Spatial mapping of tree species site suitability for the Hawke's Bay region

David Palmer, Andrew Clarke, Kit Richards, James Powrie, Les Dowling and Tim Payn

Abstract

Planting the right tree in the right place and for the right purpose is an adage commonly used in the discussion of where to establish new plantations. In reality, information to support landowner decisions around the establishment of new forests is not in a readily available or in an intuitive format. The mapping of Tree Species Site Suitability Indices for Hawke's Bay was developed to provide landowners with easy-to-understand maps to support decision-making and to complement field investigations. Specifically, tree species site suitability methodology was developed to match the species *Pinus radiata* (radiata pine), *Sequoia sempervirens* (coast redwood), *Cupressus lusitanica*, *Eucalyptus* (generic scenario), *Leptospermum scoparium* (mānuka) and *Podocarpus totara* (tōtara) to their preferred growing environments across the Hawke's Bay region. National tree species site suitability characteristics include ranges of average annual temperatures, total rainfall, elevations above sea level, site fertility including soil water availability, rooting depth, and soil fertility and tolerance to both wind exposure damage and salt water spray.

This information was compiled from existing permanent sample plot (PSP) location data, published information and expert knowledge for each of the species, to help inform us of the preferred environmental conditions for each species. Tree species growing conditions were mapped using response curves and to assign fuzzy logic (membership) values between zero and one, with one being an optimal degree of membership (DOM), and zero being no DOM. For example, is the establishment location for a tree too hot, too cold, too wet or too dry and so forth. The outcome of this project provides the regional council and landowners with maps by which to assess and compare potential tree species suitable for their local site conditions – Tree Species Site Suitability Indices – and as a basis for more detailed assessment and planning.

Introduction

The Hawke's Bay Regional Council (HBRC) wants to use afforestation as an approach to mitigating erosion. At the same time, the Government's One Billion Trees Programme (MPI, 2019) has a budget for grants to landowners, particularly farmers, to include trees on their farms. To make sure the tree species planted deliver both economic and environmental benefits, we need to identify which tree species are suited to which environmental conditions – plant the right tree in the right place.

Tree species site suitability maps can assist stakeholders with decisions around which species, or group of species, are best suited to local conditions. Site suitability combines the idea of productivity associated with a tree species, and whether or not a species will survive when established. For example, at some locations a species may grow quickly and be highly productive. However, in cooler, wetter or increasingly eroded landscapes, the species choice may simply be based on reducing erosion, improving water infiltration or carbon sequestration, albeit slowly.

This work develops maps of tree species site suitability for *Pinus radiata* (radiata pine), *Sequoia sempervirens* (coast redwood), *Cupressus lusitanica* (cypress), *Eucalyptus* spp (generic scenario), *Leptospermum scoparium* (mānuka) and *Podocarpus totara* (tōtara) across the Hawke's Bay region. We have used data on growing conditions to develop response curves and fuzzy logic to predict where a species can be planted, survive and grow from poorly to successfully, while providing an estimation of suitability between species.

Materials and methods

Defining tree species environmental and climatic characteristics

Site suitability methodology was developed to establish where the species *Pinus radiata* (radiata pine), *Sequoia sempervirens* (coast redwood), *Cupressus lusitanica* (cypress), *Eucalyptus* spp (generic scenario), *Leptospermum scoparium* (mānuka) and *Podocarpus totara* (tōtara) could be successfully established across the Hawke's Bay region.

Characteristics include ranges of average annual temperatures, total rainfall, elevations above sea level, site fertility including soil water availability, rooting depth, soil fertility, landscape aspect, frost tolerance, and tolerance to both wind exposure damage and salt water spray. These characteristics were compiled for each of the species to inform us of their preferred environmental conditions.

Published empirical data plus permanent sample plot (PSP) data was kindly provided by a number of companies and private forest holdings for radiata pine, coast redwood and cypress. Empirical data to determine site suitability characteristics for *Eucalyptus*, tōtara and mānuka honey regimes were not available. We used reports, grey literature and expert knowledge to fill in the knowledge gaps.

In the case of *Eucalyptus*, a multi-species scenario was developed, because for many of this species the specific characteristics were unknown. It was considered better to cover a wide range of environmental conditions in which *Eucalyptus* species are found across the Hawke's Bay region (Paul Millen, pers. comm., August 2019).

Mānuka for honey production also required special consideration, with two characteristics from a modelling perspective: (1) optimal conditions for growth, flowering and nectar production; (2) and the

Table 1: Spatial datasets and the values used in the response curves applied in the development of fuzzy membership maps for the tree species site suitability maps

