Ministry for Primary Industries
Manatū Ahu Matua

Transitioning Exotic Plantations to Native Forest:
A Report on the State of Knowledge

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Acknowledgements

We thank the Ministry of Primary Industries for commissioning this report. We also wish to acknowledge the many researchers, organisations, and landowners for their contributions to the existing state of knowledge on this topic.

Cover photograph

Planted rimu forming a canopy amongst a senescing central North Island ponderosa pine plantation.

1 Executive summary

The Ministry of Primary Industries commissioned a review of (1) the state of knowledge on the topic of transitioning exotic plantations to native forest and (2) of the existing data and research approaches for addressing knowledge gaps for forest carbon aspects of transitioning plantations. The existing literature was reviewed, and anecdotal evidence was compiled to inform this document.

What we do know is that at the stand scale, forest age and structure, microclimate and shade tolerance are of high importance to the structure and composition of native understorey regeneration. So too are gradients in site factors such as topography and soils. At wider scales, we know that macroclimate is an important predictor of understorey regeneration and existing modelling has indicated which areas of Aotearoa are reasonably capable of natural regeneration (i.e., warmer, higher rainfall areas close to seed sources). However, empirical surveys and forestry experiments of regeneration and tree growth along key gradients are lacking. Proximal seed sources are known to be important for forest regeneration, and this too applies to regeneration in exotic plantations. Excessive herbivory by introduced mammalian herbivores (e.g., deer, goats, pigs, possums, lagomorphs and domestic stock) filters regeneration and can severely constrain the composition and structure of understorey regeneration, and weeds can be a major limiting factor. Various options exist for addressing these threats, including defending forests using fencing or professional animal pest control operations or addressing intense weed threats (e.g., old man's beard or blackberry).

The topic of transitioning exotic plantations to native forest is relatively new and there has been insufficient time and a lack of coordinated research to determine the actual timeframes required to transition exotic plantations to native forest. Related to this, we do not know what level of regeneration is required to successfully attain a transition to native forest or to what levels old-growth native forest canopy dominants will establish in relation to biotic[1] and abiotic[2] gradients. While we know that the performance of regeneration (e.g., structure, composition, growth and biomass) will differ along the main abiotic and biotic gradients, we have few empirical data from exotic plantations to demonstrate this. Work to attain empirical data is critical, as these data would allow management thresholds to be identified as well as informing carbon and forest dynamics models. The role for species other than radiata pine (e.g., exotic angiosperms), particularly when planted in polycultures designed to provide specific structural and functional elements is also unknown and is deserving of trials and investigation.

Practical considerations for transitioning plantations are likely to include defining clear objectives (e.g., carbon forestry, soil conservation, or restoring biodiversity or cultural values), implementing effective pest control, adaptively managing stand level interventions, recognising the influences of site factors and anticipating the causes of tree instability. Transitions would be most appropriate in areas of higher rainfall with good amounts of native seed sources, healthy native forest bird populations, low numbers of browsing animals and manageable plant pest issues. Transitional forestry is only appropriate where there is committed/guaranteed long-term funding and a robust plan for ongoing forest management (including good infrastructure within the forest to support this). Covenants to guarantee this approach are also required. Given the current state of knowledge, transitions should only be attempted at scales which are reasonably manageable.

Recommendations are made for a programme of research including national scale surveys and forestry experiments conducted along important biotic and abiotic gradients. These trials would better define management needs and rates of growth and biomass/carbon accumulation in transitional forests.

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[1] That is, seed source proximity, soils, and levels of browser influence.

[2] That is, climate, topography, and canopy structure gradients.

2 Introduction

2.1 Background

The Ministry of Primary Industries (MPI) commissioned Forbes Ecology Limited to undertake a review of the current state of knowledge of transitioning exotic forest to native forest (hereafter transitional forestry) in Aotearoa New Zealand. While the regeneration of native forest species has been studied in exotic plantations over a number of decades[3], more recently, opportunities have been explored for exotic plantations to serve as a precursor to permanent native forest[4].

This report addresses the state of current knowledge of how best to transition non-harvest exotic forest to native forest, discusses information gaps and outlines the means and costs of addressing important information gaps.

2.2 Report objectives

The specific objectives of this report are as follows, as stated in the MPI Request for Proposal:

1. Report on the state of current knowledge of how best to transition non-harvest exotic forest to indigenous forest, information gaps and the means, costs and business case to fill those gaps over time.
2. Identify such datasets that exist that could support the development of carbon stock models for the transition of permanent exotic forests to indigenous, including whether these are freely publicly available or if not the terms under which they could be made so.
3. Describe the means of collecting additional data from which carbon stock models could be developed in the short term (12-18 months), including potential sites for such collection and cost estimates.
4. Identify research needs to develop additional regional carbon stock models and/or refine such models, including permanent sample plot numbers and potential sites for such plots to be established. Estimate costs for such research.

A separate output which uses information compiled in this report will address the following item:

- To the extent that current knowledge permits, provide guidance for landowners and forest investors on best practice to transition exotic forest to indigenous forest, including silvicultural and management interventions. Such guidance should cover a range of site conditions from Northland to Southland and West and East Coast reflecting variations in rainfall and indigenous seed sources.

2.3 Scope of report

This report is structured to address the transitional forest state of knowledge (report Objective 1) under the headings in Section 2 – What we Know and What we Don't Know. Practical guidance is then provided for managing a transition based on our current state of knowledge. Objectives 2-4 are addressed in Section 3.

2.4 Limitations and assumptions

Most of the emphasis in this report is on transitioning existing radiata pine (*Pinus radiata*) plantations to native forest. This is because radiata pine has received the most formal research to date and because it is currently the predominant plantation species in Aotearoa. We anticipate a demand for new plantations designed specifically as transitional forests and, in these instances, it may well be that species other that radiata pine could be more suitable as a nurse for native establishment. In

[3] McQueen, 1961; McQueen, 1973; Allen et al., 1995; Ogden et al., 1997; Brockerhoff et al., 2003.

[4] Norton & Forbes, 2013; Forbes et al., 2015; Forbes et al., 2016a; Forbes et al., 2016b; Forbes et al., 2019.

particular, the use of polycultures (rather than monocultures) to build functionality and heterogeneity into the stands from the outset requires investigation.

We also note that most of the research on transitioning has been undertaken in mature radiata pine stands that have been subject to silvicultural management (thinning and pruning) and are at a reasonably low stocking. We note that new radiata pine carbon forest is established at very high stockings and are not subject to any silvicultural management. The implications of these factors have not been studied.

Transitions are more likely to be successful in areas of higher rainfall, warm temperatures, and with good amounts of native seed sources, healthy native forest bird populations, and low numbers of browsing animals or serious plant pest issues (e.g., blackberry). A committed/guaranteed long-term financial investment with a formal plan to support ongoing forest management is also essential.

There remains uncertainty at this time over the transition from exotic to native forest and trials and surveys are recommended to help address this uncertainty. Ultimately, we need to allow adequate time to trial this approach and adapt the approach as knowledge develops. We advise against attempting transitional forestry at scales larger than what foresters can reasonably manage. We also note that even where a transition to a native forest occurs, there is no evidence that it will be represent "old-growth" native forest, nor that it will necessarily be similar in composition or structure to what might have occurred in that location in the past[5]. Alternative forest trajectories have been seen in forest successions from exotic gorse compared to those through kānuka[6] and transitional forests are expected to be similar in this regard, comprising novel mixes of species shaped by management to meet clear objectives over time.

[5] This is not necessarly a negitive consequence of forest successions commencing from exotic stands, it is more that different expectations should apply. We think it is unlikely that forests of stature and composition comparible to intact old-growth forests would eventuate from exotic plantations in foreseeable timeframes.

[6] *Ulex europeaus*; see Sullivan et al., 2007.

