Note that all four forest types have the same predicted sequestration for scenario C because this scenario involves leaving radiata pine undisturbed meaning that all native tree carbon is predicted using the understory carbon model which does not differentiate between forest type.

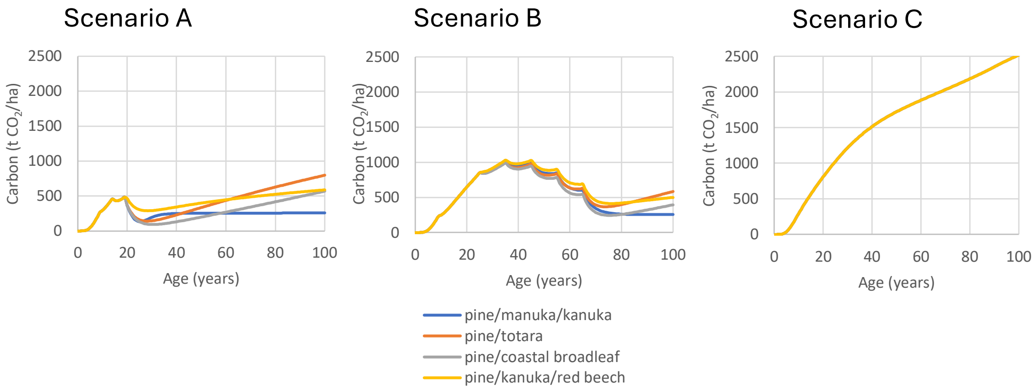


Figure 3. Predicted carbon sequestration in transition forests using our empirical model for scenarios A, B and C.

Predictions by the MJMDS model and our model for the combined radiata pine and native components of transition forests are shown for scenarios A-C in Table 3. Tables 4 and 5 show predictions separately for the pine and native tree components. In all scenarios, our model predicts substantially higher levels of carbon than the MJMDS model overall. We predict higher levels of carbon in the radiata pine component for all scenarios and in the native component for scenarios A and B, but lower native carbon for scenario C.

Table 3. Predictions of carbon sequestration (t CO_2/ha) produced by the MJMDS model and our model for all trees (radiata pine and native) in transition forests for scenarios A, B and C.

Scenario	Model	Age (years)			
		25	50	75	100
A	MJMDS model	15	44	99	187
	Our model, Mānuka/kānuka	132	253	251	251
	Our model, Tōtara	160	334	577	791
	Our model, Coastal broadleaf	131	199	375	563
	Our model, Kānuka/red beech	305	400	503	583
B	MJMDS model	403	246	106	202
	Our model, Mānuka/kānuka	852	849	281	251
	Our model, Tōtara	852	823	369	579
	Our model, Coastal broadleaf	852	781	246	390
	Our model, Kānuka/red beech	852	895	414	495
C	MJMDS model	476	579	612	675
	Our model, Mānuka/kānuka	1026	1723	2108	2519
	Our model, Tōtara	1026	1723	2108	2519
	Our model, Coastal broadleaf	1026	1723	2108	2519
	Our model, Kānuka/red beech	1026	1723	2108	2519

Table 4. Predicted carbon in the radiata pine component of transition forests for scenarios A-C produced by the MJMDS model and our model.

Scenario	Model	Age (years)			
		25	50	75	100
A	MJMDS model	0	0	0	0
	Our model	99	3	0	0
B	MJMDS model	396	202	0	0
	Our model	852	717	35	0
C	MJMDS model	469	539	528	528
	Our model	1026	1720	2074	2434

Table 5. Predictions of carbon sequestration (t CO_2/ha) of native trees in transition forests for scenarios A-C produced by the MJMDS model and our model.

