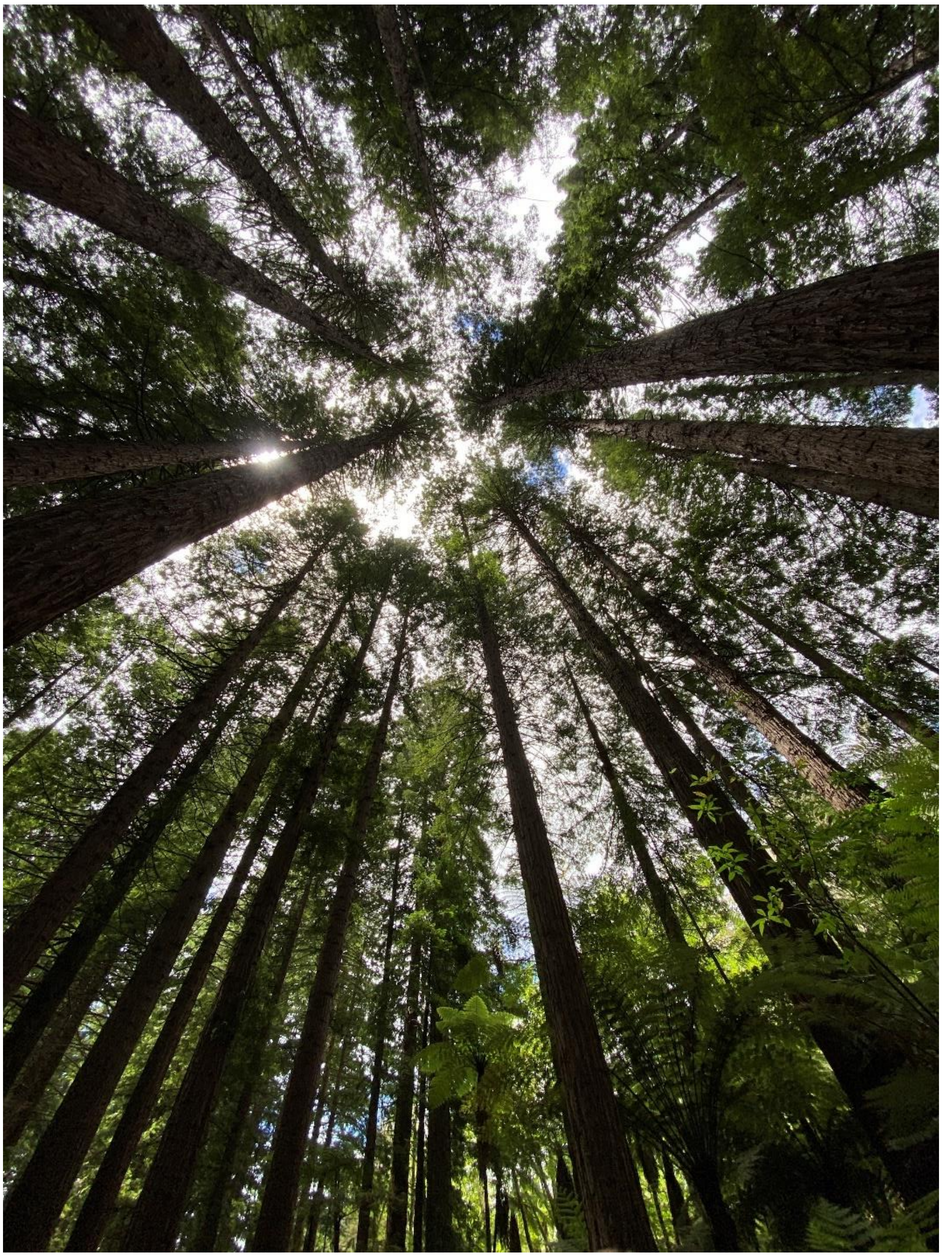
Publicly available

Final report: Stock Take of the Commercially Viable Alternatives to Pinus Radiata

Alan Jones, Ben Steer, Serajis Salekin, Dean Meason, Toby Stovold



Report information sheet

Report title Final report: Stock Take of the Commercially Viable Alternatives to Pinus Radiata

Authors Alan G. Jones, Toby Stovold
Scion

Client Minister for Primary Industries (MPI)

Client contract number QT-9852 - Contract: C0033618

PAD output number 71056734

Signed off by Andrea Stocchero

Date July 2023

Confidentiality requirement Confidential (for client use only)

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

Executive summary

The problem

Pinus radiata has emerged as the timber tree of choice within New Zealand, owing to a long history of breeding development and ongoing improvements in silvicultural practice, making this species highly commercially favourable. Owing to a large reliance of the forest industry on this single species, increasing risks arise from disease or pest outbreaks that may develop due to a changing climate and increased global interconnectivity. To address this risk, a stock take of potential alternative species to radiata pine within New Zealand is needed, which will identify potential candidates and highlight knowledge gaps.

This project

This literature search was conducted to review the available knowledge on alternative species to radiata pine, focussing on known species that have been grown within New Zealand. The potential suitability of candidate species was evaluated based on their expected growth rates (if known), together with information about their climatic range or range of site suitability. Further, information was assessed on their resilience to pests or disease, while inferring their potential climate resilience owing to information on, for example, drought tolerance. The potential economic suitability of candidate species was determined from information on timber value (where available in the literature), and their potential to be successful within a commercial plantation forestry production system.

We also completed an assessment of potential idealised growing locations for each of our shortlist commercial alternative species, based on site suitability information available from the literature.

Finally, we undertook a gap analysis assessment for each of these species, determining through a combination of literature review and expert consultation, priority areas of future development required to bring each to a market-ready condition in a commercial setting.

This work was used to produce a guide to the growing of commercially available alternative exotic forest species, which is available separately.

The guide outlines:

- commercially available exotic alternatives to radiata pine
- how suitable the species are for growers
- management conditions for each species
- potential for timber or biomass.

It is designed to support both experienced growers who are looking to diversify the exotic timber species they are managing, and new growers who need information on the commercial species available for establishing plantations and woodlots.

Key results

17 species or genera are highlighted in the literature as viable alternative species to radiata pine, with productivity characteristics that are currently relatively well-known within New Zealand. A further 28 specialist species or genera were also highlighted in the literature; however, these are less well-established nationally and consequently there is limited literature information on their growth requirements or productivity. Information on these 45 candidates was used to develop a shortlist of 12 higher-performing candidate species or genera.

This understanding was extended by evaluating the advantages and disadvantages of the shortlisted alternative species, including their potential for propagation and seedling stock availability. This review of information in the literature was also used to highlight where knowledge gaps exist for each shortlist species that might hinder their effective deployment in a commercial setting.

The shortlisted species or genera include: multiple *Eucalyptus* spp.; *Cupressus* spp.; *Sequoia sempervirens*; *Acacia* spp.; *Quercus* spp.; *Larix* spp.; *Cryptomeria* spp. and *Pinus* spp.

The spatial assessment of site suitability for shortlist species suggest that most would grow more favourably across the North Island than in the south. This was also confirmed in a detailed analysis of redwood productivity by Watt et al. (2021)[1] outputs from which were presented in this work, indicating more rapid growth rates and greater overall site favourability across the North Island, compared with the South Island. This broad overall pattern is reflected in similar spatial productivity analyses we presented for *Cupressus* spp. Exceptions to this national pattern of favourability appear with Douglas-fir, which our analysis showed was better adapted overall to conditions in the South Island. Of the eucalypts, *E. bosistoana*, E*. cladocalyx* appear to have the greatest potential growing range nationally, with suitability indicated in some lower altitude areas of the South Island, together with large areas of the North Island. *E. nitens* also indicates a wide range of potential site suitability across both islands nationally, with the most favourable growth rates visible in our analysis in parts of the South Island.

The gap analysis assessment showed that knowledge gaps exist across the entire value chain for each of the species or groups highlighted. Further, climate change is expected to be a challenge affecting all species, with only limited degrees of knowledge about such impacts for each. Consistently across most species or groups, were limitations relating to germplasm development, breeding and propagation, together with limited knowledge about wood processing, route-to-market and end-of-life processing.

Our work was used to produce a guide to the growing of commercially available alternative exotic forest species, which is available separately: https://www.canopy.govt.nz/forestry-resources/growing-exotic-forest-species/

Implications of results for current and future growers

The outcomes of this work highlight a range of species with known attributes within New Zealand, that have most potential as alternatives to radiata pine. These species should be investigated further through commercial trials and the development of domestic and export markets.

- Domestic markets for alternative species timber should be investigated and developed, particularly with high-value timbers that could potentially be developed into smaller-volume markets more rapidly using domestic processing
- A priority is to identify environmental gaps in PSP data for these species and fill these – as well as installing plots or measuring plots that include the most recent genetic material.
- This action will lead to development of robust productivity surfaces for volume and carbon for these species. Investment in species with high growth rates should be increasingly encouraged as high-volume contingency timber species for radiata pine
- Continued investment in breeding or mitigation actions should be delivered to overcome disease, weed or pest challenges with some strong alternative or contingency timber species, such as improving outcomes for red needle cast or canker disease through resistant varieties, or addressing weed problems during establishment of vulnerable species
- The gap analysis assessment can potentially inform and support the development of initiatives and research programmes responding for example to the Forestry and Wood Processing Industry Transformation Plan's action point *7.1 Enable a strategic approach to diversification*

Further work

This work has identified a range of existing knowledge-gaps relating to the silvicultural requirements, site suitability, growing risks and marketability of highlighted species. Further work should examine in detail these knowledge-gaps, together with providing mitigation actions to overcome them. Measures taken could include commercial trials and evaluations of timber processing methodologies at scale, together with interrogation of potential markets for these timbers. To address uncertainties affecting industry confidence with investment in alternative species, this work should be developed in partnership with industry stakeholders, to elucidate specific knowledge-gap areas hindering the progression of innovation. Some limitations could be rapidly addressed through simple interventions, such as silvicultural practices that reduce disease severity, damage from pests, or inhibition of seedlings through weeds. Other development areas may require complex and detailed evaluation of value chains and measures that will enable these to be established. Prioritisation should target the most cost-effective, or rapid-to-solve alternative species first, which are those with the greatest level of existing development. These more well-developed species or groups are cypress, eucalypts, redwood and Japanese cedar.

Final report: Stock Take of the Commercially Viable Alternatives to Pinus Radiata

Table of contents

Introduction

Why is there a need to diversify, and why should we have started decades ago?

Diversification into alternative commercial species will:

1. Allow the utilisation of niche sites with conditions currently unsuitable for growing *P. radiata*.
2. Enable the development of new timber markets and specialty timber uses. Diversification of timber products would potentially displace timber imports, generate wealth and complement the commodity products produced from radiata pine.
3. Provide a level of contingency to adverse environmental or market-driven events. Contingency species would be available to secure continuation of timber supply, if problems such as pests, disease or climatic change begin to seriously affect the existing *P. radiata* plantation stock.
4. provide a greater public benefit by increasing the overall species diversity of commercial forestry, which would improve both the biological and social value of our commercial forests [2]

Pinus radiata (D. Don) was first introduced to New Zealand in the mid-1800s. The species emerged as the preferred timber crop following the introduction of preservative treatment and large-scale processing and market development for treated sawn timber in the 1940s and 1950s [3]. An intensive genetic improvement programme was initiated in the 1950s, which resulted in improved form and growth rates that have secured the commercial dominance of the species, which currently comprises 89% of the country's plantation forests [4]. The tolerance of radiata pine to a wide variety of growing conditions throughout New Zealand, combined with continuous improvements in genetic performance over the last seven decades, combined with the advent of a building code that supports its wide domestic utilisation have cemented its dominance as the plantation timber species of choice in New Zealand.

The economic value of *P. radiata* timber to NZ is currently several billion NZ$ annually, comprising >NZ$6 billion in export revenue from 1.5 M ha of planted forest, with approximately half of this revenue figure again returned by domestic consumption [4]. The economic performance of this species reflects both its productivity in commercial plantations and the overall market demand for this timber.

Threats to *P. radiata*, however, exist from a range of fungal pathogens that currently attack the tree, together with an increasing risk pests and diseases being introduced to New Zealand in future. This remains an increasing factor with continued expansion of global travel and trade. Risks to the industry are compounded by investment overwhelmingly focussed only on this single species, together with selective breeding and clonal propagation of the species which considerably reduces genetic diversity in the population for commercial deployment. Further, the high stocking density and extensive scale of commercial *P. radiata* plantations introduces risk that disease and pest threats could emerge and spread rapidly. Any future events causing widespread damage or mortality in commercial *P. radiata* plantations would have significant economic consequences on the wood processing industry and the commercial forest estate. Such risks are compounded by threats from climate change and related anomalous weather conditions, such as extreme heat, drought, snowfall or wind [5]. Such events are expected to increase over the coming century. Although such conditions may be acutely damaging in themselves, they also potentially increase the susceptibility, rate of spread and level of damage associated with disease or pest outbreaks.

Improving the species diversity of commercial planting within New Zealand is a solution to this problem with several advantages. Poole (1969)[3] acknowledged the limitations of radiata pine as both a tree and a timber, suggesting the need to "examine critically the range of exotic species we can grow with a view to selecting those which might satisfy our needs". Lindsay Poole was instrumental in the NZFS in setting up a forest diversification process throughout the late 1960s to 1980s, including a large-scale forest planting programme [6]. Improving the species diversity of commercial forest plantations in New Zealand offers several advantages. As previously identified by Burdon and Miller (1995)[7], such diversification would, firstly, allow the utilisation of niche sites with conditions currently unsuitable for growing *P. radiata*; secondly this diversification would enable the development of new timber markets and specialty timber uses and thirdly; stocking with a range of different timber species would provide a level of contingency to adverse environmental or market-driven events. Contingency species would be available to secure continuation of timber supply, if problems such as pests, disease or climatic change begin to seriously affect the existing *P. radiata* plantation stock. Further, as identified by Maclaren (2005)[2], firstly, allow the utilisation of niche sites with conditions currently unsuitable for growing *P. radiata*; secondly this diversification would enable the development of new timber markets and specialty timber uses and thirdly; stocking with a range of different timber species would provide a level of contingency to adverse environmental or market-driven events. Contingency species would be available to secure continuation of timber supply, if problems such as pests, disease or climatic change begin to seriously affect the existing *P. radiata* plantation stock.

The need for this study

Planting of alternative exotic commercial tree species to date has developed largely at small scales and sporadically, relative to the large existing planted *P. radiata* estate. The only other commercial species planted significantly to date is Douglas fir (*Pseudotsuga menziesii*), which currently accounts for 6% of New Zealand's planted forest estate [8]. Although a range of other alternative species could potentially be deployed at scale without technical barriers, investment barriers discourage scales sufficient for successful commercialisation. The overwhelmingly favourable perception of *P. radiata* as the only viable source of commercial revenue is maintained by the plantation forestry industry in the absence of extensive knowledge or data on suitable alternative exotic species. Furthermore, mill and harvest systems are based around radiata pine, marketing and sale arrangements have been based on several generations of radiata pine, and management training has been based on radiata pine. This creates a very efficient radiata pine system, and a reluctance to develop new systems and operating technologies (at scale).

To begin addressing this, the existing body of literature knowledge in this area was synthesised to compile a stocktake of potential exotic alternative species to *P. radiata*. This stocktake is required to consolidate existing knowledge and to set the stage for integrating this with research results as they emerge.

Past review work and challenges identified for alternative species

A major review on this topic was compiled by Maclaren (2005) [2]. Maclaren identified six non-native genera as potential alternative species to *P. radiata*: Douglas-fir; *Eucalyptus*; *Cupressus* (cypresses); *Acacia* (blackwood); *Sequoia* (redwood); *Populus* (poplar). In this work, the cypresses, eucalypts and redwoods were identified as priority alternative species to *P. radiata*, owing to their volume productivity, timber value and potential site suitability. Secondary were blackwood and poplar, as these were only considered suitable replacement species on a restricted set of microsites. These priorities for alternative species also broadly follow the outcomes of a past review by Burdon and Miller (1995)[7], which additionally identified several *Pinus* species in their analysis.

A detailed and more contemporary review of alternative species was compiled by Dungey et al. (2020)[9], with a focus on mitigation of biosecurity risks for *P. radiata*. In this work, two main groups of species were highlighted, identifying suitable: (1) Pinus hybrids and (2) sets of alternative species. Various pest and disease risk challenges arise in most species, including Swiss needle cast and red needle cast in Douglas-fir; canker in cypresses; Dothistroma needle blight in *Pinus* species; myrtle rust and tortoise beetle in eucalypts; and rusts and sawflies on poplar. Notably, no known foliar pests or diseases are considered to affect redwood species seriously, however wood boring pests do cause some problems in the timber. The industry potential for deploying *Pinus* hybrids may be hampered by a lack of existing research in this area, combined with the limited fertility of some inter-specific crosses [9].

A literature review by Satchell (2018) [10] utilised an alternative species selection tool for steep slopes, based on species quality characteristics that were weighted for importance. This work described advantages and disadvantages of each species for afforestation and erosion mitigation of steeper erodible slopes, along with their wood properties. The NZ Farm Forestry Association extended this work into a species selection tool that allows the user to rank species according to potential for commercial return, altitude, rainfall, soil depth, soil drainage, temperature and wind [11].

A systematic evaluation of alternative species, including native timbers, by Bulman (2021)[12], incorporated a hierarchical decision analysis of expert viewpoints, to review the favourability of 115 potential species. The analysis refined the initial list of potential alternatives to 58 top-performing species and the top ten of this list were highlighted. These include: *Corymbia maculata*; seven *Eucalyptus* spp., *Quercus* spp. and *Sequoia sempervirens*. The selection analysis considered factors such as climate change risk; pest risk; timber utility; political risks; rotation length; breeding readiness; market demand; and overall competitive advantage; in relation to radiata pine. Interestingly this analysis ranked Douglas-fir in the lower half of this list, suggesting non-suitability as a replacement for radiata pine. This outcome arose from lower weighting in scores given in this study for the timber stiffness and appearance of the species, together with a slightly slower growth rate. Overall, members of the *Pinaceae* (Douglas-fir, fir, larch, pines, spruce) were ranked in the lower half of all species reviewed, which was attributed to their slower growth rates and poor wood properties (specifically treatability with preservatives) compared to radiata pine. The predominance of eucalypts in the highest ranking species from this analysis fits with wider consensus views (e.g. Nicholas 2009 [13]) on the general utility of some of these species.