3 State of knowledge

3.1 What we do know

3.1.1 Forest stand age, structure, microclimate, and shade tolerance

Stand age is a principal variable predicting spontaneous regeneration of tree species in plantation forests[7]. As plantations age, tree height, crown width and density become more variable, and gaps of differing sizes and shapes develop[8]. In particular, natural or silvicultural thinning (or pruning) might occur, thereby reducing plantation stem density with time. Given the close relationship between stand structure and stand age, plantation age is a useful surrogate measure of stand structural variability[9] and forest microclimate[10].

As stands attain greater stature, the quality and quantity of light transmitted to the forest understorey is affected (Figs. 1-4). This shift from heavily shaded to more brightly lit (and therefore less competitive) understorey conditions can be beneficial to native seedling regeneration. However, in some circumstances, a single or small number of species (e.g., tree ferns and ground ferns) can take dominance in the understorey (e.g., high levels of cover) returning high levels of light competition for native seedlings in the plantation understorey[11].

Figure 1. Example of old (89-year-old) radiata pine stand structure. Photo location: central North Island.

Figure 2. Example of old (89-year-old) radiata pine stand structure (left) compared to adjacent <25-year-old radiata pine. Photo location: central North Island.

[7] Ogden et al., 1997; Brockerhoff et al., 2003; Forbes et al., 2019.

[8] Geldenhuys, 1997.

[9] Ogden et al., 1997; Brockerhoff et al., 2003.

[10] The forest microclimate is a suite of climatic conditions that are formed within a forest and are distinct from macroclimate, the latter which represents climatic conditions outside of forest cover.

[11] Forbes et al., 2016b.

The effect of plantation canopy species identity on understorey regeneration has not been widely examined in Aotearoa[12]. Most attention has been on the dominant exotic plantation tree species, radiata pine[13]. The potential of other canopy species (e.g., angiosperms such as *Eucalyptus* and *Acacia*), especially when planted in polycultures[14], needs further examination.

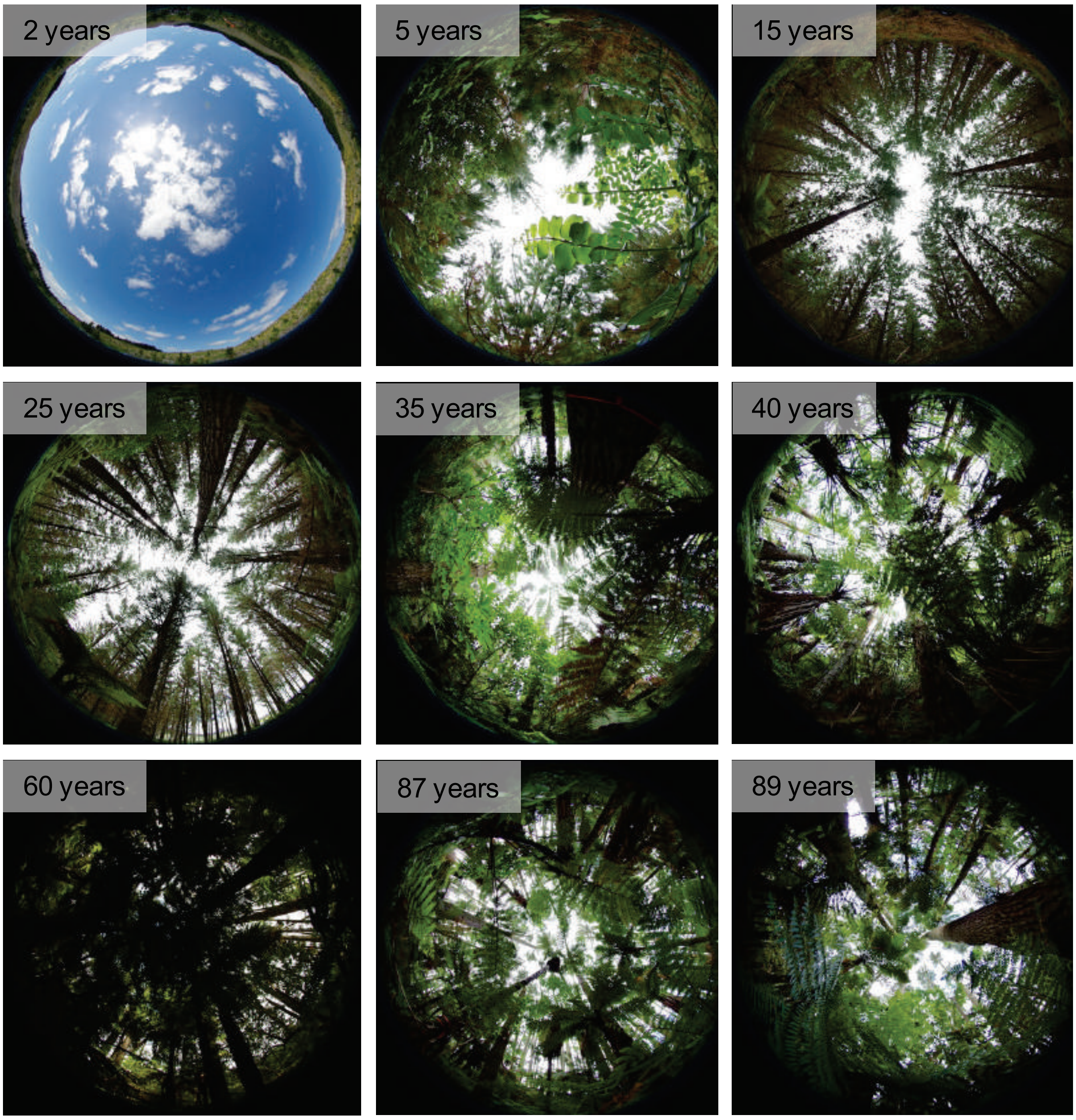

Figure 3. An example of stand structural changes over time across a chronosequence of central North Island plantations. Note the prevalence of tree ferns developing in this sequence from 35 years onward which were creating significant levels of competition for seedlings on the forest floor.

Other structural factors with potential linkages to forest regeneration have been found to increase with plantation age. Increasing litter and humus layers are known to make plantations more conducive to native plant colonisation over time[15], although deep and/or dry litter layers[16] or highly competitive

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[12] Although a plot survey comparing understory regeneration in *Pinus*, *Eucalyptus*, and *Acacia* in Tasman region was completed in early 2021.

[13] McQueen, 1961; Allen et al., 1995; Ogden et al., 1997; Brockerhoff et al., 2003; Forbes et al., 2019.

[14] Nichols et al., 2006; Felton et al., 2010.

[15] Geldenhuys, 1997.

[16] Bueno & Baruch, 2011.

shallow root zones can also limit seedling regeneration[17]. These temporal changes can in some circumstances explain aspects of understorey regeneration.

In central North Island radiata pine plantations, canopy cover is achieved rapidly (at c. 5 years) and stand structure is known to start opening towards the end of the second decade of growth. Prior to attainment of canopy closure, understorey vegetation tends to be dominated by light-demanding exotic species and shade-tolerant native species only begin to establish mid to late in the second decade[18].

A survey of light transmission to the understorey across a radiata pine chronosequence found light levels had stabilised in stands 20-30 years of age (Fig. 4). A separate study replicated in different geographical regions found canopy closure[19] by mid-rotation (16 years) to be on average 50% in low stocked and 67% in high stocked stands[20]. Sampling of canopy openness and total light transmission using hemispherical photography in radiata pine plantations in the both the Marlborough Sounds and Kinleith Forest indicated that beyond 20 years of age canopy openness is <14% and as little as 8%. The planted seedlings in the Marlborough Sounds site benefited from canopy gap creation indicating significant benefits for native seedling performance (depending on their relative shade tolerance) where canopy openness can be increased to levels of up to 18% and 26%[21].