Scenario	Model	Age (years)			
		25	50	75	100
A	MJMDS model	15	44	99	187
	Our model, Mānuka/kānuka	33	250	251	251
	Our model, Tōtara	61	331	577	791
	Our model, Coastal broadleaf	32	196	375	563
	Our model, Kānuka/red beech	206	397	503	583
B	MJMDS model	7	44	106	202
	Our model, Mānuka/kānuka	0	132	246	251
	Our model, Tōtara	0	106	334	579
	Our model, Coastal broadleaf	0	64	211	390
	Our model, Kānuka/red beech	0	178	379	495
C	MJMDS model	7	40	84	147
	Our model, Mānuka/kānuka	0	3	34	85
	Our model, Tōtara	0	3	34	85
	Our model, Coastal broadleaf	0	3	34	85
	Our model, Kānuka/red beech	0	3	34	85

3.2 Detailed comparison of predictions from our model compared with the MJMDS process-based model

To better understand how our model compares to the MJMDS model, and why the two models produce such different results, we examined another scenario covered by Mason et al. (2025) representing a pre-1990 commercial stand which receives an early thinning and is then simulated to age 40 years with no further intervention. This regime used an initial stand density of 1,250 stems per hectare and was waste thinned to 370 stems/ha at age 10.

The radiata pine sequestration predicted by the MJMDS model for this regime is compared to our model's predictions in Figure 4A which also shows regional values from the ETS radiata pine lookup tables. Relative to the lookup tables, the MJMDS model overestimates sequestration during the first 10 years, but subsequently underestimates it, reaching only one-third of the average ETS lookup table value at age 40 years. Our model tracks at or slightly above the upper ETS lookup table regional value and is 15% higher than the ETS average at age 40. This outcome is consistent with expectations, as the ETS tables incorporate an allowance for unstocked forest area which approximates about 15% of total area. The comparison with the ETS tables indicates that our radiata pine model provides realistic predictions of carbon sequestration whereas the MJMDS model seriously underpredicts this component.

Secondly, Figure 4B shows predictions from both models for the native understory developing under an intact a radiata pine canopy. Both models show very slow sequestration for this component and are generally in broad agreement although the MJMDS model predicts somewhat faster sequestration than our model.

Finally, Figure 4C compares predictions from the MJMDS model of carbon in the native component after the radiata pine has been killed using the year the radiata pine is removed as a starting point and compares this with the four regenerating native growth curves used in our model. This demonstrates that our model predicts much faster sequestration in the natives after the radiata pine is removed than the MJMDS model.

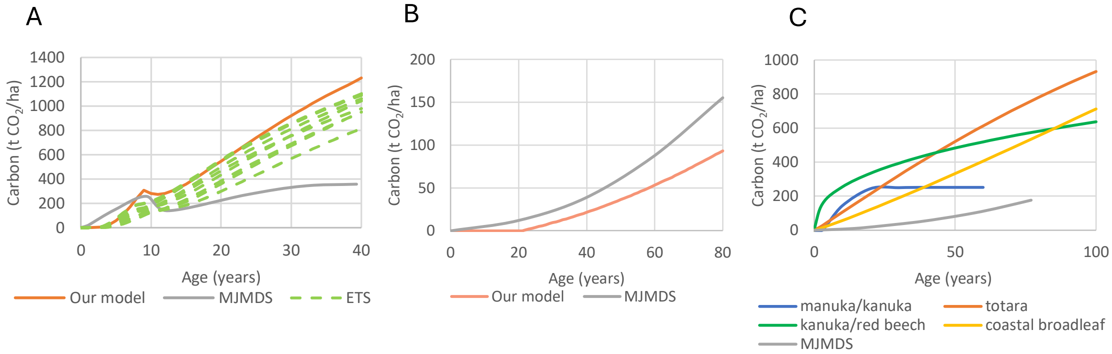


Figure 4. Carbon sequestration over time for: (A) The radiata pine component of a transition forest predicted using the MJMDS model and our model, compared with the ETS radiata pine regional lookup table curves; (B) The native understory component of a transition forest with intact radiata pine canopy predicted by the MJMDS model and our model; and (C) The native component after radiata pine trees are completely removed predicted by the MJMDS model compared with growth curves fitted using plot measurements from four different types of regenerating native forest.

These results are summarised in Table 5 which shows mean annual increments produced by the two models for each of the three modelled components of transition forests and compares these with values from the ETS lookup tables.

Table 5. Mean annual increments (of carbon sequestration (t CO_2/ha/year) for three different components of transition forests, calculated 40 years from planting (1st two components) or 40 years after removal of radiata pine (3rd component)). Values predicted by the MJMDS model and our model are compared with values from the ETS lookup tables. This shows that our model is in general agreement with the ETS tables whereas the MJMDS model predicts much slower sequestration.