However, the analysis by Bulman (2021) highlighted several high-ranking species with only a limited level of recognition to date in New Zealand, while giving low rankings to species that have been more widely recognised. Notably, *E. agglomerata*; *E. argophloia*; *E. bosistoana*; *E. laevopinea*; and *E. macrorhyncha* were ranked highly despite not previously being widely discussed as commercial timber trees in a New Zealand context. A considerable body of research on *Eucalyptus*, including dedicated forestry trials, have been conducted over the past two decades by the New Zealand Drylands Forestry Initiative. A comprehensive overview of some of the outcomes of this research into growth performance, site suitability and the processing requirements of over 20 *Eucalyptus* species with commercial potential was produced by Poole et al. (2013) [14]. In this work, five species were particularly highlighted with promising attributes for commercial growing in the North Island (*E. regnans*, *E. obliqua*, *E. meulleriana*, *E. globoidea* and *E. fastigata*).

In earlier research, a review by Burdon and Miller (1995) [15] highlighted priorities for research on alternative species, also illustrating some categorisations for species selection, which were formed on the basis of alternative species fulfilling requirements for: special purpose timber; extreme sites or growing conditions or to provide a contingency for any potential future problems with radiata pine. This work indicated priority contingency species such as Douglas-fir; *E. fastigata*; *E. nitens*; *Pinus muricata*; *P. patula*; and *P. taeda*, with *Acacia melanoxylon* and *Juglans nigra* being high-value special purpose timber species. An assessment of alternative species for bioenergy was compiled by Nicholas (1998) [8], highlighting *E. nitens*; *E. maidenii*; *E. ovata*; *E. globulus* and *Acacia mearnsii* as potentially suitable candidates on the basis of their growth rates and wood density. A related alternative species review by Hay et al. (2005) [16], also indicated favourable growth criteria for several Eucalyptus species; together with *Acacia* spp., Cupressus spp., Douglas-fir and *Sequoia* spp.. A review of alternative high-country species was compiled by Dungey et al. (2013). In this work *P. muricata*, *Abies* spp., *Picea sitchensis*, *E. paucifloria*, *E. delegatensis* and Douglas-fir were highlighted as potential candidates.

Mapping of the site suitability requirements for some potential alternative species was conducted by Meason et al. (2016) [17]. This analysis determined that the main site suitability of *Eucalyptus fastigata* and *E. regnans* predominantly lies in the North Island. Similarly, redwood and *Cupressus lusitanica* are also more suited to the North Island than the South Island and both species prefer warm air temperatures and at least moderate rainfall. *Cupressus macrocarpa* also grows most rapidly in the North Island, but care should be taken when planting this species in warm wet areas where cypress canker is problematic as it susceptible to this disease. *Cupressus macrocarpa* exhibits faster growth than *C. lusitanica* in the South Island as *C. macrocarpa* is more hardy and better able to tolerate cold air temperatures and both dry and waterlogged conditions than *C. lusitanica* [18]. Spatial surfaces have been more recently developed for redwood height (Site Index) and volume (300 Index) productivity and carbon sequestration [19, 20]. Comparisons of the spatial surfaces for volume and carbon sequestration, show that in many locations in the North Island redwood has higher productivity than radiata pine at age 40. Increases in carbon with greater stand density and age were markedly higher for redwood than radiata pine, and consequently redwood is particularly well suited for clearwood and carbon regimes with longer rotation lengths.

Significant market barriers and development challenges exist for alternative species to radiata pine in the New Zealand timber market, not least because established production chains are optimised for radiata pine. Higher-value markets for appearance timbers are mostly inaccessible for alternative or contingency species, with domestic building codes being defined around radiata pine products exclusively [e.g., NZS3604, NZS3603, NZS3640, NZS3602, NZBC B2AS1].

Objectives and scope of this work

This work addresses the need for a stock take of the current status of potential alternative commercial timber species to radiata pine in New Zealand. The focus of this report is exclusively on alternative exotic species, recognising the need for follow-on work that will target native timbers specifically. This work has the following objectives:

1. Develop a short-list of potential alternative species, based on a literature review of potentially viable alternative species
   i. Summarise the advantages and disadvantages of the short-listed species
2. Produce an overview and maps of potential idealised growing ranges for each of the species, based on available information in the literature
3. Develop an information booklet on the ready to plant shortlist species by wood supply region, and their attributes
4. Produce a project report describing methods and synthesising findings of literature review and analyses
   i. Summarise methods and results from Objective 1 and 2, including in appendices where relevant, regional or species-specific data
   ii. Where possible, include predictive modelling of species response to climate change at local-to-regional scales
   iii. Appraise the potential for alternative species to enable or support important circular bioeconomy elements, such as short-rotation biomass for biofuels, new value chains and new socio-economic models, including the valuing and benefits of ecosystem services
5. Identify any knowledge gaps on the short-listed species through literature review, expert consultation and analysis

The content of this report comprises **Objective 4**, which also includes presentation of the **knowledge gaps analysis** (**Objective 5**).

The **information booklet** (**Objective 3**) is available online and has been published at: https://www.canopy.govt.nz/assets/content-blocks/downloads/A-New-Zealand-guide-to-growing-alternative-exotic-forest-species.pdf

It was defined as outside the scope of this work to generate bespoke modelling analyses of alternative species performance, or to conduct novel assessments of exotic species that have not yet been trialled in New Zealand or lack growth information within the New Zealand context. It is also not the primary focus of this work to critically evaluate in detail the performance of all species listed in a carbon forestry context. This attribute is nevertheless closely related to growth performance, and these data have been provided where available from the literature. The primary focus of this work is to identify species with known performance qualities that could seriously be considered as alternative commercial timber stock, when planted across a range of districts and catchments. It is also outside the scope of this work to address native timber species, as this aspect is planned for a follow-on piece of work.

Methods and Results from Objective 1 and 2

1. Stocktake of the commercially viable alternatives to Pinus radiata

We initially reviewed relevant literature in this area, focussing on literature searches for sources examining alternatives for radiata pine. The general search topic used was "Alternative species to Pinus Radiata", with the following keywords:

Alternative species
Forest species diversification
Cupressus
Sequoia
Populus
Salix
Pinus
Eucalyptus
Douglas fir

The search terms were used in Scopus, PURE achievements and Google Scholar online databases, which returned a total of 37 records. In addition, the websites of relevant New Zealand authorities for silviculture, growth performance and marketability information were searched on a range of alternative timber species, including: Farm Forestry New Zealand, Forest Growers Research, New Zealand Drylands Forest Initiative, Forest Research Institute and record data from the Permanent Sample Plots (PSP) database [20], which provides information on the growth performance of a range of species at a national network of measured trial sites. Further, the wider expertise available from our professional networks was consulted to elucidate further information sources relevant to this research.

Information sources were used to determine a range of potential suitability criteria for a range of potential alternative commercial timber species, including (where available) productivity or yield data; site suitability criteria, timber uses, marketability and economic returns and any known challenges associated with each species. 17 species or genera were highlighted in the literature as alternative species to radiata pine, with productivity characteristics that are currently relatively well-known within New Zealand. A further 27 specialist species or genera were also highlighted in the literature, however, these are less well-established nationally and have limited knowledge on their growth requirements or productivity. The information on these 44 candidates was used to develop a shortlist of 12 higher-performing candidate species.

This understanding was extended by evaluating the advantages and disadvantages of the shortlisted alternative species, including their potential for propagation and seedling stock availability, where known. This review of information in the literature was also used to highlight knowledge gaps that exist for each shortlisted species, including areas that might hinder their effective deployment in a commercial setting, such as pest or disease risk, or a lack of a presently defined market.

Note: The information in our initial Objective 1 stocktake was subsequently reviewed by experts in this field with considerable direct experience with many of shortlist alternative species we highlighted. This expert review process was used to directly inform development of our **Information Booklet** "A New Zealand Guide to Growing Alternative Exotic Forest Species" (https://www.canopy.govt.nz/assets/content-blocks/downloads/A-New-Zealand-guide-to-growing-alternative-exotic-forest-species.pdf).
The booklet is informed by both the analysis presented in this literature review and comprehensive input from this expert panel. The guide to growing alternative exotic forest species should be considered a complete assessment of this area. The stocktake presented here is an initial scoping process and does not represent the complete assessment of all information for candidate species.

2. Maps of site suitability for potential alternative species

These maps were produced using either (i) productivity modelling derived from available growth information taken from the national permanent sample plots (PSPs) [21] (three species or genera), or (ii) simplified spatial analysis derived from basic available information from the literature, which uses a limited set of site suitability criteria for a number of candidate species (ten species or genera).

In the case of (i): Analyses based on the PSP data employed a machine learning algorithm to determine a combination of both site suitability and an overall national measure of timber productivity via “diameter at breast height” (DBH). This analysis generates a productivity surface for three species or genera (*Cupressus* spp., *Eucalyptus nitens*, *Sequoia sempervirens*) [22]. In this instance, the spatial modelling analyses used the full complement of environmental data available from the PSPs, which includes detailed climatic information. Areas with the greatest productivity also have the highest potential site suitability. For further information on the data used to produce these maps, please see tables in the Appendix.

In the case of (ii): Site suitability criteria used in the spatial analysis included data on the altitudinal range; minimum, maximum or average temperature, soil characteristics; annual rainfall maximum and annual rainfall minimum for each species. These data were obtained from literature[1] sources describing the ideal growing range for each of these species and, hence, the spatial surfaces derived may be more constrained than previous similar site suitability assessments. A full set of environmental data were not complete for four species or genera (*Acacia* spp., *Eucalyptus bosistoana, E. cladoclayx* and *E. quadrangulata*, see Appendix), with the spatial analyses for these species being completed using only the remaining available information. All these analyses of site suitability criteria were completed in ARC-GIS, using extensive spatial environmental information from the LRIS Portal v1.0 [23].

Note: We caution that the limited availability of robust data on site suitability from the literature for some of the shortlist species means the interpretation presented in these maps may be over-simplified. For example, a full set of environmental data were not available for four species or genera (*Acacia* spp*., Eucalyptus bosistoana, E. cladoclayx* and *E. quadrangulata*), with spatial analyses for these species being completed using only a limited set available information. Hence, some site suitability projections presented here are constrained by the limited availability of data and may not present a complete picture of their distribution. Site suitability assessment for some of these species maps at a national scale should be subject to further validation.

[1] For full details of the literature sources used, see the companion report Jones (2022) *Stock Take of the Commercially Viable Alternatives to Pinus radiata*

Results from Objective 1 and 2

1. Stocktake of the commercially viable alternatives to *Pinus radiata*

The available information from the literature highlighted several species or genera with established potential or known attributes that support their use as ready-to-plant alternative commercial species to radiata pine. Although timber productivity is an important criterion, other characteristics have important influences. Notably, the value, potential usability, and marketability of the timber of each species; together with their adaptability across a range of growing conditions; and their potential climate resilience, or resistance to pests or diseases. Finally, the readiness of some species to be planted at a commercial scale was also a selecting factor. For example, species with lower timber productivity were included if possessing higher value timber, with a low disease or pest risk, or if they had adaptability to a range of site conditions, combined with potential climate resilience, or readiness for market. Highlighted below in Table 1 is a shortlist of 12 species or genera considered to have the greatest potential in such areas. We also summarise their advantages and disadvantages.

Note: The below information is constrained by the limited availability of published literature available on exotic alternative species in New Zealand. For a comprehensive assessment, please see our published Information Booklet "A New Zealand Guide to Growing Alternative Exotic Forest Species" (https://www.canopy.govt.nz/assets/content-blocks/downloads/A-New-Zealand-guide-to-growing-alternative-exotic-forest-species.pdf), which is informed by both the analysis presented in this literature review, combined with comprehensive input from an expert panel. The guide should be considered a complete assessment of this area.

Table 1: Potential shortlist species – advantages and disadvantages

Species	Advantages	Disadvantages	Notes	Total number of permanent sample plots (PSPs) (current and inactive)
Eucalyptus fastigata	Fast growth rate, suitable as construction timber and as a source of bioenergy. Silviculture is relatively well-understood in NZ. Low pest or disease risk.	Not extensively commercially trialled in NZ to date.	Further work is needed to evaluate the performance and suitability of this species in a commercial timber plantation context.	82
E. regnans	Fast growth rate, suitable in high-value non-structural applications or as construction timber when treated, and as a source of bioenergy. Silviculture is relatively well-understood in NZ.	Prone to foliar disease. Not likely to be climate resilient.	Further work is needed to evaluate the performance and suitability of this species in a commercial timber plantation context.	101
E. nitens	Fast growth rate, suitable as construction timber and as a source of bioenergy and pulpwood. Silviculture is relatively well-understood in NZ.	Pest-prone, requires cooler locations. Low-value timber applications only.	This species is already used as a pulp-wood source in NZ.	122
Eucalyptus spp.	Large genus of fast-growing species adapted to a range of present-day or possible future climates within NZ, particularly with respect to drought. Several species have already had limited domestic trials. The timber of some species is durable and/or others can be used in high-value applications.	Some species are noted to be disease and pest prone, requiring careful siting and silvicultural management to overcome. There is limited knowledge on the suitability of many species that could have potential in NZ.	Further work is needed to evaluate the performance and suitability of this group in a commercial timber plantation context. Most prominent within this group are: ***E. saligna*****;** ***E. maidenii*****;** ***E. botryoides*****; and** ***E. globoidea***	211 other *Eucalyptus* spp. plots in the PSP network, in addition, a large body of trials established by the New Zealand Drylands Forest Initiative.

Sequoia sempervirens	Fast growth rate, timber is suited for appearance grade applications. Well-understood in NZ. Public acceptance of the species may be higher than other species. Low disease or pest risk. Potentially high rates of economic return.	Requires careful siting and appropriate silvicultural management during the establishment phase to exclude weeds and provide a nurse canopy. Not thought to be drought tolerant	The longevity of this species makes an excellent choice for permanent forests that can continuously supply carbon and timber.	76
Cupressus lusitanica	Fast growing, durable, high value timber. Low pest or disease risk, which is adaptable to warmer climates, including drought.			144
C. macrocarpa	Fast growing, durable, high value timber. Well-understood within NZ, with an existing timber market.	Prone to canker at warmer locations.	There is already an industry processing this timber	108
Pseudotsuga menziesii	Growth and silviculture is well-understood within NZ, with an existing timber market. Ability to grow in colder locations, outside the range of radiata pine.	Prone to disease and wilding pine risk. Low indications of climate resilience. Low-value uses for timber only. Highly variable growth rate.	Does not grow well in locations currently favourable for radiata pine, therefore, it may not be a suitable contingency.	217
Acacia spp.	High value timber	Slower growth rates. Potential wilding risk. Limited site suitability.	Further work is needed to evaluate the suitability and benefits available with this this group.	109
Quercus spp.	High value timber. Potentially wide climatic range with suitable species from this genus.	Slower growth rates. Some species may be susceptible to drought. Not well-understood in an NZ context.	Further work is needed to evaluate the suitability and benefits available with this group.	7
Larix spp.	Good growth rate. Domestic market already established for timber.	Climatic range may limit this species to cooler locations only. Non-durable timber with limited uses.	Further work is needed to evaluate the suitability and benefits available with this group.	55
Pinus spp. or hybrids	Potential for a range of *Pinus* species or their hybrids largely untested to date in NZ to provide suitable alternatives to radiata pine. These hybrid alternatives may deliver similar growth rates and marketability to radiata pine, while increasing climate adaptability and reducing disease risk.	Largely untested within NZ. Alternatives may provide timber for low-value applications only, or have drawbacks including low timber strength, increased wilding risk, or increased disease risk.	Most notably from the species reviewed, *P. ponderosa*, may have the greatest climate resilience potential. Further work is needed to evaluate the suitability and benefits available with this group.	87

This initial literature review stocktake identified a range of 44 candidate species or genera, previously examined by past research in New Zealand. Of these species, those with greatest potential have combinations of high growth rates, wide-ranging climatic or site-suitability potential, together with attributes that confer low pest or disease risk and potential resilience to climate change. Particular investment in species with high growth rates should be encouraged, as these could fulfill as high-volume contingency timber species for radiata pine.

In contrast, several selected species with low anticipated rates of productivity, or reduced levels of climatic adaptability, however, possess timber with a potentially high market value. This makes them potentially appropriate for inclusion also as potential radiata pine alternatives. Development of these species could take place under a lower volume, high-value economic model of timber production. This could be realised through investment in a speciality timber market for high-value timbers, involving domestic processing of this material. Domestic markets for high-value alternative species timber should be investigated and developed, with potential for lower-volume, high-value timber markets to be developed rapidly using domestic processing.

The 12 species or genera that highlighted in this shortlist of candidate species broadly agree with similar lists developed in recent or more historic review work in this area, most notably Bulman et al. (2021) [12], Dungey et al. (2020) [9] and Maclaren (2005) [2].

Note: This initial literature assessment was further developed into a published guide for alternative species in New Zealand: "A New Zealand Guide to Growing Alternative Exotic Forest Species" (https://www.canopy.govt.nz/assets/content-blocks/downloads/A-New-Zealand-guide-to-growing-alternative-exotic-forest-species.pdf), which was informed by the literature analysis presented here, together with comprehensive input from an expert review panel. The guide should be considered a complete assessment of this area.