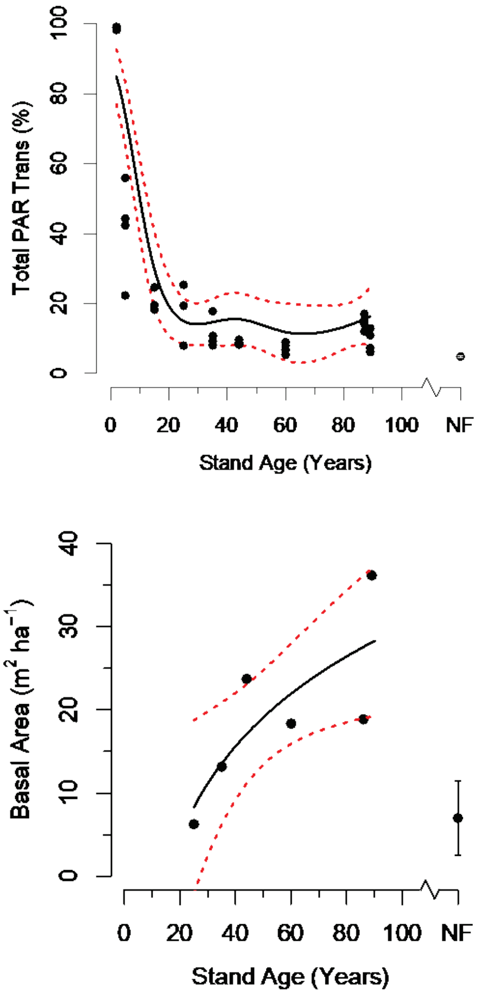

Figure 4. Modelled (A) percentage of total photosynthetically active radiation (PAR) transmission to 1.35 m above ground level and (B) tree fern basal area over time. Measures from local old-growth native forest (NF) are shown for reference. See Forbes et al., 2019.

Even-aged monocultures, such as radiata pine plantations, lack structural heterogeneity compared to natural forests or those planted in species mixtures, where interspecific competition and mixed age classes cause variable stand structure[22]. Variability in plantation stand structure leads to variability in microclimate which enables a site to support a greater diversity of species[23].

Gap-phase regeneration refers to seedling regeneration occurring in small-scale gaps such as might result from mortality of one or a few trees. Gap-phase regeneration is one of three dominant modes of regeneration in Aotearoa's natural forests[24]. Growth of many canopy forest trees can be significantly faster in canopy gaps compared to beneath intact forest canopy[25]. Mimicking a natural pattern of disturbance in monocultural plantations is therefore one way of increasing structural heterogeneity and providing

[17] Harrington et al., 2003.

[18] Ogden et al., 1997; Brockerhoff et al., 2003; Forbes et al., 2019.

[19] Due to different researchers using different measures of canopy structure, this paragraph refers to canopy cover, canopy closure, and canopy openness. These measures are distinct and as result these data are not directly comparable.

[20] Brockerhoff et al., 2003.

[21] Forbes et al., 2016a.

[22] Riofrío et al., 2017.

[23] Kerr, 1999.

[24] Lusk & Ogden, 1992.

[25] Smale & Kimberley, 1993.

microsites for shade tolerant species to escape the competition of the uniform plantation canopy[26]. However, either uniform thinning or lower stocking[27], or creation of too larger gaps can promote establishment of undesirable light-demanding (often exotic) species; meaning small gaps gradually repeated across a plantation to effect a transition is a better strategy as the forest microclimate is preserved. However, for those native species that require large scale disturbance for establishment (e.g., red beech), it may not be possible for them to establish into an exotic plantation.

3.1.2 Macroclimate

Anecdotal observations indicate that plantations in higher rainfall areas have more diverse understories than those in drier areas. Air temperature and soil moisture availability are two variables important in explaining the natural establishment of forest trees[28]. As such, macroclimate serves as one coarse predictor of the likelihood of native forest establishment.

A modelling approach has been applied previously to mainland Aotearoa to predict the probability of establishment of tree species outside of forest canopies[29]. A similar approach could be used to determine, at a national scale, which land areas have a reasonable probability of tree establishment.

Figure 5. Old-growth seed sources are an important component of transitioning exotic forest as they provide a local seed source, reducing the need to intervene through enrichment planting. Photo location: central North Island.

Figure 6. Dense five-finger regeneration in a radiata pine canopy gap where pig rooting was seen to occur 5-6 years earlier and where a five-finger seed source is within 50 m. Photo location: Port Underwood, Marlborough.

3.1.3 Propagule availability

The seeds of many of Aotearoa's forest trees are contained in fleshy fruit and are dispersed predominantly by fruit-eating birds (frugivory). For non-fleshy seeded species like kamahi, rata and beech species, dispersal is by wind or gravity[30]. The spatial probability of dispersal by both frugivory and wind is highest in close proximity to native forest seed sources[31].

Given that Aotearoa's native forest birds are important dispersers of fleshy fruits, management of these bird populations (e.g., through predator control and bird habitat retention/expansion) is important

[26] Forbes et al., 2016a.

[27] Brockerhoff et al., 2003.

[28] Gaston, 1990.

[29] Mason et al., 2013.

[30] Thorsen et al., 2009.

[31] Wotton & Kelly 2012; Canham et al., 2014; Forbes et al., 2021.

for fully functioning seed dispersal[32]. The amounts of landscape level habitat availability have been shown in other countries[33] to affect forest plant species richness, but it is unknown how Aotearoa's forested landscapes function in this regard along fragmentation gradients, and whether thresholds in the amount of habitat operate for seed dispersal.

Distance to seed source (i.e., linear metres/kilometres) has to date been the main metric applied in Aotearoa to indicate the effect of isolation from seed sources on the composition and structure of regenerating forests. This work has indicated that most dispersal occurs within 100 m or less of the seed-bearing tree[34]. This indicates that in landscapes with few native seed sources, a hectare would be a logical scale at which to assess and plan the need for actions to overcome propagule availability (e.g., assessment of regeneration and supplementary (enrichment) planting to achieve future seed sources on a one-hectare grid).

Proximity to diverse seed sources will affect the composition and structure of regeneration actually or potentially occurring within exotic plantations (Fig. 5)[35]. Depending on the regeneration potential of a given site, management is likely to be required to actively overcome dispersal limitation through enrichment planting or broadcast seeding[36]. Another method of stimulating seedling regeneration in plantations might be to disturb the soil surface, such as occurs when digging holes to plant seedlings or through pig rooting[37], particularly where native seed sources are close and other factors discussed here are amenable to native forest regeneration (Fig. 6).

2.1.1 Herbivory

Mammalian herbivores (either wild or domestic) can adversely affect forest regeneration through preferential browse across a range of herbivore densities[38], which can shape forest community structure[39] (Fig. 7). Many feral mammalian herbivores range over large spatial scales[40] and their populations can grow and expand rapidly if not adequately controlled[41]. The actual effect of mammalian herbivores on forest vegetation is contingent on a number of factors, but as a worst-case scenario, high numbers can effectively prevent native tree regeneration and successional development meaning that a transition from exotic to native forest will not occur. The assembly of desirable forest composition and structure following reduction in browser numbers is likely to require active forest management (e.g., enrichment planting and canopy gap creation)[42] and heavily browsed areas might require complete eradication of browsers to facilitate forest regeneration and succession[43].

Depending on the species being controlled, non-fencing methods of feral herbivore control include poisoning, trapping (including capture and removal), ground-based shooting (professional or

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[32] Clout & Hay, 1989; Burrows, 1994; Kelly et al., 2010.

[33] Rigueira et al., 2013; Fahrig, 2013; Rocha-Santos et al., 2016.