Component	MJMDS model	Our model	ETS lookup tables
Radiata pine trees	9.1	30.7	26.6[1]
Native understory developing under intact pine canopy	1.0	0.5	-
Native trees growing after radiata pine is removed	2.3	6.3-11.0 (depending on forest type)	6.2[2]

[1] average of the post-1989 regional radiata pine lookup tables

[2] from the post-1989 indigenous forest lookup table

3.4 *Predictions of carbon sequestration for commercial radiata pine forests left unharvested*

Scenarios D - F represent commercial radiata pine stands that are left unharvested. In these scenarios, the radiata pine is established at 833 stems/ha. All scenarios receive an early waste thinning to 500 stems/ha and are then left undisturbed. Simulations for these scenarios carried to 250 years after the radiata pine is established are shown in Figure 5. Scenario D represents what we believe is the most likely pattern of long-term mortality for radiata pine with the pine trees gradually dying between ages 90 and 170 years. Scenario E represent a radiata pine stand that is subject to high levels of mortality from age 40 years, with all trees being eliminated at age 80 years. This scenario could represent a radiata pine forest seriously damaged by extreme weather events which are likely to become more common with climate change but could also represent a stand subject to a managed gradual reduction in radiata pine carried out using poisoning for example. Scenario F represents an even more rapid mortality with the radiata pine dying out over ages 20-40 years. The simulations for these scenarios were carried to 250 years after the radiata pine was established and are shown in Figure 6. Tables 6 and 7 give carbon sequestration predictions overall and by component for these scenarios.

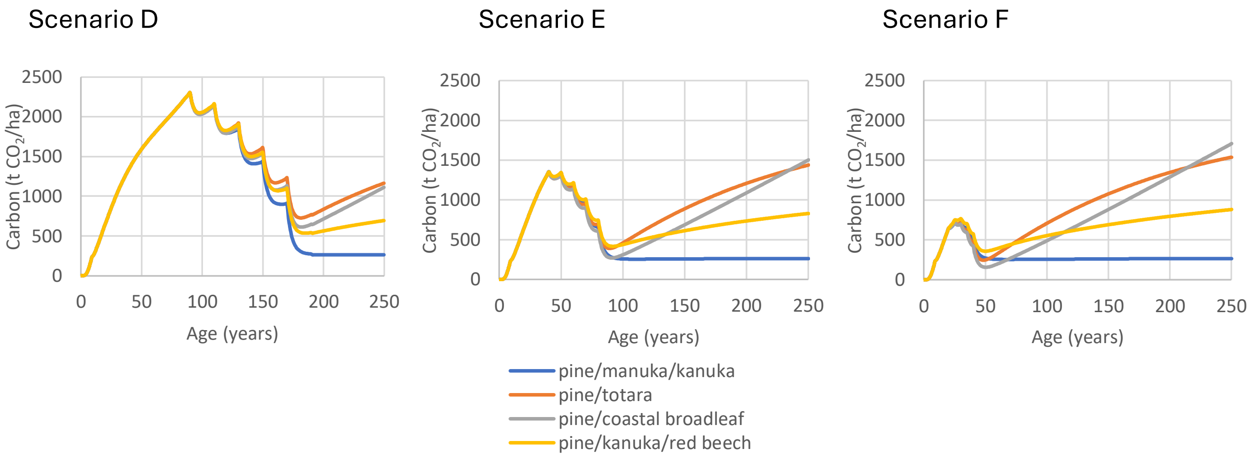


Figure 5. Predicted carbon sequestration in transition forests using our empirical model for scenarios D -and F.