2. Maps of site suitability for potential alternative species

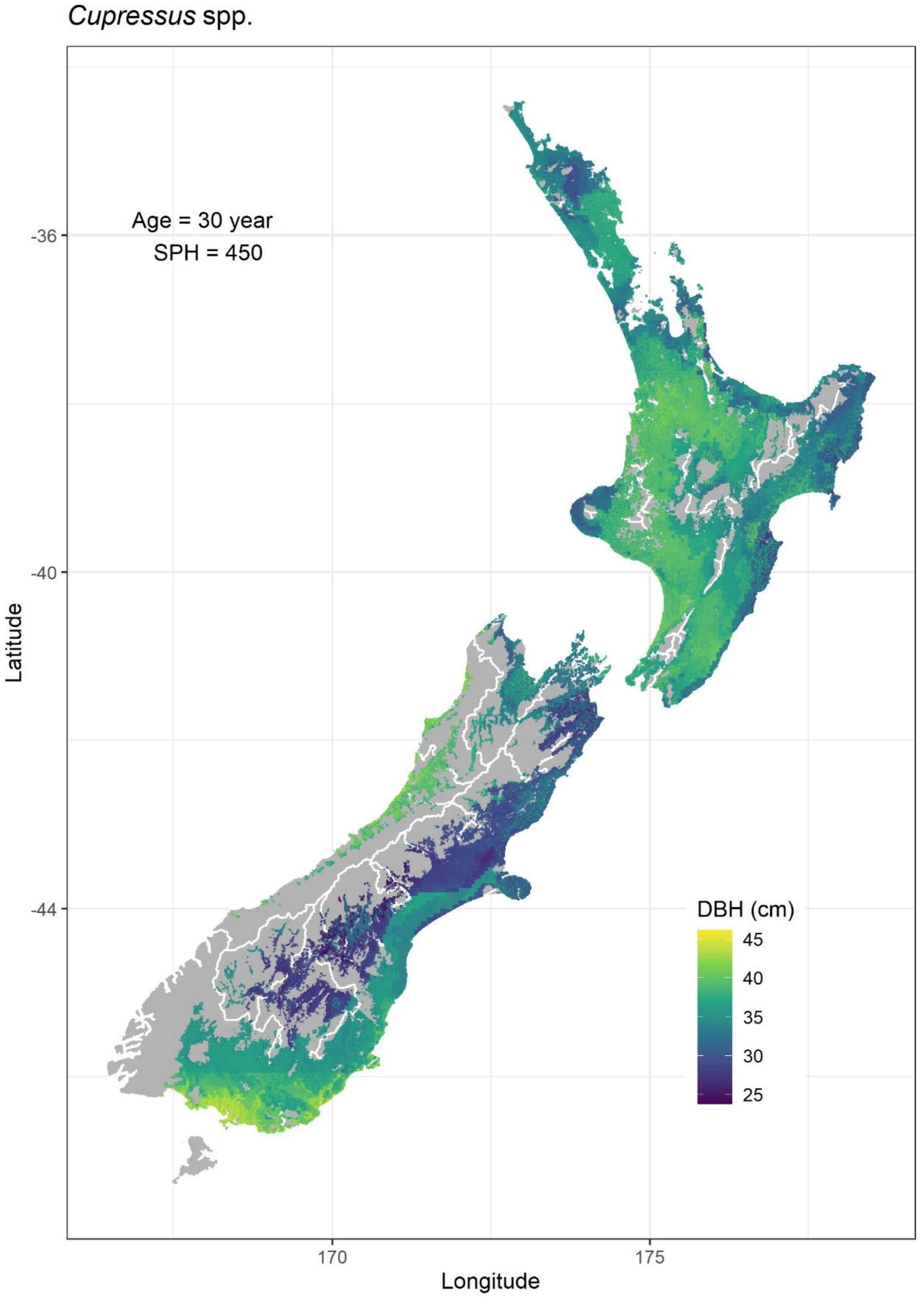
The results of this analysis utilised available information from the literature on site suitability, environmental data and climatic rages, to derive idealised optimal growing locations for each of the shortlist species. The map outputs were produced for the companion report this project Jones et al. (2022) 'Maps of site suitability for potential alternative species', but are also presented here. The analysis given in this work is the first time, to our knowledge, that estimated of optimal growing locations for a diverse set of multiple alternative commercial species has been undertaken in New Zealand and the data suggest some site suitability trends that can be used to inform future development.

Note: We caution that the limited availability of robust data on site suitability from the literature for each of the shortlist species means the interpretation presented in these maps may be over-simplified. For example, a full set of environmental data were not complete for four species or genera (*Acacia* spp*., Eucalyptus bosistoana, E. cladoclayx* and *E. quadrangulata*), with spatial analyses for these species being completed using only a limited set available information. Hence, some site suitability projections presented here are constrained by the limited availability of data. Site suitability assessment for some of these species maps at a national scale should be subject to further validation. Information for *Cupressus* spp., *E. nitens* and *Sequoia sempervirens*, including a detailed analysis of redwood productivity by Watt et al. (2021)[1], utilise growth modelling, which was achieved using permanent sample plot (PSP) measurement data. Figures showing these detailed productivity assessments should be considered relatively robust indicators of site suitability, in contrast to the simplified maps of 'site suitability', which are only derived from basic climatic and soil criteria available in the literature.

Broadly, most of these shortlist species grow more favourably across the North Island than in the South Island. This was also confirmed in a detailed analysis of redwood productivity by Watt et al. (2021)[1] outputs from which were presented in this work, which indicated more rapid growth rates and greater overall site favourability across the North Island, compared with the South Island. This broad overall pattern is reflected in similar spatial productivity analyses we presented for *Cupressus* spp. Exceptions to this national pattern of favourability appear with Douglas-fir, which our analysis showed was better adapted overall to conditions in the South Island and confirms available information in the literature indicating a preference for this species in cooler climates. Of the eucalypts, *E. bosistoana*, E*. cladocalyx* appear to have the greatest potential growing range nationally, with suitability indicated in some lower altitude areas of the South Island, together with large areas of the North Island. *E. nitens* also indicates a wide range of potential site suitability across both islands nationally, with the most favourable growth rates visible in our analysis in parts of the South Island, which will have a cooler climate than the North Island. The complete set of these species maps is presented in the following pages.

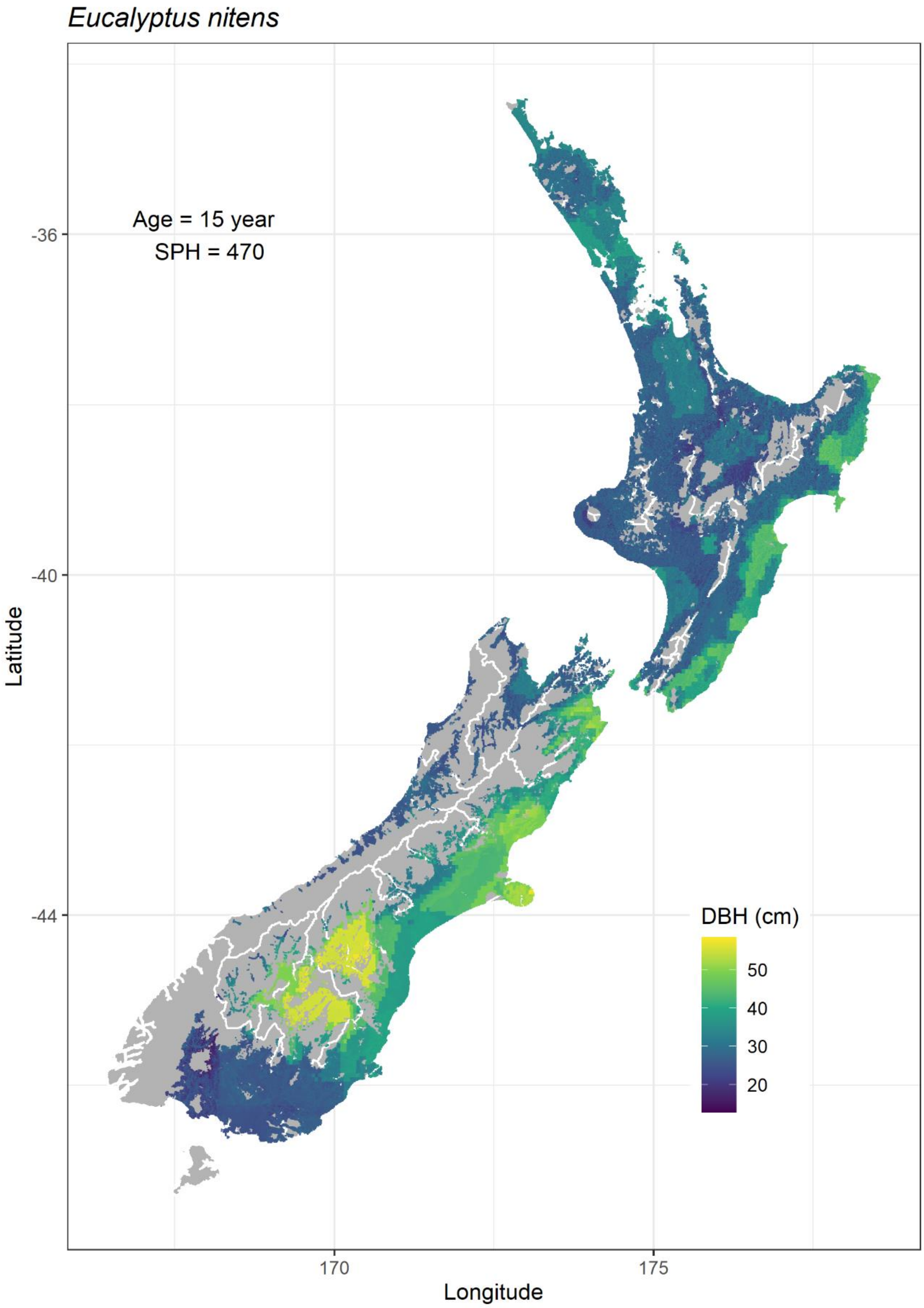
Maps of site suitability for potential alternative species

Productivity (DBH) for Cupressus spp. at 30-year rotation



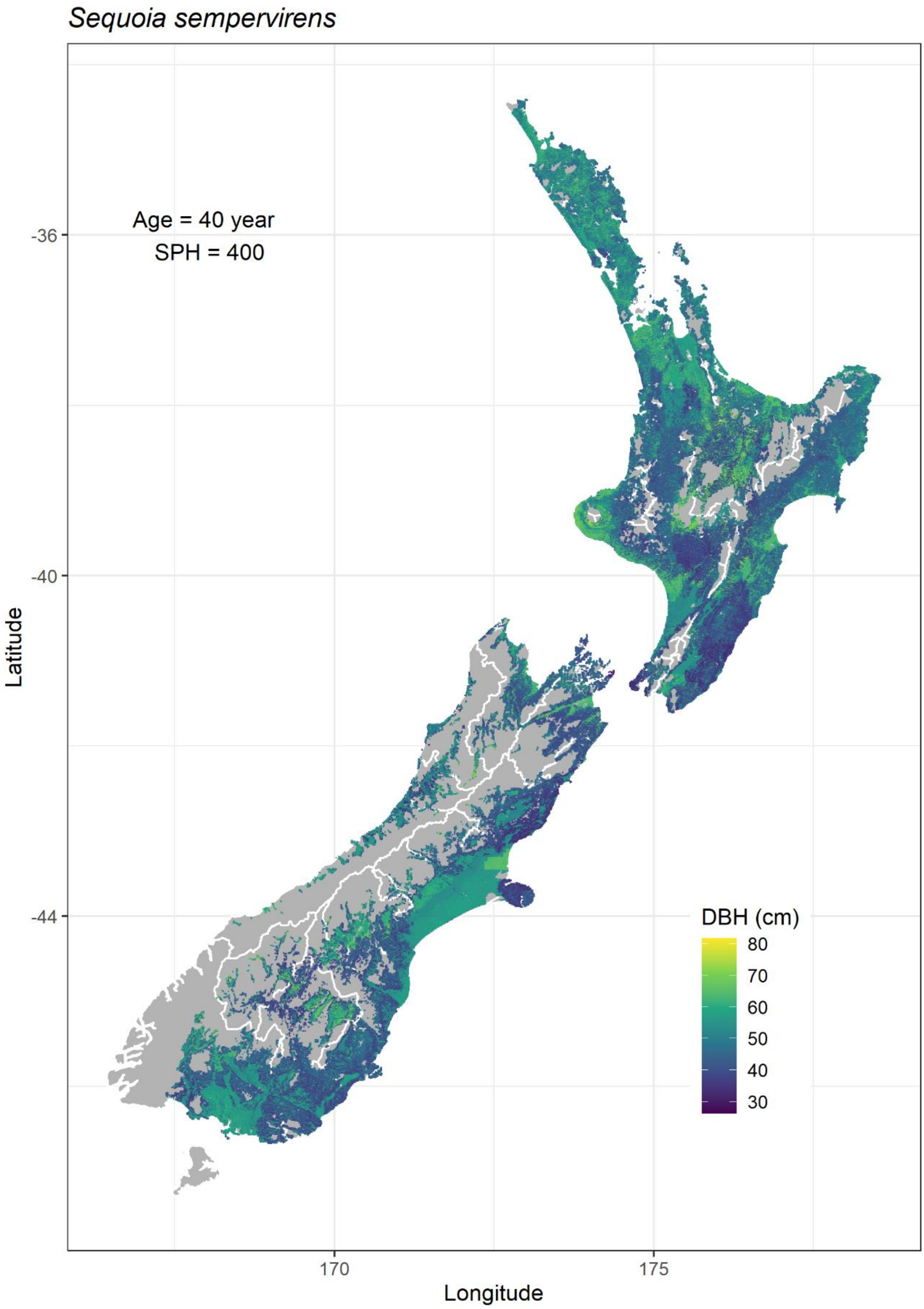
Note: DBH refers to "Diameter at Breast Height", which is a standardised measure of tree stem growth. SPH refers to "Stems per hectare", which is a measure of planting density.

Productivity (DBH) for Eucalyptus nitens. at 15-year rotation

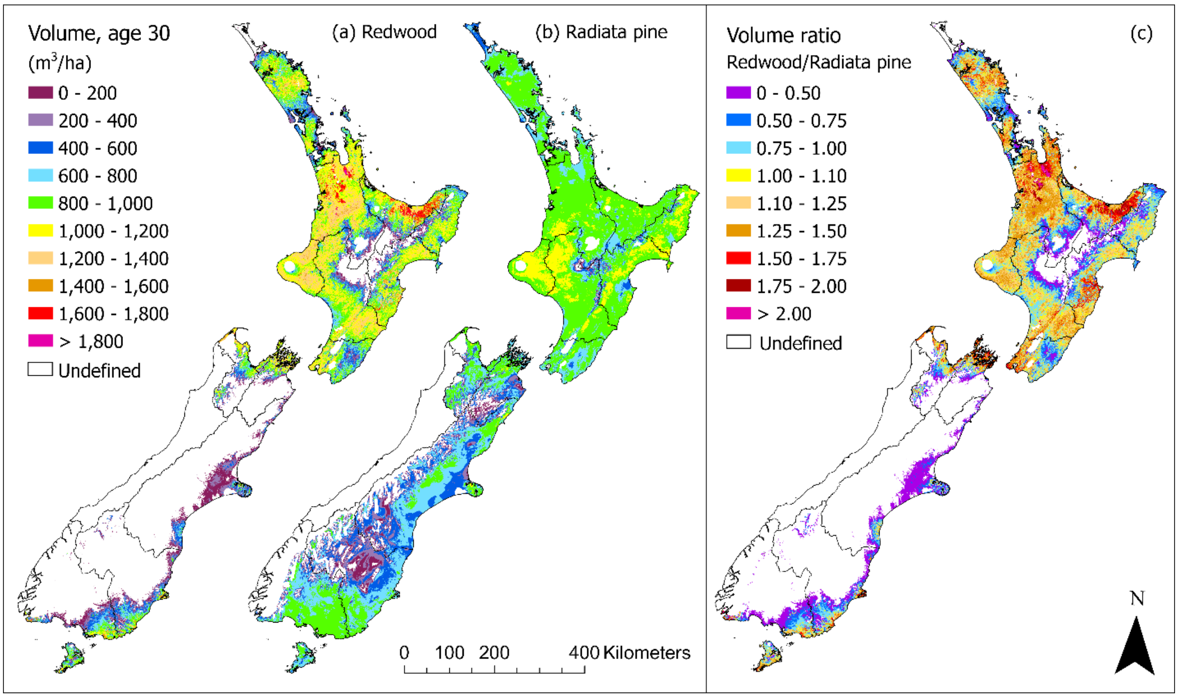


Note: DBH refers to "Diameter at Breast Height", which is a standardised measure of tree stem growth. SPH refers to "Stems per hectare", which is a measure of planting density.