[34] Kelly et al., 2010; Canham et al., 2014; Forbes et al., 2021.

[35] Forbes et al., 2019.

[36] Moles & Drake, 1999; Forbes et al., 2020; Paul et al., 2020.

[37] Although on balance, the disturbance of pig rooting is likely to outweigh the benefits to regeneration.

[38] Coomes et al., 2003; Ramsey et al., 2018.

[39] Holland et al., 2013.

[40] For instance, red deer (*Cervus elaphus*) can range 100-2,074 ha and up to 11,000 ha (Nugent et al., 2001).

[41] Hickling and Pekelharing, 1989; Moloney et al., 2021.

[42] Coomes et al., 2003.

[43] Ramsey et al., 2018.

recreational, with or without dogs), aerial shooting, Judas animals, fertility control, mustering, and commercial harvest. Fencing is an expensive alternative, both in terms of installation and ongoing maintenance. However, whatever the control or eradication method employed, it must be ongoing so long as herbivores are present in the wider landscape.

Figure 7. While unpalatable native conifers have established in this browsed *Pinus* stand, the understorey composition is largely missing palatable species. Photo credit: Paul Quinlan. Photo location: Far North District, Northland.

3.1.4 Site factors

Topography and soil chemistry were found to strongly control understorey composition in radiata pine plantations in Kinleith Forest[44]. Phosphorus declined from moist lower slopes to dry ridge sites and exchangeable soil cations increased with increasing slope[45]. Landform is known to be important for determining species composition in native forests, for instance certain native conifers tend to be found on mid-slope to ridge positions[46]. This is thought to be partly due to the balance between soil N and P, which varies with landform, and helps to determine the competitive balance between slower growing conifers and faster growing angiosperms in native forests[47]. Landform was found to be a useful predictor of native woody stem density (i.e., stems ha^{-1}) and weed cover in central North Island conifer plantation clear-fells[48]. Similar influences should be anticipated across landform and soil gradients in plantation forests.

3.2 What we do not know

3.2.1 Macroclimate effects

The application and design of transitional forestry will differ among climate zones. Delineating the suitability of this approach across climate zones would provide an important screen to guide where transitional forestry is realistic.

A modelling approach has been applied previously to mainland Aotearoa to predict the probability of establishment of tree species outside of forest canopies (Fig. 8)[49]. A similar approach could be used to determine, at a national scale, which land areas have a reasonable probability of regeneration. These data, when mapped, could serve as a screen to guide suitability for transitions, and the levels of intervention required to effect a transition in any given location. Thresholds on modelled outputs could be determined where transitioning would require such active input that the approach for establishing transitional forest is not supportable at scale beyond those thresholds/in those locations. Validating modelled outputs through ground truthing would be important.

Bioclimatic zones are another means of classifying land according to the relationships between vegetation and climate[50]. The available bioclimate zone maps are drawn at relatively coarse scales[51] which makes them less preferable for this application compared with a modelled approach.

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44 Allen et al., 1995.

45 Allen et al., 1995.

46 Ogden & Stewart, 1995; Burns & Leathwick, 1996; Carswell et al., 2007.

47 Richardson et al., 2004; Coomes et al., 2005; Carswell et al., 2007.

48 Forbes et al., 2021.

49 Mason et al., 2013.

50 Singers & Rogers, 2014.

51 E.g., Singers & Rogers, 2014.

A national layer comprising modelled probabilities of seedling establishment[52] overlaid with native vegetation cover (or an index of seed source amount/proximity), and MPI regions would be one approach to provide a coarse reference as to appropriateness of transitional forestry and of the levels of interventions required to achieve a transition at a given location in Aotearoa.

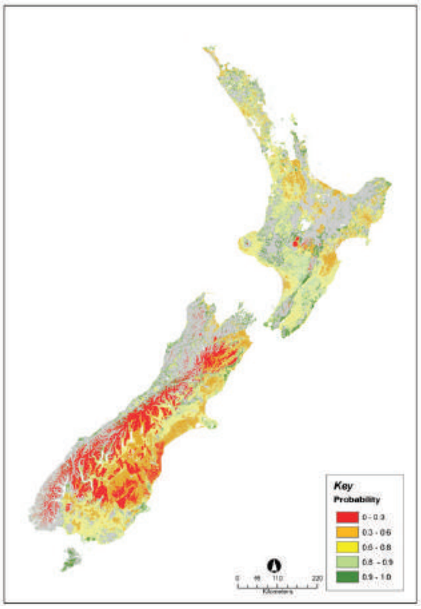

Figure 8. Taken directly from Mason et al., 2013 (Fig 3) showing predicted tree occurrence probability in non-forest vegetation in Aotearoa.

3.2.2 Timeframes

The timeframes for a transition are currently unknown and would vary along key gradients controlling forest growth and with differing levels of regeneration, intervention, and forest management. Biomass modelling of regeneration in radiata pine stands indicates that the pine biomass would peak at around year 100 and pine biomass would be largely depleted within 200 years from planting[53]. The same predictions suggest that native biomass would exceed pine biomass between 100-150 years. Although, these predictions were based on defined scenarios and actual outcomes would be dependent on several factors (discussed in this report).

Where more active approaches are taken, such as through intensive enrichment planting with high volume native tree species (e.g., native conifers) this process might be speeded up. For example, at one site, native tree biomass has been found to equal the biomass of the pine nurse within approximately 50 years from native planting (Fig. 9)[54]. However, the exotic species at this site (ponderosa pine) had been heavily impacted by a fungal disease (Dothistroma) leading to a very open pine canopy. When enrichment planting in plantations, the optimal species selection for the site and for the local plantation microclimate conditions (e.g., light conditions) is critical to the outcomes of native tree growth and to the nature of regeneration what will occur in the plantation stand over time[55].

Old growth species are an important part of transitional forestry interventions. While it is not possible to recreate an old growth forest through planting, recruitment of old growth species (naturally or through planting) will help to incorporate valuable forest traits, such as abundant fruit and nectar supply, high biomass and longevity, tall stature, and a shade tolerance suited to the forest understorey[56].

The structure and composition of the developing understorey will help explain the timeframes and the potential for a transition. For instance, tree height/age models for planted native beech and conifers planted into open sites across Aotearoa indicate tree heights of 25-30 m are attainable within 100 years[57]. Whereas, where the understorey contains only common angiosperm trees (e.g., mahoe, hangehange, putaputaweta[58]), long term expectations for stature, volume and ecological functionally should be less and, depending on the forestry objectives, management may choose to intervene by introducing tall native forest species, or those that have specific functional importance.

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[52] Similar to Mason et al., 2013.

[53] Meurk & Hall, 2006.

[54] Forbes et al., 2015.

[55] In other words, species that perform well and create stands with favourable microclimate conditions are likely to foster more favourable spontaneous regeneration compared to stands of poorly performing enrichment species; Forbes et al., 2015.

[56] Forbes et al., 2020.

[57] Bergin & Kimberley, 2012.

[58] *Melicytus ramiflorus*, *Geniostoma rupestre* var. *ligustrifolium*, and *Carpodetus serratus* respectively.

Figure 9. Approximately 50-year-old rimu planted beneath a degraded *Pinus ponderosa* plantation. Photo location: central North Island.

3.2.3 Adequacy of regeneration

We currently do not understand what level of tree regeneration is required to ensure a transition will actually occur, or even if native canopy trees that typically dominate old growth native forests are able to establish in plantations. Research is required to understand levels of native tree regeneration, and the species groups involved, occurring naturally in plantations across key gradients to identify when and what management interventions are required to achieve adequate regeneration. In the shorter term, guidance on stem densities and the compositional make-up could potentially be taken from data provided by plot surveys in existing native forests and from forest restoration best practice[59]. Specifying a minimum stem density for native canopy trees per hectare would help secure a minimum level of forest regeneration. Depending on the level of natural regeneration at a given location, this bottom line would clarify the level of management intervention (e.g., canopy opening and enrichment planting) required to support a transition thereby providing a useful threshold for forest management.