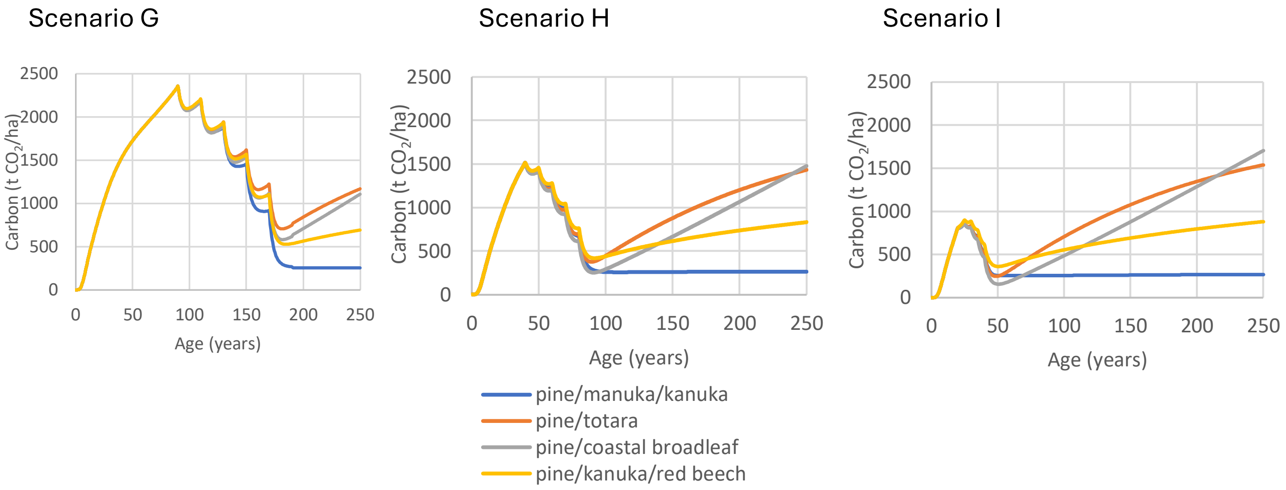
Table 6. Predictions of carbon sequestration (t CO_2/ha) produced by our model for all trees (radiata pine and native) in transition forests for scenarios D - F.

Scenario	Forest type	Age (years)						
		25	50	75	100	150	200	250
D	Mānuka/kānuka	853	1591	2034	2049	1434	261	261
	Tōtara	853	1591	2034	2041	1611	835	1163
	Coastal broadleaf	853	1591	2034	2032	1538	713	1111
	Kānuka/red beech	853	1591	2034	2053	1550	563	694
E	Mānuka/kānuka	853	1339	706	258	259	263	263
	Tōtara	853	1318	714	461	891	1211	1439
	Coastal broadleaf	853	1309	645	311	688	1090	1502
	Kānuka/red beech	853	1346	776	441	615	737	831
F	Mānuka/kānuka	719	272	255	257	262	266	266
	Tōtara	726	248	480	709	1078	1347	1538
	Coastal broadleaf	721	156	304	490	883	1292	1710
	Kānuka/red beech	754	359	464	555	692	798	884

Table 7. Predictions of carbon sequestration (t CO_2/ha) produced by our model for the radiata pine and native components in transition forests for scenarios D - F.

Scenario	Component and forest type	Age (years)						
		25	50	75	100	150	200	250
D	Radiata pine	852	1574	1978	1913	1186	0	0
	Mānuka/kānuka	0	16	56	136	248	261	261
	Tōtara	0	16	56	128	424	835	1163
	Coastal broadleaf	0	16	56	119	351	713	1111
	Kānuka/red beech	0	16	56	140	364	563	694
E	Radiata pine	852	1282	511	8	9	12	12
	Mānuka/kānuka	0	56	196	251	251	251	251
	Tōtara	0	36	204	453	882	1198	1427
	Coastal broadleaf	0	26	134	304	680	1077	1489
	Kānuka/red beech	0	64	265	433	606	724	819
F	Radiata pine	716	31	5	7	11	15	15
	Mānuka/kanuka	3	241	251	251	251	251	251
	Tōtara	10	217	475	702	1067	1332	1523
	Coastal broadleaf	5	125	299	484	872	1277	1695
	Kānuka/red beech	38	328	459	549	681	783	869

Scenarios G – I are similar to scenarios D – F except that the radiata pine receives no early thinning but s planted and left. Results for these scenarios are shown in Figure 6 and Tables 8 and 9. Finally, Scenarios G – L cover forests that are thinned early to a very low stocking of 150 stems/ha. These are shown in Figure 7 and Tables 10 and 11.