Productivity (DBH) for Sequoia sempervirens at 40-year rotation

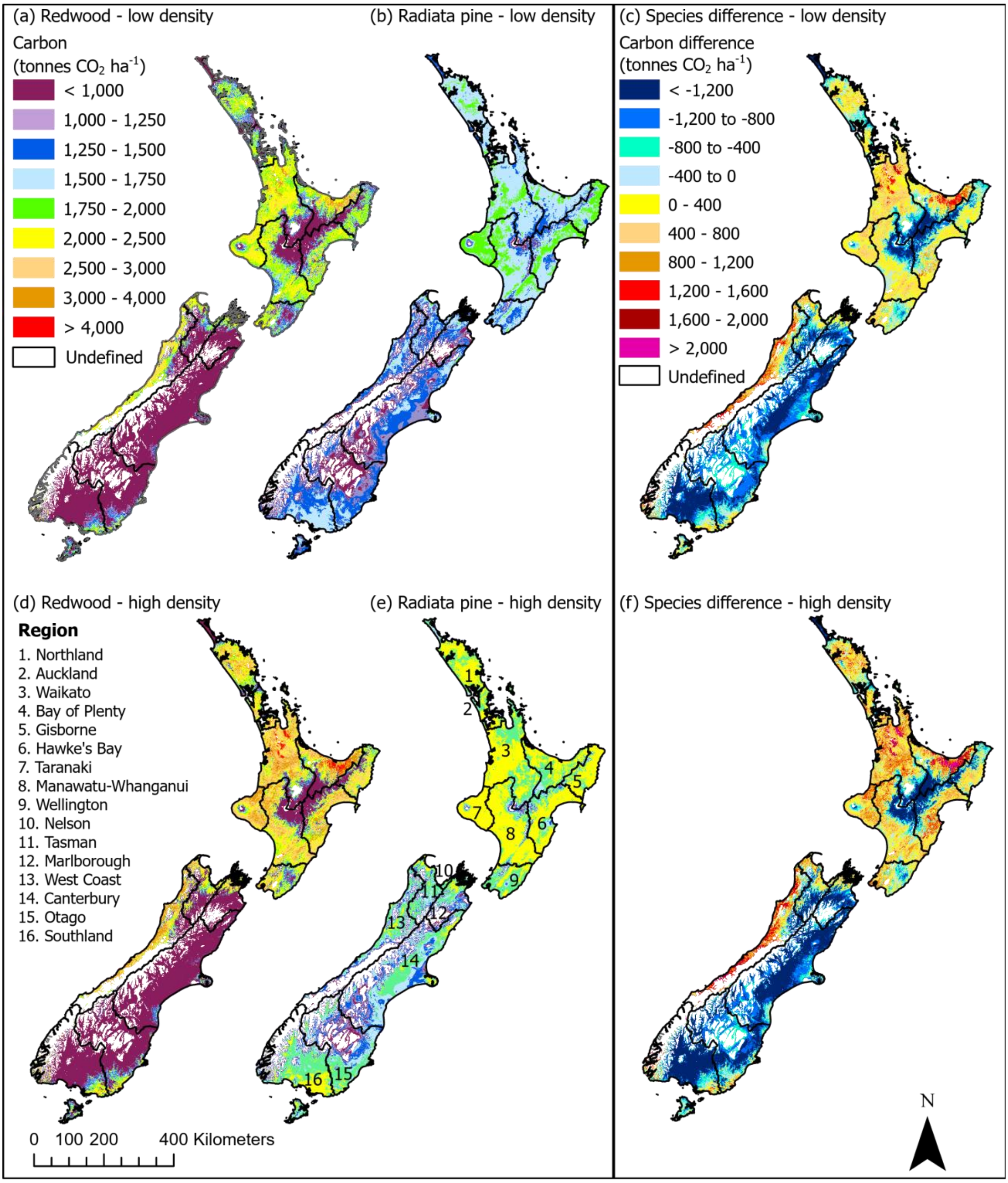


Note: DBH refers to "Diameter at Breast Height", which is a standardised measure of tree stem growth. SPH refers to "Stems per hectare", which is a measure of planting density.



Spatial variation in volume at age 30 for stands with a final crop stocking of 300 stems/ha for (a) redwood and (b) radiata pine and (c) the ratio of redwood/radiata pine volume. The west coast has been excluded from spatial predictions as there were insufficient PSP data for this region and areas with very low productivity are shown as undefined.

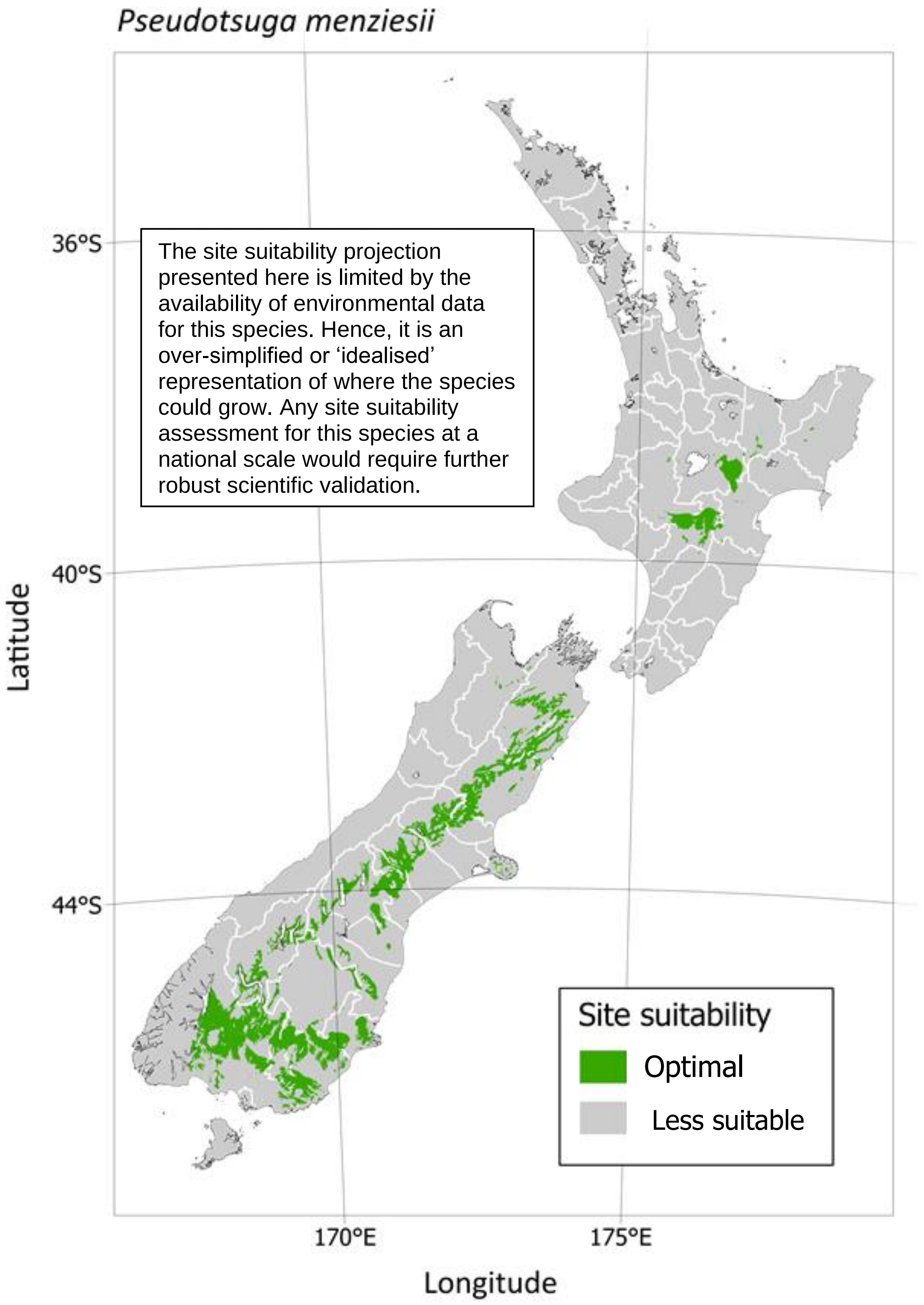
Source: Watt, M.S., Kimberley, M.O., Rapley, S., Webster, R. (2021) A spatial comparison of redwood and radiata pine productivity throughout New Zealand. New Zealand Journal of Forestry 66, 33-41. [24]



Spatial variation in carbon sequestration for redwood and radiata pine for 40 year old stands under (a, b) low and (d, e) high stand density with carbon expressed on the same scale. Also shown are (c, f) species differences in carbon (redwood – radiata pine carbon). Although predictions for the west coast are shown for redwood, these should be treated with caution as there were no plots located in this region.

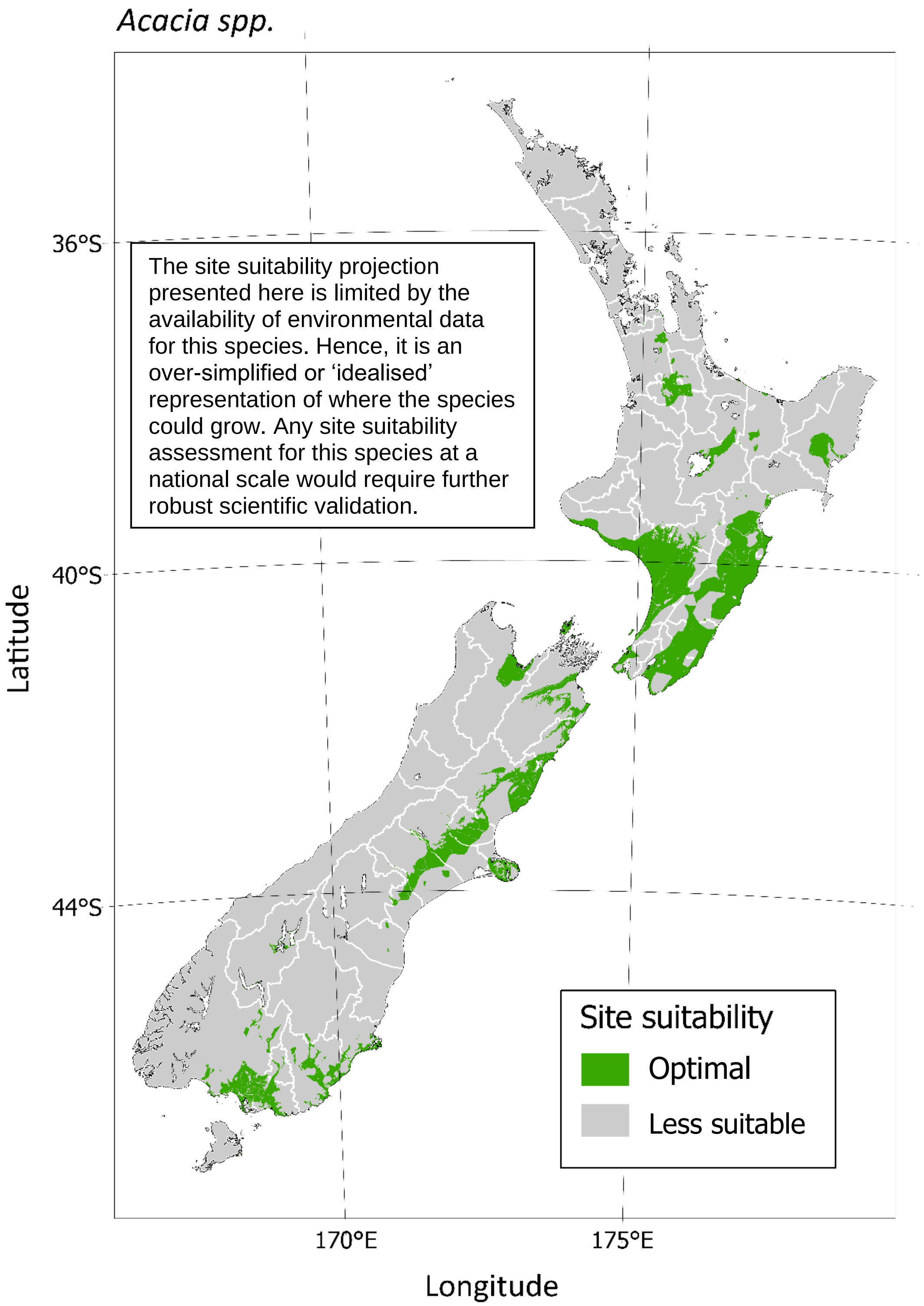
Source: Watt, M.S., & Kimberley, M. O. (2022). Comparing regional variation in carbon sequestration for radiata pine and redwood throughout New Zealand. New Zealand Journal of Forestry, 67 (1) 12 – 21. [25]

Site suitability for Douglas-fir (*Pseudotsuga menziesii*)



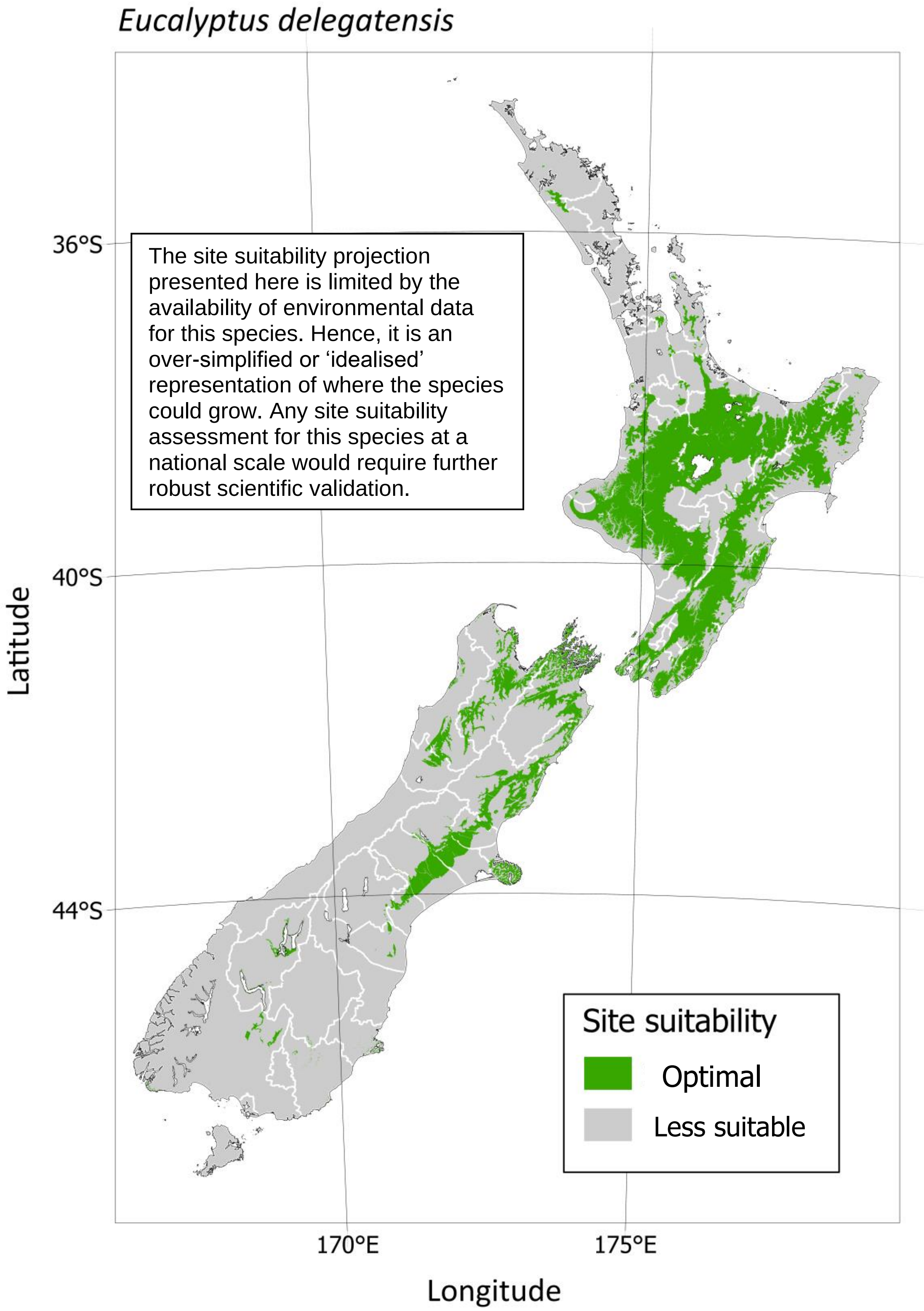
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *Acacia* spp.



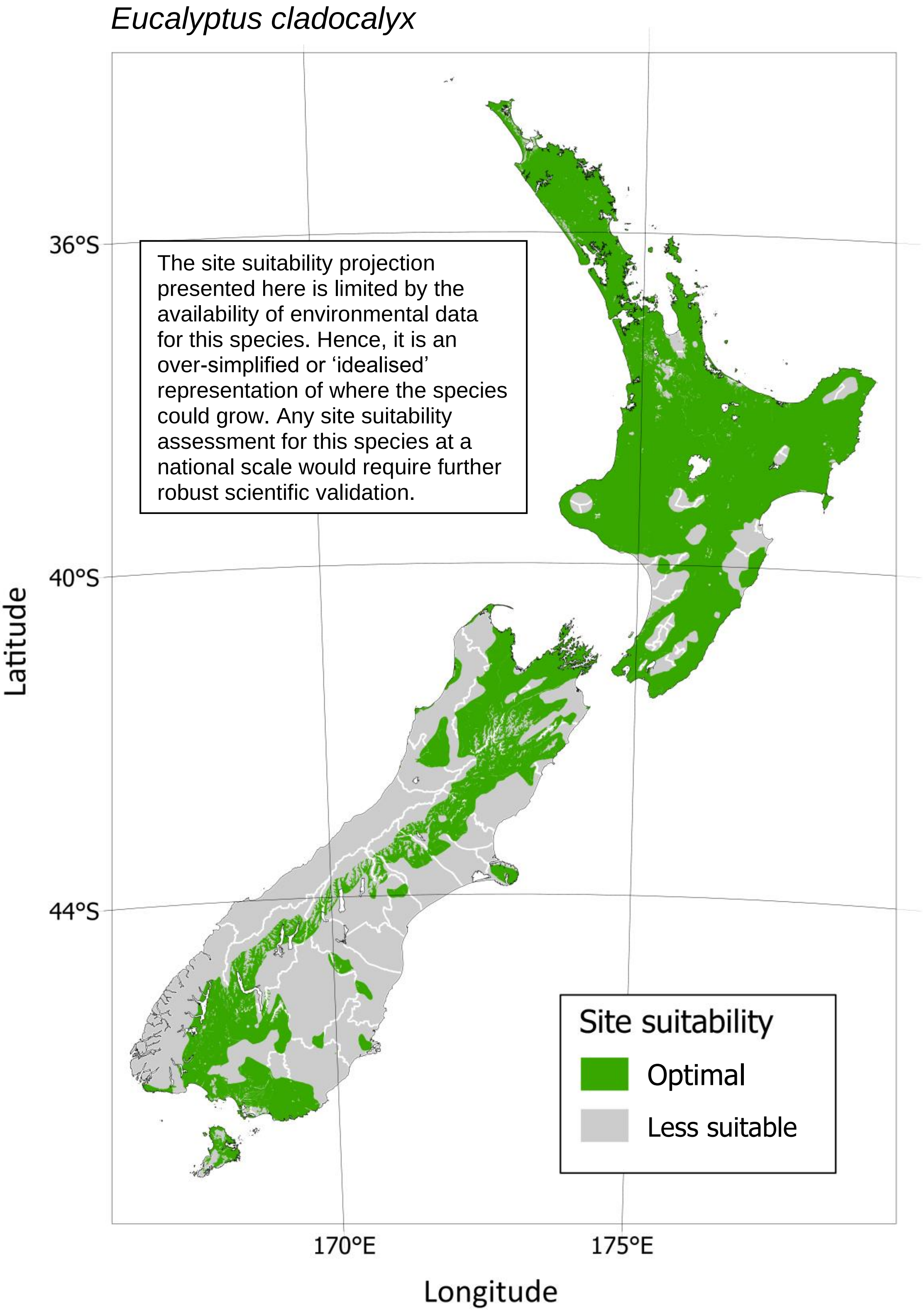
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *Eucalyptus delegatensis*