3.2.4 Growth and biomass through the transition

Almost no empirical data are available on native tree growth rates within exotic plantations, particularly data replicated along climate, topographical, seed proximity, and canopy structure gradients.

The following data are available:

- Measured radiata pine diameter and height to 60[60] and 89 years[61]. From this biomass and carbon can be calculated.
- Growth rates for exotic tree species provided by the MPI Emissions Trading Scheme (ETS) look up tables.
- Growth and carbon stocks of three native conifer species after 51 years at one location planted into a degraded ponderosa pine plantation[62].

[59] Bergin, 2011; Norton et al., 2018; van Galen et al., 2020.

[60] Woollons & Manley, 2012.

[61] Forbes et al., 2019.

[62] Forbes et al., 2015.

- Native tree growth data from native plantations[63]. However, these data do not represent growth within an exotic forest.

The following data would be required[64]:

- Growth and biomass data for a range of native and exotic tree species within representative exotic plantations across national climate gradients. This would involve planting native tree seedlings as a permanent trial replicated among climate gradients. This would be done in conjunction with canopy manipulations to attempt optimisation of growth rates. This should include plantation identities other than just radiata pine (e.g., *Eucalyptus*).
- A plot survey of natural regeneration within plantation types along national climate gradients and including gradients of seed source proximity/amount.

3.2.5 Canopy identity

Much of the focus on transitioning plantations to native forest has focused on radiata pine. To an extent this is important, given the dominance of radiata pine in the plantation sector. However, other exotic tree species could also be considered for transitional forestry. To enable this, data are required on the performance of a range of plantation species and how native regeneration and plant growth relates to canopy type. For instance, the canopy structure, light interception, and competitive interactions with natives by *Eucalyptus* will differ from radiata pine and management treatments would need to be adapted accordingly. Other aspects such as levels of litter deposition or root competition may differ among species and such factors might be significant for regeneration of native species.

Exotic plantations are typically planted as monocultures, yet a large proportion of the physical work required to support a transition aims to build heterogeneity into the homogenous stands that result from even-aged, monospecific plantings. There seems room to establish polycultures[65] of exotic tree species to encourage structural diversity (e.g., subdominant trees) which would in theory lead to greater biological diversity and better native regeneration[66]. Consideration is also required on the functional side of the exotic plantations, so that transitional forests provide differing types (e.g., feeding guilds) and timing of resources (e.g., continuous supply of nectar or fruit) to support dispersers, or so that forest structure develops providing suitable bird perches for seed deposition, as two examples[67].

These data can be gathered through surveys of existing stands and through establishing and monitoring forestry experiments. There currently appears to be wide interest in establishing forests of alternative species on private land and opportunities need to be taken to establish trials to further our understanding and provide examples for people to study and consider.

3.2.6 Dispersal function

We do not know how landscape configuration affects dispersal and which measures are most appropriate to guide transitional forestry. Surveys could be undertaken to gain a better understanding of how regeneration varies along gradients of forest habitat amount versus distance from seed source. The aim would be to identify management thresholds where enrichment planting treatments become increasingly important to address dispersal limitation.

3.2.7 Transitional forest regimes and interventions

Standard prescriptions are required for managing the transition by manipulating the overstorey to achieve particular outcomes for forest carbon[68]. Transitional interventions need to be implemented at a range of different sites. For instance, ridgelines and northern slopes may require more active inputs in the form of enrichment planting and canopy manipulations may need to be designed differently

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[63] See https://www.tanestrees.org.nz/resources/carbon-calculator/carbon-models-for-planted-natives/

[64] See the Appendix for a full list of recommended research items identified in this report.

[65] Nichols et al., 2006.

[66] Although such forests should be established as monitored trials to assess how native spceies perform in exotic polycultures.

[67] Norton, 1998.

[68] For example, see Table 6 in Scragg (2020).

depending on aspect and exposure. These aspects require field trials replicated in different climate zones to assist our understanding and to better shape management approaches.

3.2.8 Pest control

Transitional forestry will require threats to be addressed comprehensively and at scale. Often this will require control to extend well beyond the plantation into the surrounding landscape. Pests likely to require control would be possum, deer, goats, and pigs. A range of carnivore pests (e.g., mustelids, rodents, possums) could be controlled to enhance disperser populations (i.e., native birds). Also, a range of plant pests may require control, especially those species that are shade tolerant or those that will take structural dominance (e.g., blackberry and old man's beard). Technological advancements are needed to help reduce the costs of pest control.

3.3 Practical guidance based on our current state of knowledge

3.3.1 Defining objectives

Objectives for the transition should be clearly defined. For example, if a main objective of the transition is to avoid plantation clear fell in a sensitive catchment, the focus could be on simply replacing exotic cover with some form of native cover, not necessarily with high-volume native trees and if the native understorey regeneration is abundant then the exotic plantation could be removed rapidly. Whereas, if the transition is to sequester forest carbon, a more gradual transition is likely to be desirable (maximising the growth and biomass benefits of the fast-growing exotic canopy) and longer-term recruitment of high-volume native tree species will be important.

3.3.2 Pest control

Of the feral animal populations, ungulate (including pig) and possum populations are almost certainly going to require active management anywhere in Aotearoa where plantations are to be transitioned to native tree species. As some of these animals have considerable home ranges, landscape-scale population control is likely to be the best approach.

Figure 10. Example of a plantation infested with the invasive vine, old man's beard, which presents a serious threat to the future of forest regeneration at this location. Photo location: Nelson.

Browser numbers are higher in some landscapes compared to others and some areas harbour localised populations of goats or pigs. These issues will mean management needs to be much more active (more expense) to address these threats to forest regeneration and succession in the long term. Cross-boundary issues can arise where nearby landowners foster browser populations (this can occur for economic or cultural reasons) making effective control of those populations difficult.

Some areas of Aotearoa have particularly problematic plant pest issues (e.g., old man's beard or blackberry) which would again increase the level of management intervention needed for a successful transition (Fig. 10).

3.3.3 Stand level interventions

Interventions that assist the development of structural complexity in even aged monocultural plantations are particularly important and can commence following canopy closure. Canopy gap creation is a main means of incorporating stand and microclimate heterogeneity (Fig. 11). Gaps can be created by either felling to waste[69] or poisoning and leaving plantation trees dead standing, from which point they will gradually disintegrate[70] (Fig. 12).

Figure 11. An experimental canopy gap created by felling a radiata pine plantation at 18-years of age. Photo location: Port Underwood, Marlborough.

Figure 12. Poisoned exotic conifers giving way to regeneration of native forest species. Photo location: Nelson.

The gap width relative to forest canopy height is an important way to visualise and plan canopy gaps. Changes in this ratio influence the microclimate occurring within gaps[71]. Too much light transmitted into large gaps/clearings might promote the establishment and growth of light-demanding weed species. Therefore, gap size should be treated conservatively. When native trees form a dense cover beneath intact plantation cover, plantation removal can be more widespread as the exotic canopy can readily be replaced by the developing in-situ native canopy. This means there is little vulnerability to invasion of the understorey by light-demanding weeds through the transition.

Figure 13. Photo location: Port Underwood, Marlborough.

Figure 14. Dense stands of tree ferns (mainly *Dicksonia squarrosa*) casing heavy shade in this mature radiata pine plantation. Photo location: central North Island.

[69] Forbes et al., 2016a.

[70] Paul & Ledgard, 2009.

[71] Gap width to canopy height ratio (gap ratio), see Brokaw (1982) and Muscolo et al. (2014) for an overview.