Scenario G

Scenario H

Scenario I

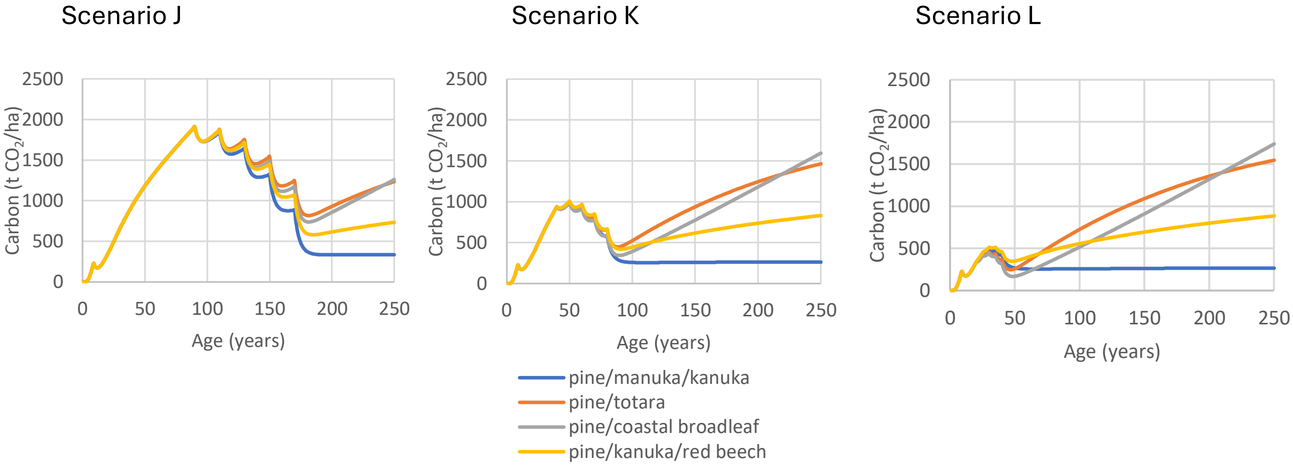
Figure 6. Predicted carbon sequestration in transition forests using our empirical model for scenarios G - I.

Table 8. Predictions of carbon sequestration (t CO_2/ha) produced by our model for all trees (radiata pine and native) in transition forests for scenarios G - I.

Scenario	Forest type	Age (years)						
		25	50	75	100	150	200	250
D	Mānuka/kānuka	853	1591	2034	2049	1434	261	261
	Tōtara	853	1591	2034	2041	1611	835	1163
	Coastal broadleaf	853	1591	2034	2032	1538	713	1111
	Kānuka/red beech	853	1591	2034	2053	1550	563	694
E	Mānuka/kānuka	853	1339	706	258	259	263	263
	Tōtara	853	1318	714	461	891	1211	1439
	Coastal broadleaf	853	1309	645	311	688	1090	1502
	Kānuka/red beech	853	1346	776	441	615	737	831
F	Mānuka/kānuka	719	272	255	257	262	266	266
	Tōtara	726	248	480	709	1078	1347	1538
	Coastal broadleaf	721	156	304	490	883	1292	1710
	Kānuka/red beech	754	359	464	555	692	798	884

Table 9. Predictions of carbon sequestration (t CO_2/ha) produced by our model for the radiata pine and native components in transition forests for scenarios G - I.

Scenario	Component and forest type	Age (years)						
		25	50	75	100	150	200	250
D	Radiata pine	852	1574	1978	1913	1186	0	0
	Mānuka/kānuka	0	16	56	136	248	261	261
	Tōtara	0	16	56	128	424	835	1163
	Coastal broadleaf	0	16	56	119	351	713	1111
	Kānuka/red beech	0	16	56	140	364	563	694
E	Radiata pine	852	1282	511	8	9	12	12
	Mānuka/kānuka	0	56	196	251	251	251	251
	Tōtara	0	36	204	453	882	1198	1427
	Coastal broadleaf	0	26	134	304	680	1077	1489
	Kānuka/red beech	0	64	265	433	606	724	819
F	Radiata pine	716	31	5	7	11	15	15
	Mānuka/kanuka	3	241	251	251	251	251	251
	Tōtara	10	217	475	702	1067	1332	1523
	Coastal broadleaf	5	125	299	484	872	1277	1695
	Kānuka/red beech	38	328	459	549	681	783	869


Scenario J

Scenario K

Scenario L

Figure 7. Predicted carbon sequestration in transition forests using our empirical model for scenarios J - L.