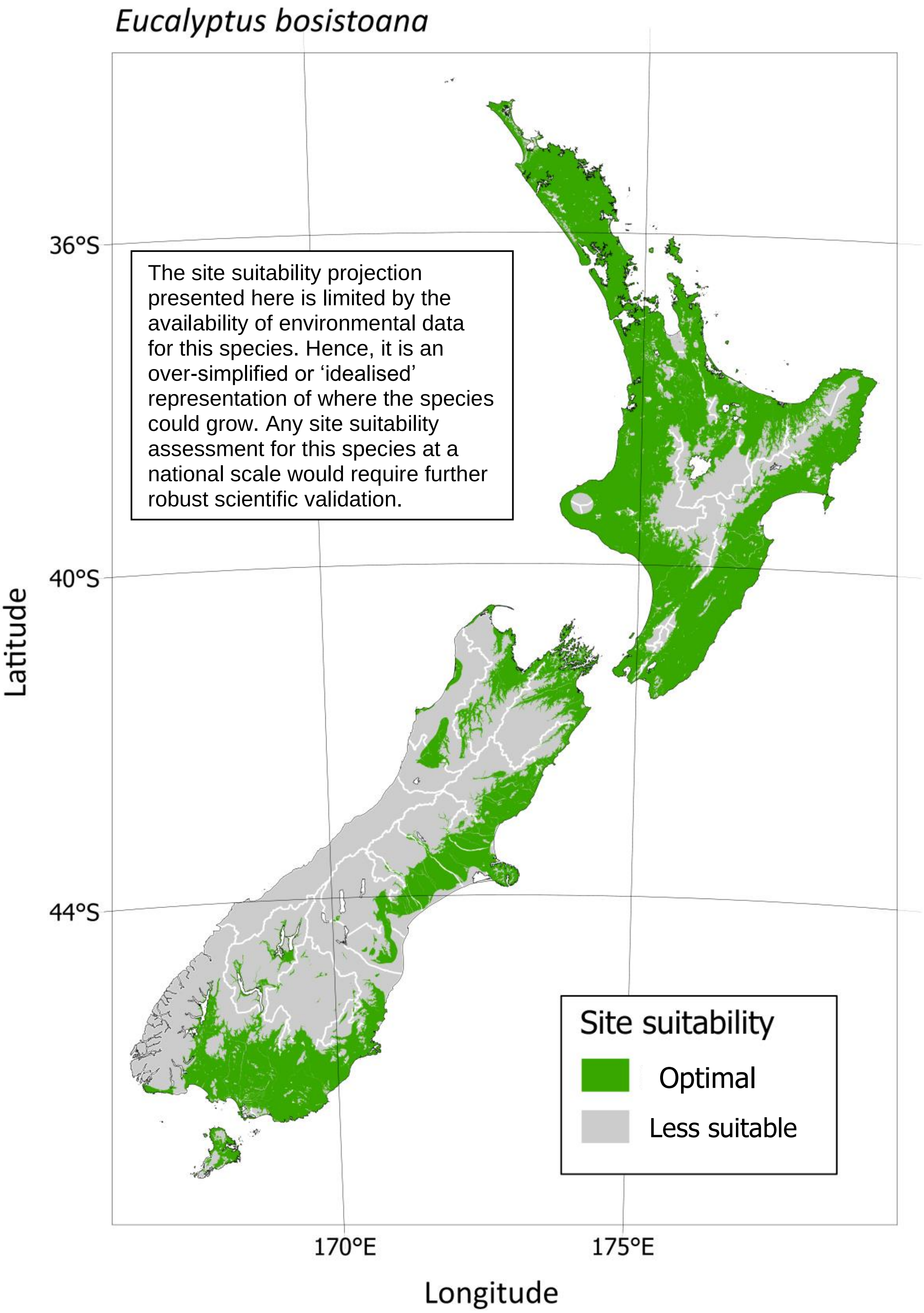
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. cladocalyx*



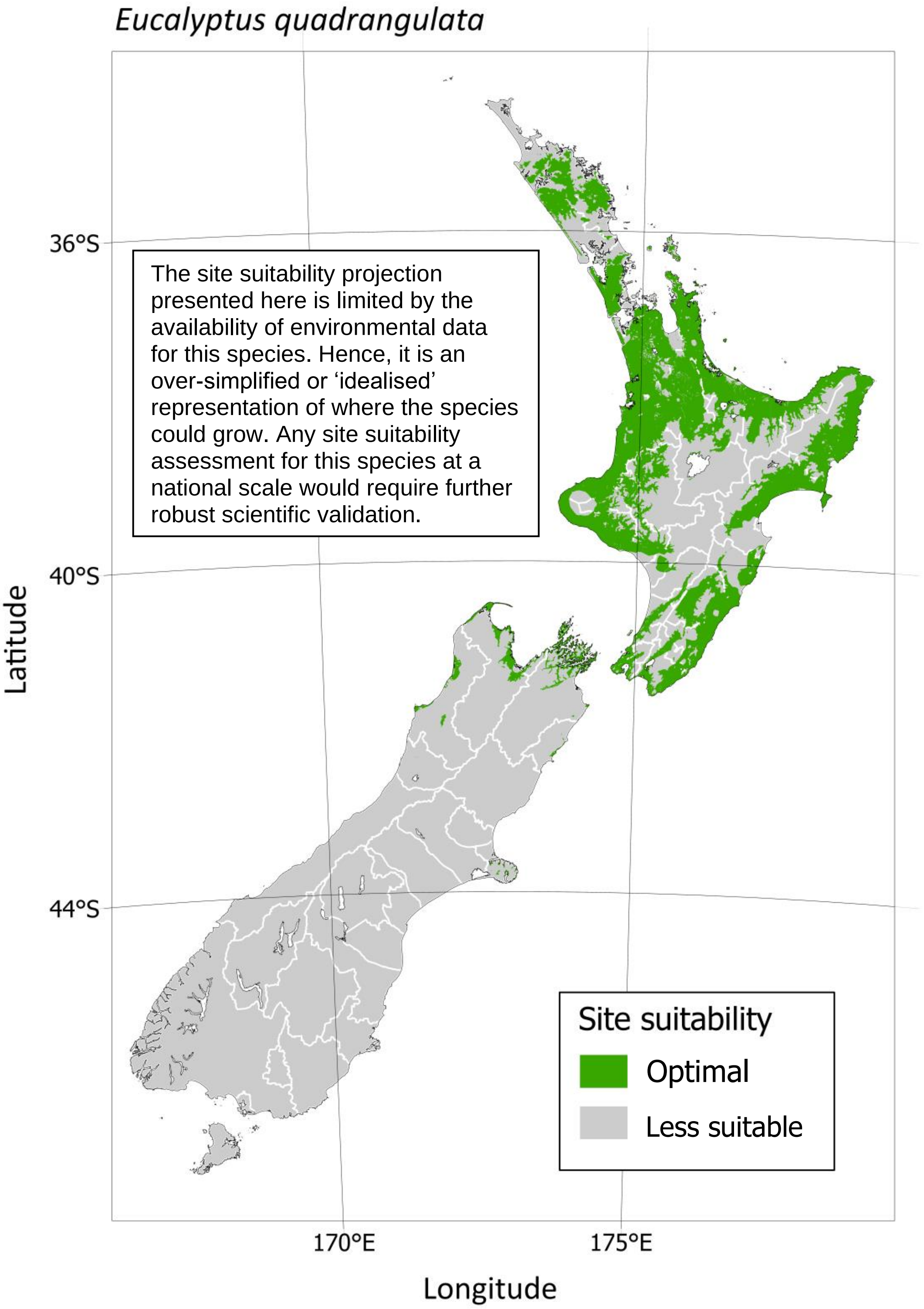
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. bosistoana*



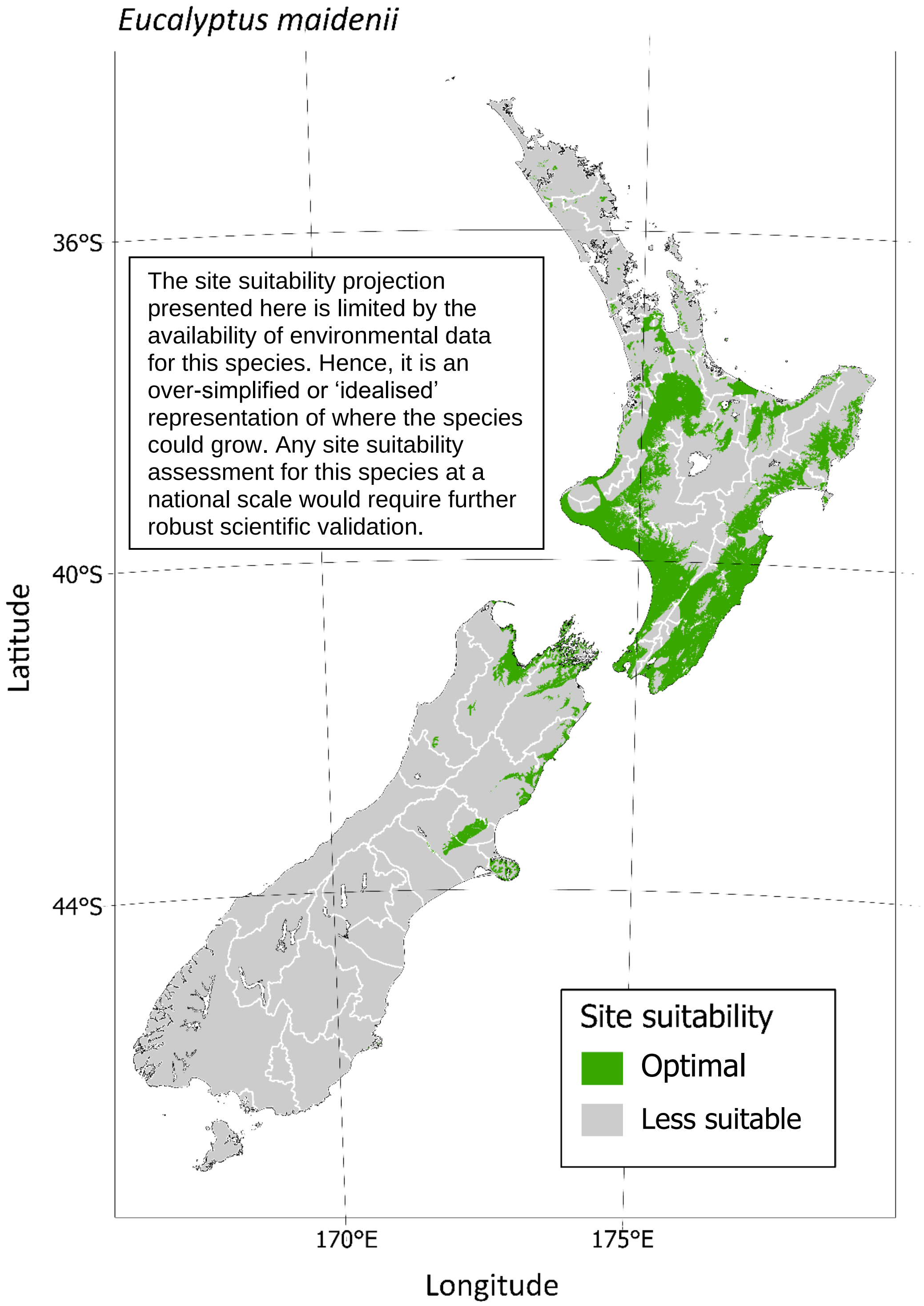
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. quadrangulata*



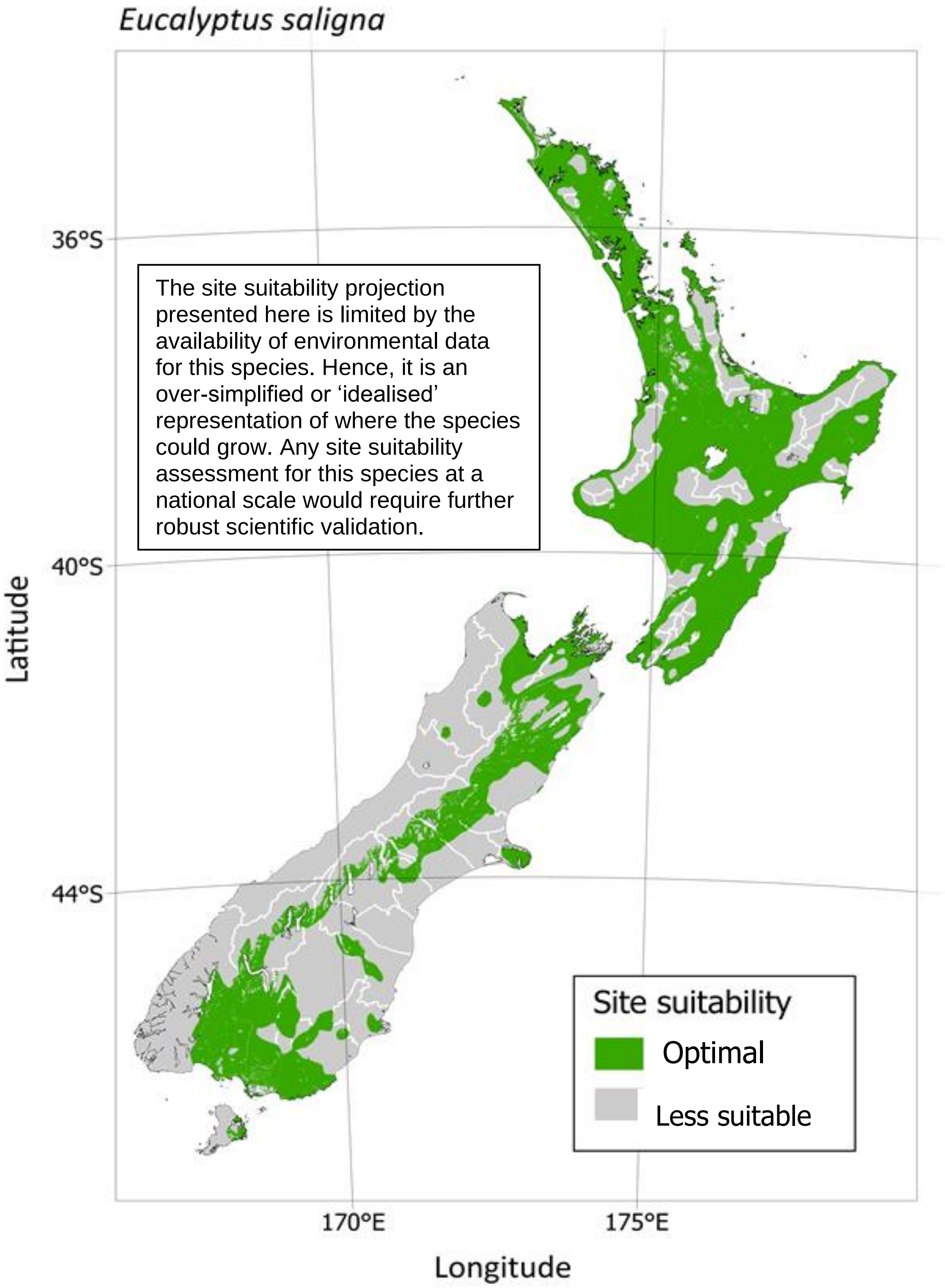
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. maidenii*