Gaps created by felling in 18-year-old radiata pine accelerated the height growth of planted tawa (in small gaps) and tōtara (in large gaps). Expanded gap ratios[72] of small gaps were 0.4±0.03 and large gaps were 0.58±0.03[73]. A subsequent survey of natural regeneration 6 years after gap creation found the effect of gap creation and gap ratio to be highly significant on measures of native regeneration[74]. Anecdotally, within felled gaps it appeared a concentration of native regeneration occurred around downed pine logs. It is speculated that perhaps the logs were providing a favourable microclimate effect for regeneration[75] (Fig. 13). Downed trees also serve as refuges for regeneration, being less accessible by large browsing mammals such as deer[76].

Predominantly native regeneration was found beneath wilding pines poisoned (drill and fill treatment) and left dead standing in the Marlborough Sounds[77]. In theory, gaps comprising dead standing trees would provide a more complex forest microclimate and therefore a greater range of establishment sites. It is possible that the dappled light associated with dead standing trees (compared to gaps created by felling) would allow a larger gap ratio to be created while still preserving a favourable microclimate. Overhead wood retained as dead standing trees might also provide a temporary source of perches for seed dispersing birds, enhancing the seed rain.

Artificial canopy gaps are favourable locations in which to introduce old-growth tree species that have traits requiring a forest microclimate[78]. Other treatments such as seed broadcasting and soil disturbance to expose the soil seed bank thereby stimulating seedling establishment can also be trialled in the more favourable microclimate associated with canopy gaps.

Gap treatments will require monitoring and adaptive management to help promote the recruitment of native trees to the canopy.

In some instances, dense understorey growth can develop and compete with regenerating woody individuals[79] significantly slowing their growth and progression towards the forest canopy. One example of this is dense tree fern stands which have been found to develop and persist in central North Island radiata pine plantations (Fig. 14). Where plantations are being transitioned, interventions to reduce the level of competition experienced by tree seedlings should be considered.

3.3.4 Macroclimate

Given the importance of macroclimate in determining the distribution of plant species at regional scales, the ease of a transition will depend greatly on the climate of a given locality. Transitions will be most appropriate in areas of higher rainfall. At some point along rainfall gradients, management to achieve adequate regeneration would become so active that a transitional forestry approach is unlikely to make ecological nor economic sense.

3.3.5 Seed sources and dispersers

Forest regeneration is dependent on a ready source of propagules. Where suitable seed sources are too distant, or scarce, regeneration and succession are reduced. The retention and management of forest areas and animal disperser populations are therefore a fundamental requirement for transitional forest management. Old-growth remnants, secondary forests, riparian corridors, and other vegetation areas in the plantation landscape matrix offer opportunities to boost regeneration function at the landscape level and restorative management should be directed towards these source areas as part

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[72] Expanded gap ratios represent the ratio of the height of the canopy surrounding the gap to the diameter of the gap, plus the area extending to the bases of the canopy trees surrounding the gap (rather than diameter being projected down from the edge of the canopy).

[73] Forbes et al., 2016a.

[74] Marshall, 2020.

[75] Forbes et al., 2016a.

[76] Whyte & Lusk, 2019.

[77] Thomas & Ledgard, 2009.

[78] Forbes et al., 2020.

[79] Forbes et al., 2016b.

of the transitional forestry approach (Figs. 15 and 16). However, predator control may also be required to ensure there are sufficient seed dispersing birds.

Figure 15. Good levels of natural forest are essential for high levels of spontaneous regeneration. Photo location: Waingake, Tairāwhiti.

Figure 16. A matrix of native and exotic forests helps provide a good ecological context for transitioning plantations to native forest. Photo location: Waingake, Tairāwhiti.

Enrichment planting will be an essential tool to direct and speed up successional development in transitional plantations (just as it is an important intervention in many degraded secondary forest communities[80]). Planting old-growth species into favourable conditions (such as canopy gaps) provides a level of certainty (assuming ongoing management of pests is sufficient) that the species required to form an independent and stable forest canopy in the future are present (Fig. 17)[81].

3.3.6 Site factors

Anticipating how site factors will influence regeneration provides an important part of a successful transition. For instance, in principle, southern slope aspects are likely to regenerate more readily compared to northern aspects and the more nutrient-rich lower slope and terrace landforms may develop thicker vegetation cover creating heavy shading and requiring management to address these adverse levels of competition. Ridgelines and northern slopes may require more active inputs in the form of enrichment planting and canopy manipulations may need to be designed differently depending on aspect and exposure. These aspects require field trials to further our understanding and to better shape management approaches.

Figure 17. Lowland totara planted amongst *Eucalyptus*. Photo location: north Canterbury.

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[80] Forbes et al., 2020.

[81] Luken, 1990.

3.3.7 Tree stability

Instability of planted radiata pine may be an issue where root development has been impeded[82], where interior trees are exposed at a newly created forest edge, or where stands are subjected to extreme winds (Fig. 19), particularly when those winds coincide with excessive rainfall[83]. Other scenarios where tree instability is likely to be an issue are on shallow soils on steep slopes with a solid underlaying bedrock (e.g., in parts of Tairāwhiti). Tree stability should be considered when planning transitions in exotic plantations. Where native regeneration is adequate, examples have been noted where canopy openings created by radiata pine windthrow have stimulated regeneration in the canopy gap (Figs. 19 and 20).

Figure 18. Windthrow in a permanent radiata pine forest, where despite good climate and seed source contexts, excessive herbivory appears to be preventing gap-phase regeneration. Photo location: central North Island.

Figure 19. Canopy gap created by windthrow and colonised by native tree species. Photo location: Project Rameka, Golden Bay.

Figure 20. Ground-based view of the above canopy gap created by windthrow and colonised by native tree species. Photo location: Project Rameka, Golden Bay.

[82] This can be caused by factors such as unfavourable soil properties or shallow perched groundwater (Irvine, 1970; Mason, 1985).

[83] Irvine, 1970; Martin & Ogden, 2006.

3.3.8 Previous land use, number of rotations

The effect of differing land uses, or planting preparation treatments, have not been systematically studied.

A small number of species are known to be able to survive plantation clear-fell[84] (this phenomenon is termed advanced regeneration) particularly where the harvest operation does not severely disturb the ground (Fig. 21). Methods of low intensity harvest could assist with the levels of advanced regeneration carried through into the newly established plantation (although this will not work where sites are desiccated prior to establishment). Prior investigations undertaken indicate that the effect of number of prior forestry rotations probably has little effect on parameters of understorey regeneration[85]. However, no research has been undertaken into the ecology of mycorrhizal fungal communities occurring in exotic plantations specifically in the context of understorey regeneration by native forest flora and there may be an effect by rotation number on mycorrhizal communities which could in turn influence native plant establishment.

Figure 21. Retaining advanced regeneration is one way of increasing understorey dominance by native species early in the forest transition. This makomako (*Aristotelia serrata*) established in the previous plantation and has survived clear-fell harvest.

3.3.9 Monitoring, protection, and adaptive management

Long term active monitoring, funding and adaptive management are essential to ensure adequate levels of regeneration and succession are occurring. Initial observations of a range of landscape and site factors would be required to help inform an appropriate transitional management regime at a given location. Beyond these initial observations, monitoring would focus on management interventions so that transitional forest management can be refined and adapted. Topics would include things like pest levels and their control and gap treatments and their effectiveness in terms of forest growth and development.

Taking gaps as an example for monitoring, monitoring could cover the following elements:

- Gap size and shape and their ongoing effectiveness on regeneration.
- The presence/absence of light-demanding flora as an indicator of microclimate suitability for shade-tolerant flora,
- The traits of species present as an indicator of succession to more advanced forest compositions comprising old-growth species[86],
- The extent and levels of cover by native species indicating security of the treatment from light-demanding invaders (i.e., looking for signs of the exotic canopy being replaced by a native canopy),
- The occurrence of weed invasions,
- Signs and levels of herbivory indicating the effectiveness of current management and immediate browser management needs.