Table 10. Predictions of carbon sequestration (t CO_2/ha) produced by our model for all trees (radiata pine and native) in transition forests for scenarios J - L.

Scenario	Forest type	Age (years)						
		25	50	75	100	150	200	250
J	Mānuka/kānuka	490	1179	1655	1738	1323	335	335
	Tōtara	490	1179	1655	1748	1544	930	1236
	Coastal broadleaf	490	1179	1655	1740	1488	857	1261
	Kānuka/red beech	490	1179	1655	1748	1448	615	734
K	Mānuka/kānuka	490	1005	613	258	260	263	263
	Tōtara	490	990	663	524	939	1245	1465
	Coastal broadleaf	490	981	599	392	776	1181	1595
	Kānuka/red beech	490	1010	681	447	619	740	834
L	Mānuka/kānuka	412	267	256	258	262	266	266
	Tōtara	419	259	498	725	1090	1356	1545
	Coastal broadleaf	414	169	328	516	910	1320	1738
	Kānuka/red beech	447	349	464	556	693	799	884

Table 11. Predictions of carbon sequestration (t CO_2/ha) produced by our model for the radiata pine and native components in transition forests for scenarios J - L.

Scenario	Component and forest type	Age (years)						
		25	50	75	100	150	200	250
J	Radiata pine	484	1105	1509	1513	1012	12	12
	Mānuka/kānuka	5	75	146	225	311	323	323
	Tōtara	5	75	146	235	532	918	1224
	Coastal broadleaf	5	75	146	227	476	845	1249
	Kānuka/red beech	5	75	146	234	436	603	722
K	Radiata pine	484	899	390	7	9	13	13
	Mānuka/kānuka	5	106	223	251	251	251	251
	Tōtara	5	91	273	517	930	1233	1452
	Coastal broadleaf	5	82	209	384	767	1168	1582
	Kānuka/red beech	5	110	291	440	610	727	821
L	Radiata pine	405	21	5	7	11	15	15
	Mānuka/kanuka	7	246	251	251	251	251	251
	Tōtara	14	237	493	718	1079	1341	1530
	Coastal broadleaf	10	147	323	509	899	1305	1723
	Kānuka/red beech	43	328	459	549	682	784	869

4 Discussion

There has been considerable debate concerning the fate of planted exotic forests, such as those dominated by radiata pine, which are abandoned and left to natural processes. Do the exotic trees regenerate themselves, resulting in a forest that remains predominantly exotic indefinitely? Or does a diverse understory of native species gradually establish and eventually replace the exotic overstory, transforming the stand into a native forest? We believe the model we developed in this study provides, for the first time, valuable insights into the long-term dynamics of such forests, at least with respect to their carbon profile.

Results from a simulation of such a forest using our model is shown by scenario D in Figure 5 and Tables 7 and 8 illustrating how carbon stored in exotic and native tree components of an unmanaged radiata pine stand changes over time, tracking these dynamics across a 250-year period from the time of planting. This simulation shows that the carbon sequestration of this forest will proceed through the following well-defined phases:

1. **Phase 1, 0-50 years: Rapid sequestration by the radiata pine.** In this phase, we see the amazing capacity for radiata pine to sequester carbon from the atmosphere. Over this period, a conventionally thinned radiata pine stand removes 31 tonnes of CO_2 per hectare per year while an unthinned (plant-and-leave) stand removes 34 tonnes per hectare per year. During this phase, a native understory develops under the pines but it stores minimal levels of carbon.
2. **Phase 2, 50-100 years: Slowing sequestration by the radiata pine and gradually increasing sequestration by the native understory.** This phase is marked by a rapid slowing in sequestration by the pines which average 6.8 tonnes CO_2 per hectare per year over the period. The native understory begins sequestering significant levels of carbon averaging 2.3 tonnes per hectare per year. At the end of this phase, the forest achieves its peak carbon storage level of about 2050 tonnes of CO_2 per hectare.
3. **Phase 3, 100-200 years: Gradual death of radiata pine trees resulting in a steady loss in carbon partly offset by sequestration by native trees.** During this phase, the radiata trees gradually die, and all the carbon they have stored is lost. This loss averages 19 tonnes of CO_2 per hectare per year over the period but is partly offset by the mainly native trees steadily replacing the pines which sequester from 1.3 to 10.4 tonnes of CO_2 per hectare per year depending on their species composition. However, the net effect is that the carbon stock in the forest declines from 2050 tonnes per hectare to between 260 and 835 tonnes per hectare, depending on the native species composition.
4. **Phase 4, 200-250 years: Steady sequestration by the replacement mainly native forest.** Over this period, the mainly native forest which has replace the radiata pine sequesters at a steady rate of between 0 and 8 tonnes per hectare per year depending on its species composition. By age 250 years, this new forest stores between 260 tonnes per hectare (kānuka/mānuka) and 1160 tonnes per hectare (tōtara).