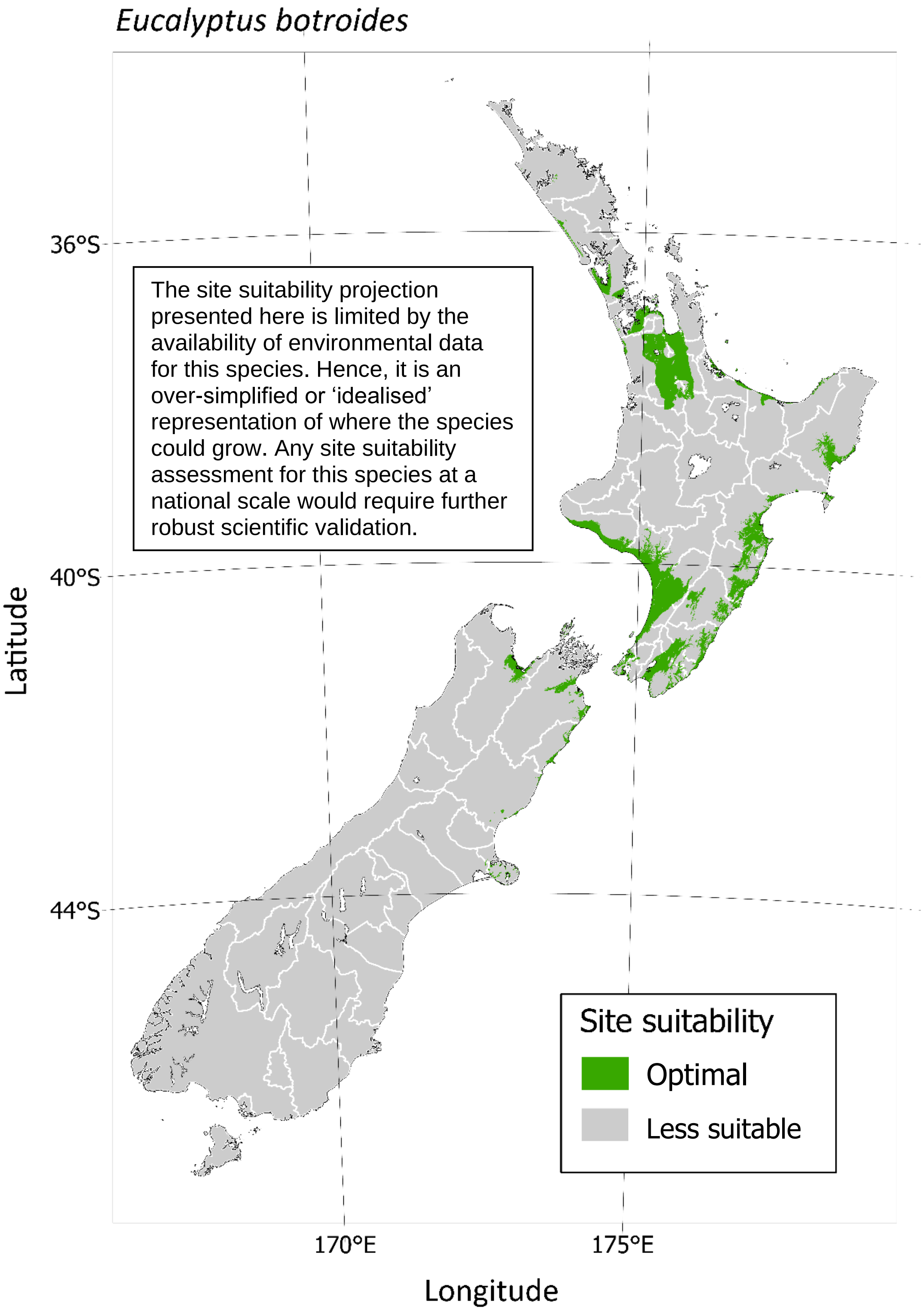
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. saligna*



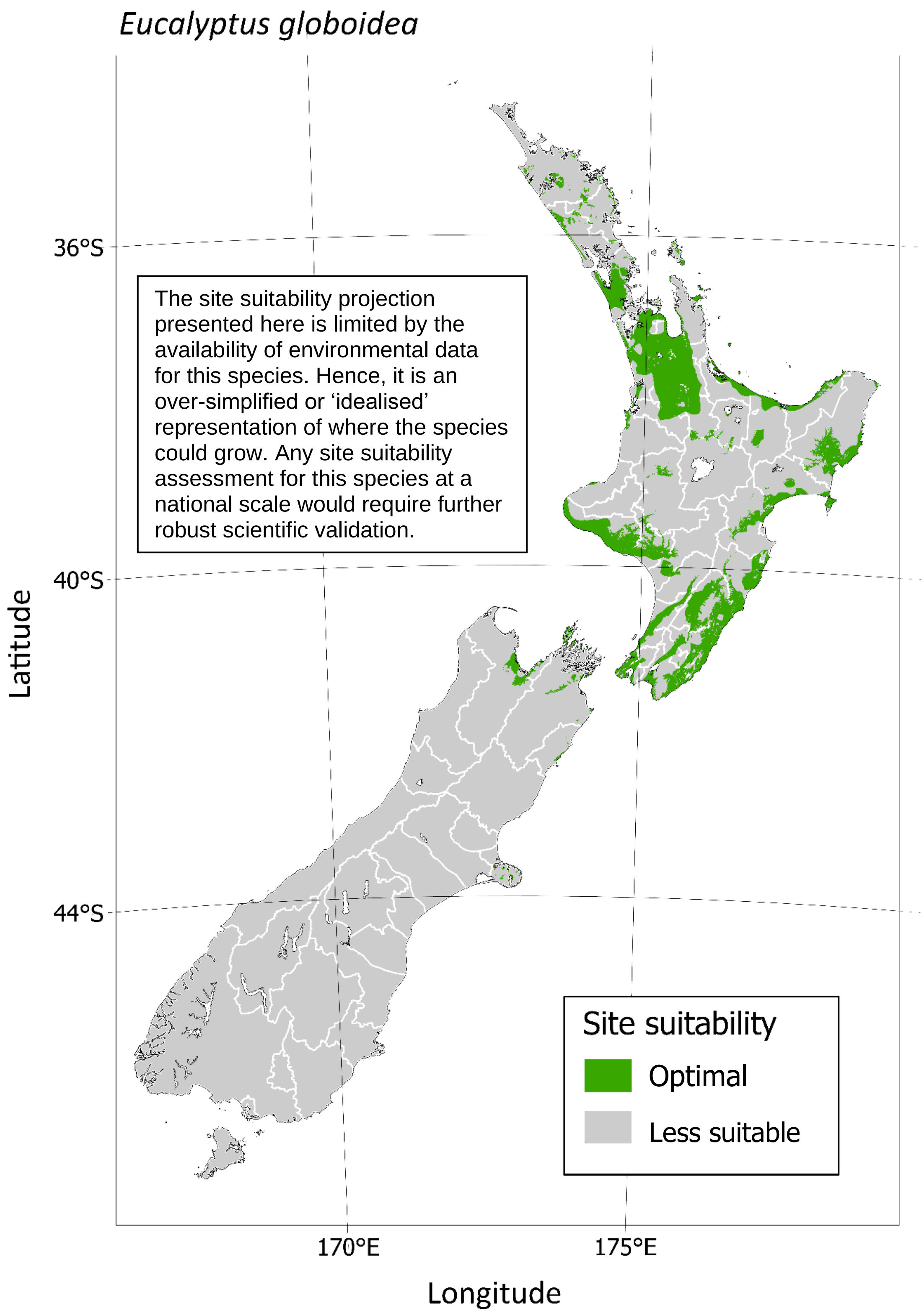
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the 5literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. botroides*



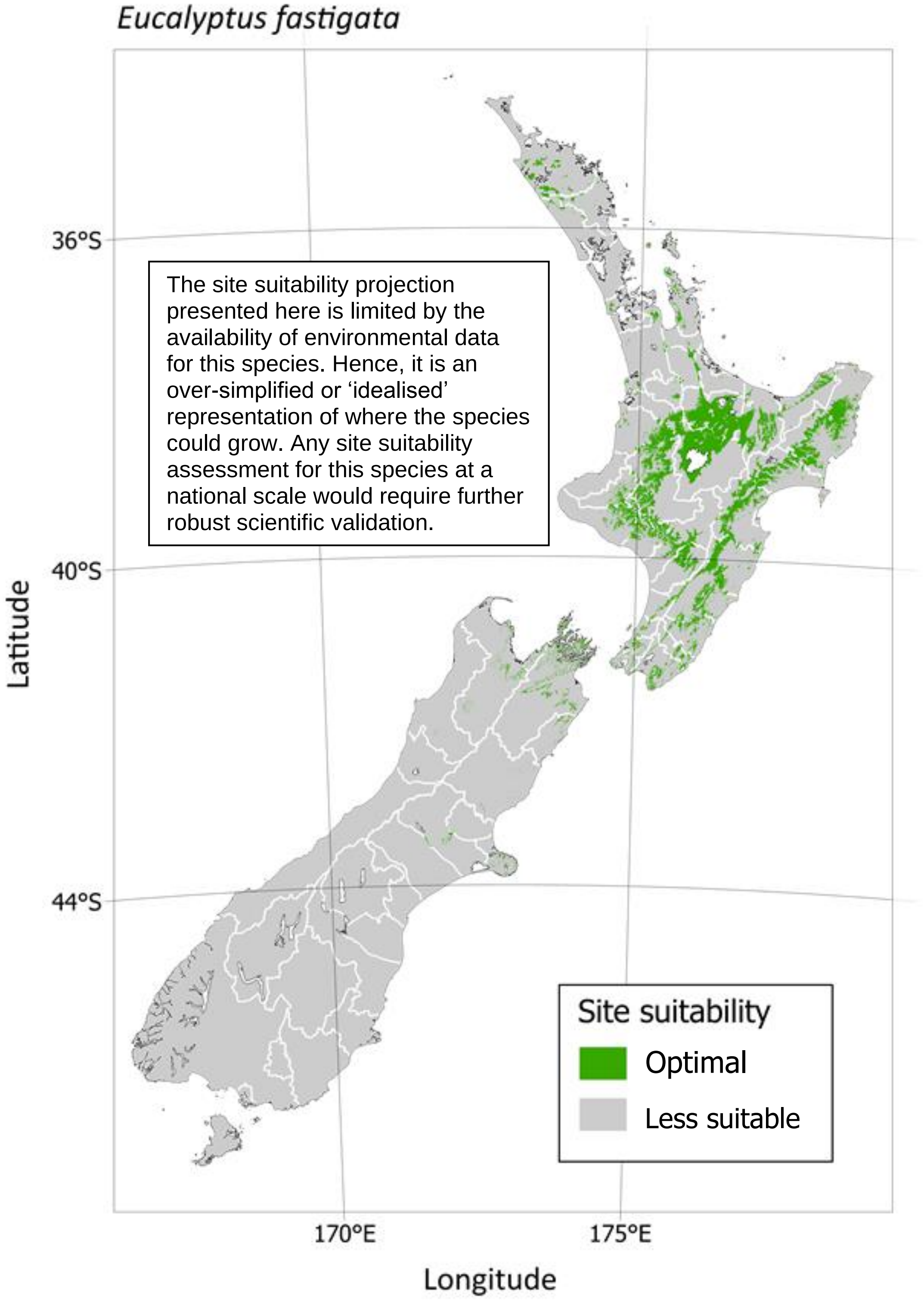
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. globodea*



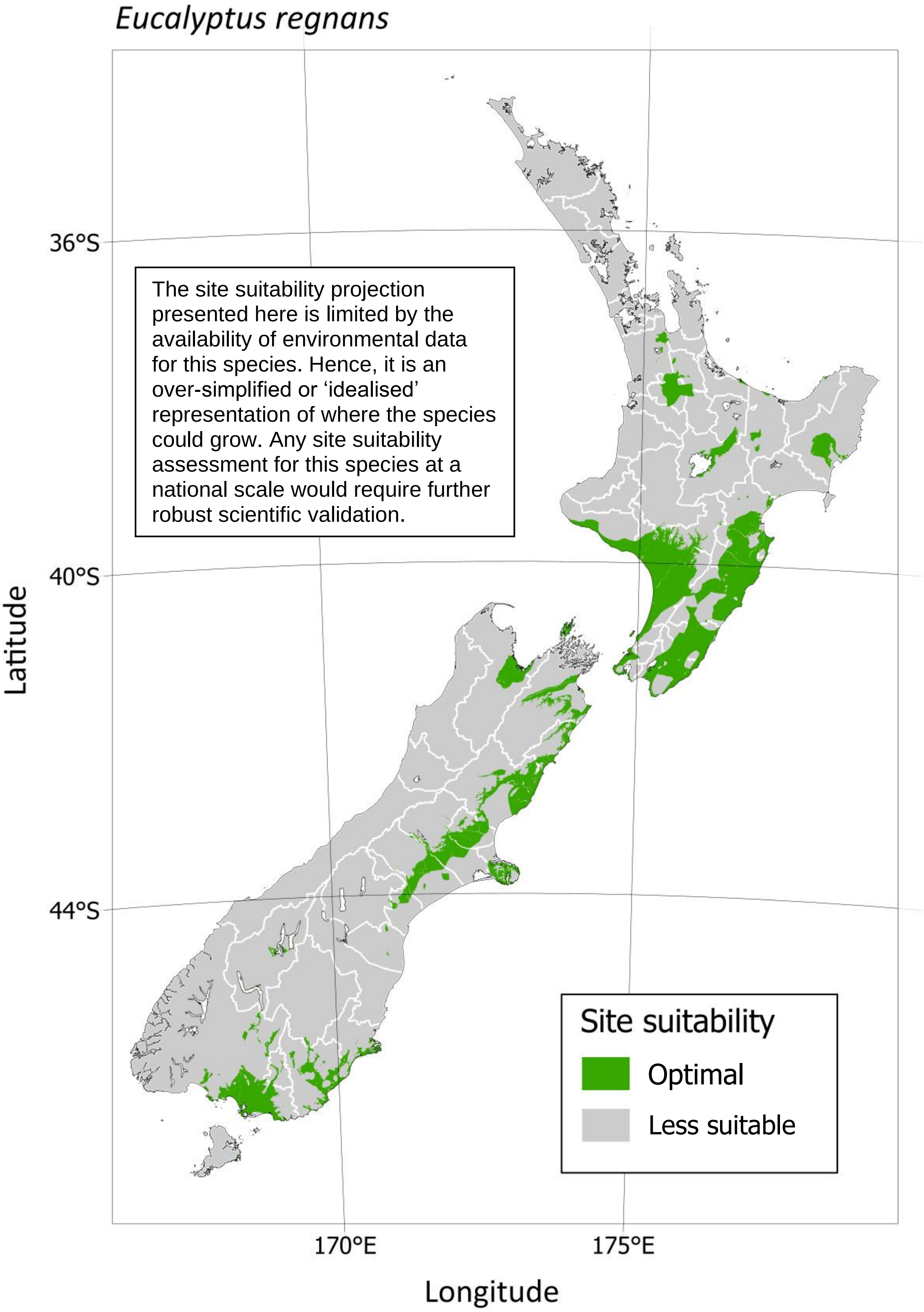
Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. fastigata*



Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Site suitability for *E. regnans*



Note: This figure indicates potential areas of optimal site suitability for this species only, which is based only on a limited set of ideal growing conditions for this species available from the literature. There are no growth rate parameters fitted to the spatial model.

Predictive modelling of species response to climate change at local-to-regional scales

Our spatial assessment of site suitability across the available rage of potential alternative species with site suitability information in the literature was challenged by the incomplete level of information published on ideal growing conditions for these species. As mentioned, the site suitability maps produced, particularly for several *Eucalyptus* species and *Acacia* spp., may already be constrained by the limited data available. This hinders further extrapolation of existing data to predict the impact of climate change on productivity or site suitability for these species. Robust evaluations of the climate change impacts on a set of tree species is also a complex undertaking. A recent New Zealand study on a single commercial species, *Pinus radiata*, required complete expert integration of detailed climatic and biophysical modelling data, including modelled information on global climate change models (GCMs), forest productivity, CO_2 fertilisation, wind damage, fire risk and disease damage [26]. An equivalent outcome for each of the shortlist species in this project would be beyond the relatively limited resource available to undertake this research. The climate change response analysis completed for *P. radiata* in New Zealand by Watt et al. (2019)[26] indicated that climate change in combination with CO_2 fertilisation would increase productivity by over 30% by the end of the century. However, it was also found that this accelerated growth would increase risks of wind damage, together with increased wildfire risk and a small increase in disease risks. It is likely that similar challenges and opportunities would arise under a changing climate for each of our shortlist species. The Watt et al. (2019) study also indicated a climate-induced increase in annual growing days for *P. radiata*, a finding which if extended to our shortlist species, suggests some potential for expansion of their viable commercial growing ranges. This could see some of the species currently showing favourability for North Island growing locations or lower-altitude sites, becoming more suitable in areas across the South Island, or some higher-altitude sites.

The circular bioeconomy and ecosystem service benefits of alternative species

The priority species highlighted in this project have a range of potential attributes suitable for development into new circular bioeconomy value chains. There are opportunities with the shortlisted alternative species to develop new high-value products, potentially incorporating new domestic wood processing facilities. Higher productivity shortlist species may be ideal for high-volume timber or wood fibre feedstock applications, such as pulpwood, or bioenergy. It is likely that some eucalyptus species could fulfill this role particularly well.

In the first instance, some *Eucalyptus* species have high growth rate attributes, suggesting value to contribute to growing forest bioenergy feedstocks. *E. fastigata*, *E. regnans* and *E. nitens* have fast growth rates and rapid growth during the initial growth phase post-planting. These attributes suggest suitability for short rotation forestry. The most prominent species to support this are likely to be non-durable eucalypts,

Of the other shortlisted species which are mainly suitable as commercial timber species, Douglas-fir is the world's most traded softwood [8]. It has suitability for growing across parts of South Island, which makes this a potential contingency timber species for this region, notwithstanding acknowledged wilding risks. A range of other eucalypts have suitabilities for timber markets, particularly the more durable stringybark species. Many eucalypts produce hardwood timbers with features suitable for high value uses, such as furniture or veneers. Domestically produced eucalypt timber has the potential, therefore, to replace imported hardwoods in many high-value uses. The durability of timber varies according to species, with the ash-eucalypt group being generally non-durable and the stringybark group being suitable for outdoor applications. The typical internal rate of return (IRR) for eucalypt plantations is considered to be around 8% [12]. Processing of eucalypt and other hardwoods into sawn timber products requires technology and methods that differs from New

Zealand's other planted softwoods, which may hinder development of value chains from these species.

Redwood timber is highly marketable owing to its attractiveness and low weight, combined with its outdoor durability and adequate strength and stiffness, which is approximately 70% that of radiata pine [27]. Demand for redwood timber exists in overseas markets in Asia. There is also a small domestic market limited by current availability of quality grades. As redwood timber is used for decorative purposes, its value per cubic metre is markedly higher than that of industrial softwoods such as radiata pine [28]. Internal rates of return (IRR) for redwood have been estimated to be as high as 10.5% on good sites which exceeds those of radiata pine under best case circumstances [2]. Further investment in the development of redwood value chains shows clear promise for the development of new plantation forestry value chains.

Cypress timber has similar aesthetic qualities to native kauri, making it suitable for furniture and other high value uses. It is also durable and can be used in external applications such as weatherboard, housing cladding and joinery. There is an existing market for high-quality, knot free cypress timber in Asia, but this has not currently been exploited to fulfill its potential. Scented cypress timber can be used for structural applications, is attractive and is suitable for above-ground uses where natural durability is required [66]. These attributes, combined with existing market demand suggest benefits available for the development of new value chains involving this species.