Protection of existing native vegetation embedded in the plantation matrix for their role as habitats and seed sources is essential. Protective mechanisms (covenants) should be placed on transitional forests to ensure they are not transferred to other forestry regimes, such as clear fell timber harvest, in the future.

Transitional forests need to be managed under the guidance of a comprehensive management plan. Such plans should include monitoring in a style that informs adaptive management (see above) and

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[84] E.g., *Dicksonia squarrosa* (Ogden et al., 1997), *Aristotelia serrata* (A. Forbes personal observation).

[85] Allen et al., 1995.

[86] Weiher et al., 1999.

will require ongoing funding as transitional plantations are likely to require management for many decades and potentially longer. A mechanism is therefore required to ensure that the management of transitional forests are supported financially on an ongoing basis from the outset of any transitional forestry project.

The establishment of infrastructure to support this management is also required from the outset when the costs of doing this (e.g., putting access tracks in) is cheaper. There also needs to be consideration given at the outset to the management or wilding spread from the transitional forest and the way the forest is to be managed in relation to the threats posed by fire, insect pests and diseases.

4 Modelling carbon stocks in transitional forests

4.1 Modelling methods

Modelling forest growth and development is a specialist area and ultimately the choice of model should be determined by a specialist and the data requirements confirmed accordingly.

4.1.1 Tree growth, biomass, and carbon

Parameters of tree growth can be modelled from empirical tree growth data using regression analysis[87]. Volume estimates can be converted to estimates of above and below ground carbon using the allometric equations which are available for Aotearoa's trees species[88]. With repeated measurements of the same trees of known age estimates of sequestration can be made.

4.1.2 Forest dynamic modelling

The LINKNZ[89] model simulates forest gap dynamics and stand development under Aotearoa's conditions[90] and has been applied previously to native regeneration in exotic plantations[91]. This model use species- and site-specific data to predict growth, mortality, and recruitment in a forest ecosystem. The model can be extended to provide estimates of whole tree biomass using allometric equations available for Aotearoa's tree species. A model such as LINKNZ would provide a means of quantifying the timeframes and biomass across an exotic to native transition in particular abiotic circumstances and with interventions applied.

4.2 Availability of existing data

Growth biomass and carbon sequestration for three native conifer species grown within a *Pinus ponderosa* stand in one location of Aotearoa are available and the stand was last surveyed in 2013[92]. We are not aware of other existing data demonstrating native forest

growth and biomass over time (i.e., repeat measurements in stands of known age) from exotic stands in Aotearoa. The National Vegetation Survey Databank[93] is likely to hold survey records for survey plots in exotic plantations. In the short term, modelling could be undertaken based on the most relevant data available and based on some management assumptions (e.g., our idea of a minimum number of native tree stems per ha supported by active management to ensure such minimum stockings are achieved).

4.3 Nature of new data required

Additional data are required regarding levels of regeneration occurring within plantations across climate gradients. This would require a national scale survey using standardised forest survey methods[94] in exotic plantations of both radiata pine and angiosperms (e.g., *Eucalyptus*) to quantify the composition and structure of understorey regeneration in plantations along climate gradient (see example of bioclimatic zones from Singers & Rogers, 2014; Fig. 22) and representing each of the ETS regions (Fig. 23). Topography, seed source proximity, and canopy architecture should be incorporated into the experimental design. Plots and trees within plots would be permanently marked to allow for

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[87] Examples include: Bergin & Kimberley, 2003; Richardson et al., 2009; Richardson et al., 2011; Kimberley et al., 2014.

[88] Beets et al., 2012.

[89] Hall & Hollinger, 2000.

[90] Carswell et al., 2012.

[91] Hall, 2001; Meurk & Hall, 2006.

[92] Forbes et al., 2015.

[93] https://nvs.landcareresearch.co.nz

[94] Department of Conservation, 2019.

long-term monitoring with one main goal being the development of regional carbon stock models for transitional forestry in Aotearoa.

Additional data are required showing the growth and survival of native tree species in exotic plantations along gradients of climate, topography, and canopy structure. These data would provide an empirical basis for modelling the carbon in transition from exotic to native forest. This would involve planting native seedlings to form a network of plantation trial sites where the growth and survival of individual planted trees is monitored over time.

4.4 Means of collecting additional data, potential sites and cost estimates

An amalgamation of bioclimatic zones and ETS regions yields 10 distinct climate regions for sampling (Table 1). In each region, three independent plantation stands[95] would be required. In each stand, north and south facing topography would be required. A transect from ridge to lower face would be established, one each on a north and a south face. Canopy manipulations coupled with enrichment planting would be implemented at ridge, mid-slope, and lower slope positions. At each slope position, a permanent 20 × 20 m vegetation plot would be centred on the canopy gap. Ecosourced canopy trees would be planted at 2 m spacing (2,500 stems ha^{-1}) across the survey plot[96] (Table 1). Natural regeneration, pine stand characteristics and canopy architecture/light transmittance would be measured at each plot location.

Site identification for this trial would be determined initially using GIS layers to identify candidate plantations in each region and then permission for establishing permanent plots on private land (in permanent plantations) would be required followed by ground truthing of study sites to confirm final locations. Animal browser pests and other pest management would be required at each stand to ensure the planted seedlings survive. Due to a lesser availability of angiosperm plantations, an additional and more subjective spatial arrangement would likely be required. Replicating a similar layout at perhaps half the scale as the radiata pine work would be a good target to work towards for angiosperm plantations.

Data gained from the permanent plots could be used in the analysis of regeneration occurring in plantations and to establish tree growth and carbon in the long term. The data would assist in determining management thresholds for transitional forestry.

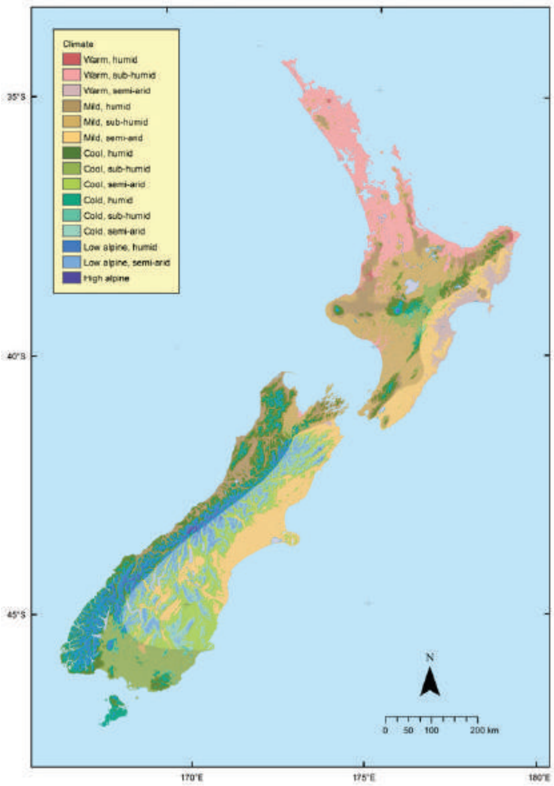

Figure 22. Bioclimatic zones from Singers & Rogers (2014).