Our simulations show that if radiata pine mortality occurs earlier than what is assumed in scenario D, either though natural events or managed intervention, the peak level of carbon stored in the radiata pine will be lower and it will occur earlier, the response in native sequestration will also occur earlier as shown in scenarios E and F.

Our models also show that if a highly stocked radiata pine stand is planted and left, it will sequester higher levels of carbon over the initial decades, but long-term stocks both pine and native will be very similar to conventionally thinned stands. This can be seen by comparing scenarios G – I to scenarios D – F.

Finally, scenarios J – L show that a very low stand density of radiata pine sequesters much less carbon in the early years but shows little difference in long-term sequestration.

Our model requires various assumptions, and we now list these assumptions and discuss their likely validity:

1. Assumptions made to model growth during Phase 1 (0-50 years): Sequestration is simulated using a widely used radiata pine empirical growth model with associated carbon equations. This part of the modelling is well tested and validated.
2. Assumptions made to model growth during Phase 2 (50-100 years): Radiata pine sequestration is modelled using the same growth model used in Phase 1 which, although perhaps less reliable at these older ages, can be considered well tested. During this phase, the native understory is modelled using a model we developed using plot data from Tairāwhiti. Because this is a simple linear model, we believe its predictions should be reasonably reliable despite our need to extrapolate beyond age range used in its development.
3. Assumptions made to model growth during Phase 3 (100-200 years): In this phase it was necessary to make an assumption that is somewhat speculative concerning the likely longevity of radiata pine trees. However, varying this assumption by extending or reducing radiata pine longevity would only result in a change in the timing of the carbon decline during this phase. It is inevitable that such a decline must occur.
4. Assumptions made to model growth during Phase 4 (200-250 years): In this phase, the main assumption concerns the rate of sequestration of the native forest replacing the pine forest. However, we provide four alternatives forest types that we believe should cover the slowest to fastest levels of sequestration likely during this phase.
5. Assumption that the radiata pine forest will eventually be replaced by a mostly native forest: This assumption mainly relies on the observation that the mix of understory species in a radiata pine forest is overwhelmingly native (e.g., in our Tairāwhiti survey, 98% of understory carbon was stored in natives). However, it would be good to test this assumption further by surveying existing radiata pine forests that have been transitioned into native forest by management intervention (e.g., by poisoning). The method of undertaking 'coupe thinning' (a number of trees killed in one area or scattered trees killed) could have an influence on native regeneration due to either small or large canopy gaps being established. Large canopy gaps also introduce a greater chance of weed species establishing and dominating.
6. Assumption that all carbon in decaying dead wood is eventually released into the atmosphere: The radiata pine model simulates the transfer of live biomass to the dead wood and litter pools but then assumes these pools release all their carbon into the atmosphere as they decay. However, it is known that a proportion of this carbon ultimately transfers into the soil, and some studies suggest this is a significant percentage (Stokland and Alfredsen, 2024). If this is considered, the loss of carbon from the dying radiata pine trees could be substantially less than our simulation indicates. Further investigation is warranted to determine the likely extent of this effect.
7. Assumptions concerning dead wood in the native tree component: In our simulation of native trees, we only modelled the carbon in the live trees (above and below ground). We did not attempt to model carbon transferring to the dead wood pool. However, over time, this pool could become substantial. In mature New Zealand native forests, the dead wood pool can amount to 20-30% of the live biomass pool (Kimberley et al. 2019). Therefore, because our model does not consider the carbon in the native tree dead wood pool, the sequestration rates we used for the native component are probably underestimates.