Blackwood (*Acacia*) has high-quality dense timber, which is valued internationally for furniture and veneers. Currently, there is only a limited domestic market for blackwood, with significant potential in developing an overseas market, owing to the existing demand. Domestically, demand currently exceeds supply for this timber, as a result of limited expansion of the total planted area. This indicates opportunity to upscale planting of this species and exploit opportunities to develop future markets for this timber.

Japanese cedar (*Cryptomeria*) is widely used for decorative panelling and cladding, joinery, gates, doors, beams, arches and even wine barrels and wooden sandals. The heartwood is moderately durable and is similar to redwood, with fragrant timber that has excellent working properties. Currently, most Japanese cedar utilised domestically is imported from Japan, as this is a cheaper alternative to imported western red cedar for exterior cladding. There is clear opportunity to develop domestic growing of Japanese cedar, which could substitute for imports and be exported to existing markets in Asia and Australia.

Poplar timber has uses in furniture, Flooring, decking, farm pallets, fence posts, battens and railings. One challenge with poplar timber is its low durability, which can be improved by chemical treatment. It is, however, not generally considered suitable for durable uses. Higher density cultivars such as Kawa may be used for structural applications. There is an existing international market for poplar logs, and it is also uses as a veneer on plywood. Poplar fibre is used in producing high quality paper. Domestically, poplar timber is planted widely, mainly for erosion control. There is opportunity to develop new value chains from this timber, particularly if breeding and silvicultural knowledge from its native range in Europe is used to inform this.

Collectively, the range of shortlist species highlighted have potential to be developed into a range of high value or high-volume wood products with further investment into developing them as commercial timber species. This would allow potential for more species diverse sets of commercial plantings nationally, which is currently dominated by one species, radiata pine. The socio-economic benefits and ecosystem services available from commercial forests could be enhanced if a mix of exotic species were grown within 'transitional' forest management systems, potentially also incorporating adaptive silvicultural practices such as continuous cover forestry and the ecological co-benefits of growing multiple commercial tree species in one setting [29].

Knowledge-gaps to increase the viability of alternative species deployment in commercial forest settings

Overview

To complete this work, Scion collaborated with 10 experts from the alternative species growing, wood processing sectors and academia, coordinated by Forest Growers Research in a virtual workshop setting. For each of the below shortlisted species or groups, the authors and the panel of experts reviewed information on a range of potential existing issues with each species, together with individually appraising detailed knowledge gaps for each. We then identified specific areas of research opportunity that could be filled to address these gaps (Table 2).

Douglas-Fir
Cypress
Durable eucalypts
Non-durable eucalypts
Redwood
Japanese cedar
Poplar
Acacias – blackwood, silver wattle
Grand fir and other firs
Larches
Oaks
Pine species or hybrids

In the second section of our analysis, we focussed on the factors limiting the value chain for each species (Table 3). Our assessment used a 'traffic light' grading system to highlight levels of limitation across each stage of the value chain, from germplasm development to end-of-life, also incorporating into this assessment 'global' risk or licence to operate elements that potentially constrain each species from commercial deployment. This value chain assessment followed an established value chain structure conceptualised for commercial forestry, developed by Scion (Figure 1).

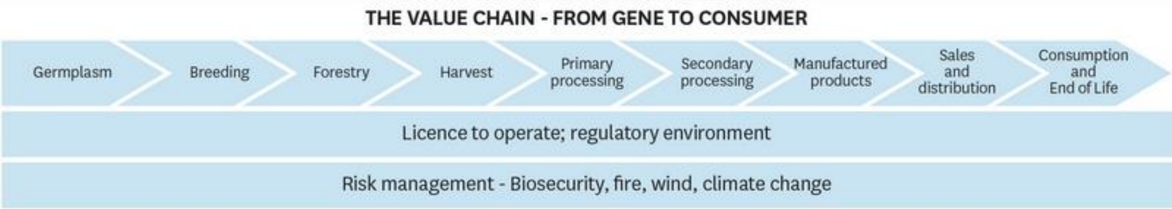


Figure 1: The value chain for commercial timber – from gene to consumer

Results and discussion

Commentary

Our Gap Analysis assessment workshop highlighted a range of priorities for future development from experts in experienced in developing market-ready alternative species over the past two decades. In general, our panel recommended it would be advantageous to address the most cost-effective, or rapid-to-solve gap analysis problems first. Overall, it was also noted that:

- Integrated approaches to growing alternative species are needed to directly link silvicultural practice with radiata pine, rather than seeing each as distinct enterprises. This could be effective when implementing, e.g. mixed-species continuous cover forestry.
- We will need to upscale seed orchards, nursery capacity, understand propagation by species and we need a planting workforce, if we are to increase planting of alternative species.
- There are challenges with the high price of seedlings for alternative species, which may be overcome following investment in scale-up of production of some species.
- Contingency species will need to be produced at a similar price to other available timber types to remain competitive.
- If timber from a specialty species is significantly more valuable than competitors, then a higher cost to produce can be carried.
- Full value chain business cases for various species and products, which includes the cost of emissions, should be developed, including a full lifetime analysis to demonstrate the value of some alternative species.
- Economic analysis of alternative species benefits must include required level of returns to the grower that will encourage planting.
- Licence to operate remains a key issue in forestry currently with wildings, fire risk and water use with competing species are also important issues.
- Climate change is an important issue affecting all regions across New Zealand and this will have an impact on which species are suitable, but could represent a development opportunity for species with adaptable physiology.
- Developments are needed in building standards legislation to enable the wider use of alternative species in construction settings.
- Decision Support Systems for each species should be centralised so all can be compared on one website.
- There is an overall gap in terms of public knowledge and awareness of alternative species, which should be addressed by familiarising the public with the options available and information on how to grow them. Alongside this, there needs to be education of forestry advisors and architects or designers to ensure other species are more frequently considered.
- The challenge for all of these species is to get sufficient forest established in a location and at a scale that sustainable supply of good quality logs to develop a regional value chain.

Table 2: Gap analysis - Research

We reviewed information presented in the Table 1 for research knowledge gaps, for each of our shortlist species, genera or major tree species groupings. This table identifies research responses to known challenges associated with each grouping. Notably, climate change was highlighted as an issue affecting each species listed and we have detailed the specific nature of this relationship for each. Collectively, this analysis determined some consistent themes across these groupings. Most notably, there are limits constraining progress with effective breeding solutions to timber quality, pest or climate issues. There are also challenges around effective processing of timber from some groupings.

Table 2: Gap analysis - Research

Species	Issue	Gap	Opportunity to fill
Douglas-Fir	Licence to operate due to wildings	We do not know how to manage spread	• Having sterile plants • Optimise chemical control
	Swiss needle cast disease impacting growth	• We do not have chemical or breeding solutions developed or in development	• Breeding trials to identify tolerant genotype • Develop chemical control management protocols
	Climate change impact on species	• We don't know the impact of a changing climate on pest, diseases, growing sites, productivity, and wildings	• Modelling to understand spread of diseases under future climates • Identify new optimal sites for growing D-fir under future climates
Cypress	Cypress canker	• We do not have complete information on hybridisation and climatic optimisation to reduce disease incidence	• Species selection and the use of hybrids and clones that are resistant to the disease • Site selection and climatic optimisation to reduce disease incidence
	Uncertainty around breeding for growth, form and heartwood quality	• We do not have sufficient breeding information on producing the qualities needed for marketable timber	• Research on the ideal attributes of breeding stock
	Uncertainty around rooting and propagation of desired clones, together with ideal regimes for the species	• We do not have sufficient information to understand the ideal silvicultural conditions for these species in a commercial setting	• Research on how to improve commercial outcomes for breeding stock
	Uncertainty around processing of timber and ideal qualities of processed timber	• We do not have sufficient understanding of the ideal commercial processing requirements of timber from these species	• Research on how to improve economically effective commercial processing at scale and timber quality of products from these species
	Climate change impact on species	• We do not understand how the species to site matching will vary with climate change	• Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Durable eucalypts	Uncertainties with species site suitability	• We do not know the optimal sites and growing locations for all these species	• We need to complete mapping of site suitability for all species
	Uncertainty about growth and form, and heartwood quality, and quantity, for these species can be further optimised for timber production	• We have not tapped into all genetic gain of these species to produce ideal growth forms for timber production	• We need to continue to optimise growth, form and wood properties for these species through breeding
	Disease and pest tolerance for these	• We do not have sufficient knowledge to improve the	• We need to undertake research on how to improve

Species	Issue	Gap	Opportunity to fill
	species can be low on some sites	disease and pest tolerance in these species	the disease and pest tolerance of these species
	Propagation success of clones is low, limiting the capacity for deployment in a commercial plantation setting	• We do not have sufficient knowledge of how to improve the propagation success of clones in a commercial setting • We need to determine the durability of cloned stock with in-ground testing	• We need to conduct research on how to improve the propagation success of cloned stock and in service durability
	Optimal regime criteria for each of these species is not well-known	• We do not have sufficient knowledge of the optimised regimes for each of these species	• We need to conduct research on the optimal regime characteristics for each of these species
	Marketing for timber products of these species is not well-developed	• We do not have sufficiently advanced marketing for each of these species	• We need to further develop marketing durable eucalypts to help develop markets for their products • We need to conduct work to include the species in material and building standards.
	Climate change impact on species	• We do not understand how the species to site matching will vary with climate change	• Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Non-durable eucalypts	Wood defects in non-durable eucalypts reduces range of potential applications	• We do not know how to reduce log-end splitting in non-durable eucalypts to improve timber processing outcomes • We have insufficient knowledge of densification and thermal modification with these species	• We need to complete analysis of optimal processing requirements for these species, including densification and thermal modification and breeding for fit-for-purpose timber properties
	- *E. nitens*: leafspot fungi; *Paropsis* browsing - Myrtle rust Barron Road Syndrome	• We do not have complete information on the methods to control these pathogens and pests, or their relationship to spatial variations in climate	• Breeding trials to determine pathogen or pest-resistant genetic material • Field trials to determine effective treatments • Modelling to understand disease and pathogen spread
	Climate change impact on species	• We do not understand how the species to site matching will vary with climate change	• Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Redwood	Uncertainty about the growth form, heartwood development and durability of clones	• We do not have sufficient information about the variability of these factors in clonal stock	• We need to complete research on the timber quality and growth form of clones
	Climate change impact on species	• We do not understand how the species to site matching will vary with climate change	• Evaluating likely responses of site suitability to climate change using a

Species	Issue	Gap	Opportunity to fill
			combination of modelling and gradient studies
Japanese cedar	Limited genetic stock available in NZ reduces range of applications	We are not able to optimise breeding of this species for timber qualities	• Importation of genetic stock • Breeding trials to optimise timber qualities and range of applications
	Climate change impact on species	We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Poplar	Very susceptible to possum browsing	We need to understand the most effective hybridisation methods to reduce possum browsing	Breeding and field trials to evaluate the most effective hybrids for wood quality and reduced possum browsing
	Climate change impact on species	We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
	Current breeds available have low wood density and low suitability for timber applications	We do not possess breeds with a range of timber qualities suitable for a range of solid applications, including durable uses	Breeding and field trials to test potential breeds from Europe that may have better timber qualities
Acacias – blackwood, silver wattle	Potential wilding risk	We need to understand how to manage possible risk of wilding spread	Field trials and spatial modelling to understand wilding spread risk
	Climate change impact on species	We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Grand fir and other firs	- Limited understanding of provenance or breeding - Limited seed availability	- We need a better understanding of provenance effects and breeding - We need to establish seedstock	Breeding and field trials, combined with development of nursery stock
	Climate change impact on species	- We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Larches	- Limited understanding of site suitability, provenance or breeding	- We need a better understanding of provenance effects on site suitability and breeding development	Breeding and field trials to fully exploit the growing advantages of this group
	- Climate change impact on species	- We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies
Oaks	- Limited understanding of provenance or breeding	- We need a better understanding of provenance effects and breeding	Breeding and field trials
	- Climate change impact on species	- We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies

Species	Issue	Gap	Opportunity to fill
Pine species or hybrids	Seed supply at scale does not allow effective assessment of potential hybrids	We need a better supply of seed stock for different species to enable assessments of hybridisation	Importation of seed material and development of seedling stock
	Climate change impact on species	We do not understand how the species to site matching will vary with climate change	Evaluating likely responses of site suitability to climate change using a combination of modelling and gradient studies

Table 3: Gap analysis - Value chain

We completed an assessment of limiting knowledge gaps in all 11 value chain processes associated with timber production, processing, manufacture, sales and end-of-life for each of our priority species or species groups (Table 2, p. 12). In this process we followed the "value chain for commercial timber – from gene to consumer" structure developed by Scion. Two further 'global' risks were included in this assessment. These were limitations that would potentially affect every other aspect of the value chain: (1) management risks and (2) social license to operate. In this analysis we show the level of urgency using a 'traffic light' coding system for each value chain step, with areas of greatest priority for research development indicated in red. It should be noted that success is only possible with green across the whole chain. Funding should focus on the species closest to commercial success. Our review determined that overall, the greatest initial limitations in the value chain with most species overall arise with germplasm availability, breeding development and propagation capacity. Secondly, there were also identified value chain challenges with wood processing and manufacture, sales and distribution and end-of-life processing to varying degrees with most species or groups.

Table 3: Gap analysis - Value chain

Species	Risk management	License to operate	Germplasm	Breeding	Propagation	Planting	Silviculture	Harvest	Primary Processing	Secondary Processing	Manufactured products	Sales and distribution	End of life
Douglas-Fir	CC	Wildings											
Cypress	CC						Disease						
Durable Eucalypts	CC		Further introductions needed	Further improvement needed	Limited seedstock		Pests, siting and growth models	Short rotation/small scale harvesting systems			Work required on standards		
Non-durable Eucalypts	CC				Limited seedstock		Pests and siting						
Coast redwood				None	Limited clonal stock		Siting						
Japanese cedar				None	Limited clonal stock		Limited knowledge						
Poplar	CC			No domestic	Clonal only								
Acacias – blackwood, silver wattle	CC	Wilding		Limited									
Grand fir and other firs				None									
Larches		Wilding		None									
Oaks													
Pine species or hybrids	CC	Wilding in some cases		Limited									

Table 3: Gap analysis – value chain information presented using a 'traffic light' grading system showing level of priority . "CC" refers to climate change. Columns 1 and 2: "Risk management" and "License to operate" are global risks potentially affecting the whole value-chain.

Additional commentary by species or species group

Cypress

Climate change impacts are an important consideration for this species in the future, particularly relating to problems with cypress canker. To address this, a range of cypress species from different climates could be imported. In particular, long-lived Himalayan cypress is noted for its considerable range. Furthermore, it will be necessary to evaluate new hybrids with suitable timber traits and disease resistance. This could be accomplished by expanding the number of hybrids in current breeding programmes, particularly making hybrids between Eastern and Western cypresses, which could be completed in collaboration with US researchers. Market analysis is needed to fully exploit the potential of cypress timber both domestically and in overseas markets. Refinements to building codes would help this, to recognise the structural properties of *C. ovensii* and other hybrids. The future potential for development of densification and thermal modification of cypress timber to improve durability could increase the range of suitable applications.

Naturally durable eucalypts

There is potential to collaborate with Australian researchers on the breeding of some species, such as *E. cladocalyx*. Also, to collaborate on innovative wood processing suited to short rotation sawlog/peeler regimes. Further durable eucalypt species from Australia could be included in the list of domestically grown species to provide greater climatic adaptability, including: spotted gums, grey gum, and white mahogany. Good seed sources are needed to enable this, which will involve improved seed and in situ testing of this material. Other species, such as *E. globoidea* and *E. bosistoana* have well-developed domestic breeding programmes, including clonal breeding research of *E. bosistoana* but are constrained by a current lack of funding. Further importations from natural Australian populations are required for *E. globoidea* along with deployment of a second generation breeding population. This would benefit from undertaking genomics of this species. Further development and evaluation of *E. bosistoana* clones and possible hybrids is necessary, including prioritisation of those with favourable traits. Focus on durable Eucalypt breeding should include improvements in heartwood volume and hardwood quality, noting that all species need further work, on growing, establishment and marketable products.

Non-durable eucalypts

The wood properties of these species require development to enhance their potential for use in a range of applications. These changes could be made through further breeding work, for example, *E. fastigata* is currently durability class 3, but could potentially be uplifted to class 2 with further breeding development. Log splitting remains an issue with this species, which could also be addressed with this work. There is potential to use these species in composite applications, such as cross laminated timber (CLT) and glue-laminated timber, with further potential to combine with radiata pine timber in some products. There is also potential to investigate densification and thermal modification of non-durable eucalypts to improve their range of applications. *E. nitens* has known insect problems.

Coast Redwood

The main companies growing Coast Redwood have selected a group of clones selected for growth and form, improved basic density, heartwood durability (as assessed by Suter block testing, NIR analysis, or both) and ease of propagation. Clonal archive material was propagated from numerous trees selected from the Rotoehu Provenance Trial and these are located at ProSeed for a potential breeding programme. Research is required on promoting the flowering of this material. There is a programme of work currently being undertaken to identify trees of superior growth and form and wood properties that can increase the clonal archive material that will contribute to the development of a seed orchard.

Japanese Cedar

We need to better understand the timber properties of this species, but only limited development has taken place over the past 60 years since initial clonal selections were made in New Zealand. Timber quality and consistency is important for export markets.

Poplars

Currently, all breeds have been selected for growth and form, owing to their extensive use in soil conservation. Wood quality and wood density aspects have received less attention by breeding work, and this is an opportunity for further development. It will be difficult to know where to begin this, which could take two decades, but examples from European breeding programmes and related knowledge about this species could prove useful here. A market already exists for appearance-grade timber with this group. One hybrid present domestically ('yogi') has high wood density, but its wood properties are untested. Thermal modification is a further development opportunity that would increase the range of suitable applications for this timber such as flooring, however, structural applications may remain elusive.