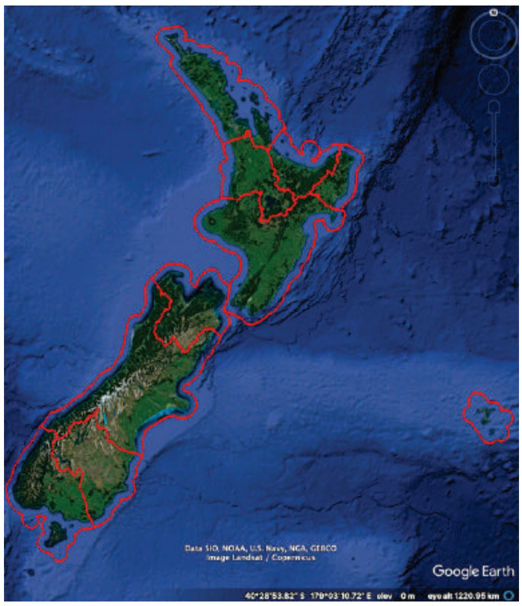

Figure 23. Aotearoa's Emissions Trading Scheme regions.

[95] Stand age and plantation stem stocking would need to be selected and held constant among sites.

[96] This equates to 100 native trees planted per plot, 300 per aspect per stand, 600 per stand, 1,800 per region, and 18,000 nationally.

Table 1. Allocation of native seedlings across climate, landform native forest proximity and canopy gradients to form a permanent plot network for assessing transitional forestry treatments across Aotearoa.

Main Bioclimatic Zones	ETS Region	Bioclimatic Zone - ETS Region Combination	Aspect	Landform	Ridge-to-valley transects per Stand[97]	Transects Per Region	Plots Per Region	Seedlings per plot	Seedlings per region
W-SH	Auckland								
W-SH & M-SH	Bay of Plenty	Northland, Auckland, Northern Waikato, Coastal Bay of Plenty			2	6	18	100	1800
W-SH & M-SH	Waikato/Taupo								
W-SH & M-SH	Waikato/Taupo	Southern Waikato, Taupo, Inland Bay of Plenty			2	6	18	100	1800
W-SA & M-SA	Gisborne	Gisborne			2	6	18	100	1800
W-SA & M-SA	Hawke's Bay	Hawke's Bay, Wairarapa	North and south	Ridge, mid face, and lower face	2	6	18	100	1800
W-SA & M-SA	Hawke's Bay	Manawatu-Whanganui, Taranaki			2	6	18	100	1800
M-SH & M-SA	Nelson/Marlborough	Nelson/Marlborough			2	6	18	100	1800
M-SH & M-SA & C-SA	Canterbury	East of Main Divide			2	6	18	100	1800
M-SH & M-SA & C-SA	Canterbury	West of Main Divide			2	6	18	100	1800
M-SA & C-SA	Otago	Otago			2	6	18	100	1800
C-SH & LA-H	Southland	Southland			2	6	18	100	1800

Notes. W-SH = Warm - sub humid, M SH = Mild - sub humid, M-SA = Mild - semi arid, M-SH = Mild - sub humid, C-SA, C-SH = Cool – sub humid, LA-H = Low Alpine – Humid.

[97] Two transects per stand, one north facing and one south facing.

Cost estimates to obtain and plant native seedlings, set up permanent plots and undertake the baseline measurement, undertake canopy treatments, and commence pest control over 1,000 ha (100 ha at each site) of plantation surrounding the trial sites. It is noted if transitional forests were held in private ownership where pest control is already underway those pest control costs would not apply.

Table 2. Cost estimate for seedling and planting, baseline plot establishment, canopy treatments and pest control for the radiata pine component transitional forestry permanent plot network[97].

Items	Estimate ($)
Seedling and planting	144,000
Baseline plot establishment	360,000
Canopy treatments	96,000
Pest control	20,000
	620,000

Assumptions underpinning this cost estimate:

- Seedling cost $8/plant to allow for larger grade (seedlings >60 cm tall at planting) and planting costs,
- $2,000 per plot for establishment, with allowance for accommodation and travel costs,
- Canopy gaps team of four working for 6 weeks at $100/hr,
- Pest control provision is $20/ha over 1,000 ha.

In addition, it is suggested to allow 50% ($310,000) of the above budget for replication of these treatments in permanent angiosperm plantations.

Also in addition, it is envisaged that modelling (i.e., seedling growth and survival, forest dynamics, the probability of seedling establishment) would be undertaken by a combination of private consultants and Crown Research Institute scientists at market rates. The cost estimates for modelling tasks are better developed in detail in due course.

The above cost estimates are indicative and would require further refinement through provision of provider estimates and confirmation of methods and the approach in due course. A multidisciplinary group of scientists would be required to deliver the surveys, experiments, and modelling that is recommended here.

[97] Ongoing costs associated with annual remeasurement of forestry trials are beyond the scope of this estimate.

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6 Appendix

6.1 Priorities and purposes of work needed to address knowledge gaps

Priority	Topic	Item #	Item	Carbon sequestration	Regeneration & succession	Forestry practice
First	Regeneration (composition & structure) along key biotic and abiotic gradients	1	National-scale plot survey assessing understorey composition in radiata pine and other exotic angiosperm stands along gradients in macroclimate, slope aspect, landform position, and canopy structure. Aims to determine levels of regeneration occurring along gradients and to inform a minimum stem density threshold for transitional forest management	Yes	Yes	
First	Growth and mortality of enrichment plantings	2	Coupled with Item 1, monitoring the growth and survival of native tree species planted into permanent radiata pine and angiosperm plantations. Aims to provide a systematic evidence base for native tree growth rates across key biotic and abiotic gradients in Aotearoa's plantation stands	Yes	Yes	

First	Dispersal along fragmentation gradients and whether thresholds in the amount of landscape-scale habitat operate for seed dispersal	3	Inclusion of surveyed landscape-scale native forest configuration as a covariate in Item 1. Aims to identify relationships between levels of native cover and attributes of regeneration in plantation understories, from which management thresholds could be based		Yes	
First	Native seed broadcasting and soil disturbance trials	4	Trials of seed broadcasting and soil disturbance in permanent exotic plantations to investigate less resource intensive methods of native tree establishment at scale. This could be coupled with canopy treatments required for Item 1. Aims to trial treatments other than planting nursery-raised seedlings to diversify exotic plantation understories		Yes	Yes
First	Predicting regeneration and levels of intervention using spatial models with ground-truthing	5	Modelling the probability of regeneration[99] coupled with estimated levels of intervention to effect a transition. Overlays of MPI ETS Regions and native seed sources, including validation through ground-truthing. Aims to provide mapped predictions across Aotearoa of land areas which have a reasonable probably of regeneration, and hence would identify land areas that are suited to transitional forestry		Yes	

First	Standard permanent transitional forest management plan, silvicultural approaches and management prescriptions for transitional forestry	6	Develop a standard permanent transitional management plan, approaches and silvicultural prescriptions for permanent forestry using transitional approaches. Approaches to be forest-ecosystem based, and designed to deliver particular objectives (e.g., biodiversity focus, soil erosion avoidance, carbon sequestration & storage). Include management thresholds to provide firm targets and to trigger adaptive forest management. Include monitoring methods. This work aims to standardise transitional forestry and align forestry methods with emerging/current best practice	Yes	Yes	Yes
Second	Modelling tree growth, survival and forest dynamics	7	Based on data gathered in Items 1 and 2, modelling: • Tree growth, survival and biomass, • Forest dynamic modelling of the transition at points along empirically measured gradients. This modelling aims to quantify forest development and biomass through a transition from exotic to native forest	Yes	Yes	Yes
Second	Investigation into optimal exotic nurse forests	8	Polycultures comprising species with strong nurse traits, and	Yes	Yes	Yes

			which offer structure and functionality conducive to native regeneration and successional development promoting the recruitment of native tree species to the forest canopy. Aims to develop a suite of transitional forestry models available for people to consider and select according to their site and forestry objectives			
Second	Mycorrhizal ecology	9	Ecology of mycorrhizal fungal communities occurring in exotic plantations and how these relate to native understorey regeneration. Aims to further our understanding of this branch of forest ecology with an emphasis on implications for management to support transitional forestry		Yes	