Although we are confident our model provides realistic predictions, we must acknowledge that our predictions of carbon sequestration for both the radiata pine and native components of transition forests are far higher than those obtained by Mason et al. (2025) using their hybrid modelling approach. We believe, that both our radiata pine and native models provide predictions that are in line with actual experience as indicated, e.g., by the ETS lookup tables both for both radiata pine and regenerating natives (see Table 5). Possibly the slow growth rates predicted by Mason et al. (2025) for natives stems from their use of growth rate measurements from LUCAS plots which are generally in highly stocked stands often on less productive sites, where individual tree growth rates can be extremely slow.

One aspect of our modelling concerns the importance of the species mix of the native forest which gradually replaces the radiata pine forest. The native forest types we considered ranged from regenerating mānuka/kānuka in Tairāwhiti forest which showed rapid early sequestration but slowed and plateaued at a relatively low level of carbon stock (although our data only covered the first 60 years of development), through to tall canopy communities such as broadleaf forest and tōtara dominated regeneration in Northland which shows a steady level of growth for at least 150 years, and may have the potential to ultimately provide a long-term store of carbon comparable to that achieved, but only temporarily, by radiata pine. The study highlights the need to obtain data and develop models for different types of regenerating native forest in New Zealand.

Perhaps we could consider our four forest types as representative of the following situations regarding the likely ecological character of the native forest ultimately replacing the radiata pine:

1. Mānuka/kānuka – represents sites with limited seed sources and/or high levels of browsing pressure. This forest type represents a worst-case scenario for natives as it assumes they remain indefinitely as a treeland with limited successional ability and therefore capacity to store carbon. Without limitations, most mānuka/kānuka forest is likely to develop into a diverse forest containing tall canopy species with good potential to store high levels of carbon.
2. Tōtara – represents sites with good seed sources of tall-tree species such as tōtara and other tall native conifers.
3. Coastal broadleaf – represents sites in central New Zealand with good seed sources and limited browsing.
4. Kānuka/red beech – represents sites in lowland southern New Zealand with good seed sources and limited browsing.

There is potential for factors contributing to native forest development such as browse pressure and availability of native seed sources including tall canopy species to have a significant effect on forest development trajectories.

The study underscores the need for further research into several aspects of the carbon cycle and ecology of transition forests, including the species composition and characteristics of native forests replacing radiata pine, the growth rates of different types of regenerating native forests, and the role of dead wood and its interactions with soil in carbon dynamics.

5 Conclusions

This study has developed and applied a new empirical model to explore the long-term carbon dynamics of radiata pine forests that are either abandoned and left to natural succession or managed through a transition into native forests. Our results provide the first quantitative insights into how carbon storage in such forests evolves over a 250-year period, capturing the transition from exotic to predominantly native forest.

The simulations reveal four distinct phases: (1) rapid sequestration by radiata pine in the first 50 years, (2) slowing pine sequestration with increasing contributions from native understory between 50–100 years, (3) substantial carbon loss associated with pine mortality over the next century, partly offset by native regeneration, and (4) renewed sequestration by the replacement native forest, with long-term carbon stocks strongly dependent on species composition.

While our model relies on several assumptions, comparison with the ETS lookup tables suggest that both our radiata pine and native forest predictions are realistic and consistent with field experience. Nonetheless, key uncertainties remain, particularly concerning radiata pine longevity, the contribution of dead wood and soil carbon pools, and the long-term trajectories of different regenerating native forest types.

The findings highlight that the eventual carbon outcomes of transition forests are highly contingent on the species mix of the replacing native forest. Scenarios range from relatively low long-term carbon storage in mānuka/kānuka dominated forests to potentially high levels in tōtara or broadleaf forests. Addressing these uncertainties requires further data collection and model development, especially for regenerating native forest types across a range of ecological contexts.

Overall, this study shows that while radiata pine transition forests sequester substantial amounts of carbon in the early years, meaningful development of native forest is unlikely until the pine canopy is removed or naturally senesces. As radiata pine declines, a corresponding reduction in forest carbon storage is inevitable.

Acknowledgements

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