Oaks

There is a lack of seed availability for oaks generally and biosecurity rules may need to be changed to allow importation of acorns. Knowledge is also needed about flowering times to establish seed orchards. Some hybrids and Mexican species are known to have fast growth rates and there needs to be a shortlist developed of the best species available. Timber handling is an issue, as some timbers are susceptible to cracking on drying, so slow rates of drying are needed. Opportunities arise with oaks for agro-forestry grazing.

Blackwoods (Acacias)

Blackwoods have a wilding problem which must be addressed. Silvicultural knowledge needs to be improved, particularly with managing existing regenerating stands in the South Island, which would be more effective than starting new plantations outright.

Grand-fir

The known species present in New Zealand (*A. grandis*) may be less suitable for a range of timber applications than potential alternatives, such as *A. vajarii* and *A. religiosa*. The advantage of this genus, in terms of shade tolerance and wind hardiness, should be exploited. This genus may be suitable for continuous cover forestry, or when planted in similar growing situations to redwood.

Larch

There is no existing clonal programme for larch. Challenges exist with this species for poplar rust and wilding risks, that both require further development. Larch is the alternative sexual host for poplar rust. Poplar rust can only reproduce asexually on poplars; it needs Larch for any genetic variation to occur. There seed fertility of hybrid larches is relatively unknown also.

Summary

The results of this assessment highlight areas of future research development for priority ready-to-plant alternative species that would facilitate their expansion as commercial species within New Zealand. The development areas suggested herein indicate that economic benefits could be derived from investment in research developing knowledge and effectiveness of the germplasm, breeding and propagation of most of our priority species. The value of timber products from these species would be enhanced through further research development on processes to improve primary and secondary wood processing, together with routes-to-market and end-of life processing. Collectively, this assessment has demonstrated clear areas of research priority for each of our individual species or groups which should be implemented to increase the diversity of New Zealand's planted forest inventory.

Recommendations and conclusions

This work highlights the opportunity available to further develop a specific range of ready-to-plant commercially suitable alternatives to radiata pine. The species or groups identified in this work already have multiple decades' evaluation on breeding, planting and silviculture, but not necessarily within New Zealand. Hence, improvements in the commercial viability of these species can be made if specifically tailored investment is made to improve existing knowledge within a domestic setting. These areas of focus should include developing individual knowledge on improved breeding, planting and silviculture for most of these species or groups. Further benefits for the commercialisation of these will be available through investment in developing wood processing knowledge and technology appropriate to the unique qualities of their timbers.

Utilising a range of species in commercial plantation forestry offers a range of co-benefits that extend beyond obvious advantages of increased market diversification or system resilience. Increasing the range of species available for commercial planting would allow different models of forest management to be employed, particularly if high-value timber species are planted. This would allow commercial forestry to move away from the conventional high growth rate production model of radiata pine forestry that has dominated in New Zealand. New forms of plantation management with alternative species could include continuous cover forestry, or mixed species plantations that exploit the ecological benefits of a range of species with synergistic functional traits. In combination with the slower growth rates of some alternative timber species, this suggests a new model of commercial forestry with longer rotation lengths and multiple species, which would provide increased ecosystem service benefits over the conventional 28-year harvest radiata pine monoculture model that predominates currently. Such forests could be planted with a range of benefits in mind, including improved biodiversity values and enhanced recreational or tourism use. Collectively, increased use of a range of exotic alternative commercial species would probably stimulate the creation of new bioeconomy activities, particularly in rural areas where decentralised processing of specialist wood timbers could be a possibility.

Overall, there are clear bioeconomic, environmental and social benefits available from further commercial development of a range of alternative timber species highlighted in this work. Development work should focus the most cost-effective, or rapid-to-solve alternative species first, which are those with the greatest level of existing development. These more well-developed species or groups are cypress, eucalypts, redwood and Japanese cedar.

Acknowledgements

We are thankful for the assistance of Forest Growers Research (FGR) who helped coordinate and fund the time of experts who contributed and reviewed this this work, and provided funding towards printing costs of the commercial alternative species booklet. We also directly thank: Marco Lausberg, Rob Webster, Paul Millen, Vaughan Kearns, Dean Satchell, Gary Fleming, Clemens Altaner, and Tripti Singh who contributed to the booklet and gap analysis discussion, together with Evan Powell (Te Uru rakau), Parnell Trost and Jurgen Muller (MPI), who contributed to the workshop that enabled expert panel discussions on this topic.

References

1. Watt, M., et al., *A spatial comparison of redwood and radiata pine productivity throughout New Zealand.* NZJ For, 2021. **66**: p. 33-41.
2. Maclaren, J., *Realistic alternatives to radiata pine in New Zealand–a critical review.* NZJ For, 2005. **50**(1): p. 3-10.
3. Poole, A.L., *Forestry in New Zealand*. 1969.
4. Association., F.O., *Facts & Figures 2019/20 NEW ZEALAND PLANTATION FOREST INDUSTRY*, F.O. Association, Editor. 2019.
5. Watt, M.S., et al., *Assessment of multiple climate change effects on plantation forests in New Zealand.* Forestry: An International Journal of Forest Research, 2019. **92**(1): p. 1-15.
6. Michael Roche. *Poole, Alick Lindsay - Biography*. Dictionary of New Zealand Biography; Available from: https://teara.govt.nz/en/biographies/6p6/poole-alick-lindsay
7. Burdon, R. and J. Miller, *Alternative species revisited: Categorisation and issues for strategy and research.* New Zealand Forestry, 1995. **40**(2): p. 4-9.
8. Ministry for Primary Industries, *National Exotic Forest Description*. 2021, Ministry for Primary Industries, .
9. Dungey, H., et al., *The current and future potential of contingency species to mitigate biosecurity risk for the New Zealand forest sector.* 2020.
10. Satchell, D. and S.F. Solutions, *Trees for steep slopes*. 2018, Sustainable Forest Solutions report for NZFFA/FOA Environment Committee ….
11. Farm Forestry New Zealand, *Species selection tool*. 2022.
12. Bullman, L., *Forestry Species to Fill Speciality Applications*. 2021, Forest Growers Research.
13. Nicholas, I., *Best practice with Farm Forestry Timber species–No. 2: Eucalypts.* NZFFA Electronic Handbook series, 2009.
14. Poole, B., G. Waugh, and J. Yang, *Potential for growing and processing durable eucalypts in New Zealand.* Solid Wood Initiative, Rotorua, New Zealand, 2013.
15. Burdon, R., Miller, M.A., *Alternative species revisited: categorisation and issues for strategy and research.* New Zealand Forestry, 1995. **40**: p. 4-9.
16. Nicholas, I., *Alternative species for Bioenergy, Handout to IEA Field Tour, Central North Island, New Zealand: March 13 1998.* , F.R. Rotorua, Editor. 1998.
17. Meason, D., Belle, P., Lumnitz, S., Todoroki, C., *Alternative Species Site Mapping Review and Analysis*. 2016, Scion.
18. Miller, J.T. and F.B. Knowles, *Introduced forest trees in New Zealand: recognition, role, and seed source. Vol 19. The cypresses (revised edition). FRI Bulletin No. 124, 33pp. .* 1992.
19. Watt, M.S., et al., *A spatial comparison of redwood and radiata pine productivity throughout New Zealand.* New Zealand Journal of Forestry, 2021. **66**: p. 33-41.
20. Watt, M.S. and M.O. Kimberley, *Comparing regional variation in carbon sequestration for radiata pine and redwood throughout New Zealand.* New Zealand Journal of Forestry, 2022. **67**(1): p. 12-21.
21. Hayes, J. and C. Andersen, *The Scion permanent sample plot (PSP) database system.* Age (years), 2007. **16**: p. 100.
22. Lin, Y., Salekin, S., Meason, D. F. (In review),, *Modelling tree diameter of less commonly planted tree species in New Zealand using a machine learning approach. .* Forestry: An International Journal of Forest Research, 2022.
23. Landcare Research, *LRIS Portal v1.0*, in *Landcare Research,*, Landcare Research, Editor. 2022, Landcare Research,: Landcare Research,.
24. Watt, M.S. and M.O. Kimberley, *Spatial comparisons of carbon sequestration for redwood and radiata pine within New Zealand.* Forest Ecology and Management, 2022. **513**: p. 120190.
25. Watt, M.S., Kimberly, M. O., *Comparing regional variation in carbon sequestration for radiata pine and redwood throughout New Zealand.* New Zealand Journal of Forestry Science, 2022. **61**(1).
26. Watt, M.S., et al., *Assessment of multiple climate change effects on plantation forests in New Zealand.* Forestry: An International Journal of Forest Research, 2019. **92**(1): p. 1-15.
27. Farm Forestry New Zealand. *Redwood - Coast redwood, Sequoia sempervirens*. 2022; Available from: https://www.nzffa.org.nz/farm-forestry-model/species-selection-tool/species/redwood/coast-redwood/.

28. Rapley, S., *Redwood in New Zealand.* New Zealand Journal of Forestry, 2018. **63**(1): p. 29-33.
29. Jones, A.G., et al., *Transitional forestry in New Zealand: re-evaluating the design and management of forest systems through the lens of forest purpose.* Biological Reviews, 2023.

Appendix

A1 Data used to generate map figures for *Cypressus* spp.; *Eucalyptus nitens*; *Sequoia sempervirens*.

Reference: Lin, Y., Salekin, S., Meason, D. F. (In review). Modelling tree diameter of less commonly planted tree species in New Zealand using a machine learning approach. Forestry: An International Journal of Forest Research

Table 1. Descriptive statistics of data (Min.=Minimum; Max.=Maximum; St. Dev.=Standard deviation; PET= Potential evapotranspiration; RH=Relative humidity; VPD=Vapour pressure deficit)

Species	Source	Variables, unit	Mean	Min.	Max.	St. Dev.
Cypressus spp.	Stand	Age (year)	**17**	1.5	78	13
		DBH (cm)	20.629	0.100	101.600	11.229
		Height (m)	12.282	0.000	42.500	6.234
		Stocking (stems/ha)	894.761	17	5,000	612.787
	Site	Altitude (m)	205.986	**0**	747	150.751
		Slope (°)	9.803	0	45	8.675
		Aspect (°)	180.682	**0**	**359**	45.80
	Climate	Min. Temperature (°C)	-4.032	-12.400	2.100	2.540
		Max. Temperature (°C)	31.033	25.800	39.900	2.354
		Mean Temperature (°C)	11.884	4.267	15.498	2.159
		Min. Rain (mm)	2.790	0.843	7.805	1.186
		Max. Rain (mm)	4.812	1.924	12.566	1.832
		Mean Rain (mm)	3.774	1.571	9.660	1.441
		Min. Radiation (MJ/m2)	12.659	9.220	14.980	1.084
		Max. Radiation (MJ/m2)	14.404	12.167	17.113	1.050
		Mean Radiation (MJ/m2)	13.638	11.539	15.512	0.906
		Min. PET (Kg/m^2)	2.130	0.993	2.856	0.239
		Max. PET (Kg/m^2)	7.910	6	12	1.160
		Mean PET (Kg/m^2)	2.319	1.420	3.051	0.246
		Min. RH (%)	45.653	21.200	61.700	8.649
		Max. RH (%)	98.986	97.200	100	0.602
		Mean RH (%)	82.280	74.896	80.663	2.649
		Min. Soil Moisture deficit (Kg/m^2)	-135.793	-153.000	-62.100	11.147
		Max. Soil Moisture deficit (Kg/m^2)	95.314	15	274	37.844
		Mean Soil Moisture deficit (Kg/m^2)	-36.976	-84.609	1.078	14.652
		Min. VPD (hPa)	4.704	3.200	7.700	0.639
		Max. VPD (hPa)	23.151	18.300	28.200	2.444
		Mean VPD (hPa)	11.774	9.096	15.051	1.626

		Min. Frost (days/year)	12.266	**0**	**160**	17.144
		Max. Frost (days/year)	31.905	**0**	**210**	26.366
		Mean Frost (days/year)	21.423	**0**	187.077	21.274
Eucalyptus nitens	**Stand**	**Age (year)**	8	2	27	5
		DBH (cm)	16.199	0.100	104	10.501
		Height (m)	14.255	0.200	48.200	7.822
		Stocking (stems/ha)	1,154.586	25	28,572	1,720.257
	Site	**Altitude (m)**	339.967	15	700	171.870
		Slope (°)	6.401	**0**	36	5.661
		Aspect (°)	198.407	**0**	359	45.825
	Climate	**Min. Temperature (°C)**	-6.504	-12	2	3.221
		Max. Temperature (°C)	30.659	24.900	37.600	1.802
		Mean Temperature (°C)	10.353	6.409	14.905	2.003
		Min. Rain (mm)	2.794	1.114	6.717	0.950
		Max. Rain (mm)	4.279	2.033	10.527	1.531
		Mean Rain (mm)	3.598	1.770	8.656	1.226
		Min. Radiation (MJ/m2)	12.799	8.583	14.981	0.975
		Max. Radiation (MJ/m2)	14.160	10.695	15.699	1.078
		Mean Radiation (MJ/m2)	13.545	10.610	15.194	0.962
		Min. PET (Kg/m^2)	1.952	1.387	2.773	0.241
		Max. PET (Kg/m^2)	7.665	5.700	11.400	0.802
		Mean PET (Kg/m^2)	2.106	1.731	2.924	0.233
		Min. RH (%)	48.443	24.300	59.400	6.021
		Max. RH (%)	98.544	97.400	100	0.572
		Mean RH (%)	83.007	76.711	87.704	1.270
		Min. Soil Moisture deficit (Kg/m^2)	-129.984	-62.100	-153.000	9.489
		Max. Soil Moisture deficit (Kg/m^2)	65.414	21.100	153.400	31.697
		Mean Soil Moisture deficit (Kg/m^2)	-29.273	-70.794	-0.067	11.024
		Min. VPD (hPa)	4.550	3.200	6.900	0.736
		Max. VPD (hPa)	22.517	17.700	27.200	2.154
		Mean VPD (hPa)	10.913	9.157	14.491	1.442
		Min. Frost (days/year)	37.066	**0**	113	32.355
		Max. Frost (days/year)	62.050	**0**	157	40.592
		Mean Frost (days/year)	48.491	**0**	121.667	34.832
Sequoia sempervirens	**Stand**	**Age (year)**	18	2	110	22
		DBH (cm)	21.359	0.100	173	24.391

		Height (m)	12.297	0.100	70	12.075
		Stocking (stems/ha)	815.764	25	1,964	393.957
	Site	**Altitude (m)**	287.938	19	622	159.978
		Slope (°)	15.820	**0**	44	12.638
		Aspect (°)	193.41	**0**	359	50.781
	Climate	**Min. Temperature (°C)**	-3.832	-10.100	0	1.825
		Max. Temperature (°C)	31.400	25.900	35.700	1.771
		Mean Temperature (°C)	11.679	8.482	14.479	1.642
		Min. Rain (mm)	2.662	0.881	7.662	0.940
		Max. Rain (mm)	4.684	2.370	10.088	1.443
		Mean Rain (mm)	3.649	1.678	8.638	1.102
		Min. Radiation (MJ/m2)	13.257	10.173	14.980	0.866
		Max. Radiation (MJ/m2)	14.600	12.101	17.070	0.902
		Mean Radiation (MJ/m2)	13.973	11.690	15.502	0.703
		Min. PET (Kg/m^2)	2.296	1.573	2.969	0.253
		Max. PET (Kg/m^2)	8.464	6.100	10.400	1.164
		Mean PET (Kg/m^2)	2.483	1.965	3.051	0.230
		Min. RH (%)	44.193	24.600	57.700	5.708
		Max. RH (%)	98.633	97.400	100	0.690
		Mean RH (%)	79.752	74.896	86.366	3.373
		Min. Soil Moisture deficit (Kg/m^2)	-139.740	-147.300	-93.300	7.139
		Max. Soil Moisture deficit (Kg/m^2)	126.420	46.415	21.900	309.500
		Mean Soil Moisture deficit (Kg/m^2)	-43.625	-82.743	0.002	15.397
		Min. VPD (hPa)	4.683	3.600	5.800	0.535
		Max. VPD (hPa)	22.432	18.300	27.400	2.455
		Mean VPD (hPa)	11.313	9.269	13.494	1.129
		Min. Frost (days/year)	7.976	**0**	41	7.624
		Max. Frost (days/year)	24.837	**0**	79	15.759
		Mean Frost (days/year)	15.678	**0**	58.844	11.122

A2 Table2: Data used to generate map figures for *Acacia spp.*; *E. delegatensis*; *E. bosistoana*; *E. quadrangulata*; *E. cladocalyx*

Species	Minimum temperature (°C)	Mean annual temperature minimum (°C)	Mean annual temperature maximum (°C)	Annual rainfall minimum (mm)	Annual rainfall maximum (mm)	Altitude minimum (m)	Altitude range maximum (m)	Soil characteristics
Acacia spp.	-	10	14	750	1250	0	500	Free draining to moderately free-draining
Eucalyptus delegatensis	-5	10	13	700	2500	160	1500	Well-drained, deep
Eucalyptus bosistoana	-6	-	-	600	2500	0	500	Well-drained
Eucalyptus quadrangulata	-6	12	15	1000	2500	-	-	Well-drained
Eucalyptus cladocalyx	-6	-	-	1000	2500	-	-	Well-drained
Eucalyptus saligna	-7	-	-	900	1800	-	-	Well-drained
Eucalyptus maidenii	-6	11	14	800	1800	5	350	Moderately well-drained
Eucalyptus botroides	-8	12	15	700	1300	0	150	Moderately well-drained
Eucalyptus globoidea	-5	12	15	1000	1500	0	300	Moderately well-drained
Pseudotsuga menziesii (Douglas-fir)	-12.5	7	10	750	1500	200	1200	Moderately well-drained

Information sources for these site suitability criteria are cited in the companion report: Jones (2022) *Stock Take of the Commercially Viable Alternatives to Pinus radiata*.