Spatial layer	Species	DOM 0	DOM 0.5	DOM 1
Elevation (m)	*Pinus radiata*	>1,020		<375
	Sequoia sempervirens	>585		<335
	Cupressus lusitanica	>590		<340
	Generic *Eucalyptus*	>700		<450
	Podocarpus totara	>500		<350
	Leptospermum scoparium	>500		<300
Total rainfall (mm)	*Pinus radiata*	<755, >2300 x		1165 – 1620
	Sequoia sempervirens	<925, >2215 x		960 – 1660
	Cupressus lusitanica	<1145, >3195 x		1380 – 1875
	Generic *Eucalyptus*	<500, >2500 x		900 – 1500
	Podocarpus totara	<750 – >2100 x		1000 – 1200
	Leptospermum scoparium	<750 – >1800 x		900 – 1300
Mean annual temperature (°C)	*Pinus radiata*	<7.7		>14.1
	Sequoia sempervirens	<9.8		>13.4
	Cupressus lusitanica	<10.4		>14.5
	Generic *Eucalyptus*	<11.0		>16.0
	Podocarpus totara	<9.8		>14.1
	Leptospermum scoparium	<12.0		>15.0
Profile available water (PAW) (mm)	All species except *Leptospermum scoparium* a	–	89	>250
Distance from coast (km)	*Sequoia sempervirens*	<1.5		>5.5
	Cupressus lusitanica	<1.5		>5.5
Wind exposure	*Sequoia sempervirens*	>1.36 (exposed)		<1.17 (sheltered)
	Cupressus lusitanica	>1.36 (exposed)		<1.17 (sheltered)
	Generic *Eucalyptus*	>1.36 (exposed)		<1.17 (sheltered)
Frosts October (days)	Generic *Eucalyptus*	>5		0
Rain December/January (days)	*Leptospermum scoparium*	>10		<8
December/January temperature (°C)	*Leptospermum scoparium*	<10		>14
Aspect	*Leptospermum scoparium*	–	South	North

x : Rainfall was developed as a trapezoid response curve, hence the upper value was set to twice that of the maximum value where it becomes a zero degree of membership (double the upper values become a DOM of zero) ideal conditions for bees to forage for food in December and January. This gave us information for the 10 variables listed in Table 1, which we then combined to give overall suitability maps for each species across the Hawke's Bay region using a fuzzy logic approach.

Fuzzy logic

We used fuzzy logic to spatially define landscapes suitable for the species of interest. Fuzzy logic approaches are used to manage vague and fuzzy concepts and potential uncertainty. Fuzzy membership (fuzziness) provides an indication as to what degree a property of interest belongs to a class, or degree, of membership. In geospatial terms, fuzzy logic can be used to manage uncertainty and vagueness in a property where a statement can be true (value = 1.0), false (value = 0.0), or somewhere in-between.

Response curve and spatial dataset development

We developed response curves for each variable, defining the values that indicate a site is totally unsuitable (degree of fuzzy membership = 0.0) and those that indicate optimal suitability (degree of fuzzy membership = 1.0 true). In most cases, all other values were assigned using a linear relationship between 0 and 1. The response curve for rainfall is trapezoidal as high rainfall can be as limiting as low rainfall.

For radiata pine, coast redwood and cypress, values were assigned using summary statistics. For the generic scenario, mānuka and tōtara, values for the response curves were developed from the literature and expert knowledge where observed data was not available. The degree of fuzzy membership (DOM) values used for different species are listed in Table 1.

Developing tree site suitability maps

Modules were developed using the ArcGIS Python library (https://developers.arcgis.com/python/) for the input layers representing elevation, total annual rainfall, mean annual temperature, profile available water (PAW), distance from the coastline, wind exposure, days of ground frost, number of rain days in December and January, average temperatures for December and January, and aspect (https://data.linz.govt.nz/). Input data at each pixel on the map was converted from actual value (e.g. X mm of rainfall) to fuzzy values between 0.0 and 1.0.

A final Python module combined these values by calculating the product of the fuzzy input layers to produce a site suitability map for each tree species. The advantage with this approach is that the input parameters from the site suitability characteristics can easily be reset and maps updated as new information becomes available.

Results

The site suitability maps developed for *Pinus radiata*, *Sequoia sempervirens*, *Cupressus lusitanica*, *Eucalyptus* (generic scenario), *Podocarpus totara* and *Leptospermum scoparium* are shown in Figure 1.

The results suggest that radiata pine can be planted across much of the Hawke's Bay region, but is especially suited in the northern areas and along the southern coastal areas. Overall, the map suggests higher altitude areas as not suitable, whereas total annual rainfall values are unsuitable along the inland coastal areas, and mean annual temperature reduces suitability across most elevated areas of Hawke's Bay.

Coast redwood has a similar spatial pattern to radiata pine for elevation and temperatures. However, rainfall values are more restrictive along the inland coastal region. Coast redwood has the additional limitation of salt intolerance, while exposure to wind can cause damage to plantations.

Cupressus lusitanica is mostly suitable at lower elevations in the northeastern regions of Hawke's Bay. Its patterns for elevation and temperatures are only subtly different visually from radiata pine and coast redwood, but rainfall is limiting in the south of the region.

Eucalyptus species may be most suited from the northern coastal regions and inland to reasonably elevated locations. The maps also suggest that this species could be grown along coastal Hawke's Bay, and in the south, although with a lower suitability compared to the northern regions. However, rainfall eliminates a substantial region in southern Hawke's Bay. Also, wind exposure and the number of days of ground frost restrict a substantial part of the elevated regions of Hawke's Bay.

Elevation, total annual rainfall, mean annual temperature, the number of rain days in December and January, temperature in December and January, and the influence of aspect all play substantial roles in mānuka site suitability. Mānuka for honey tends to be most suitable in the warmer parts of the region. Mānuka site suitability is as much about the bees' ability to forage for nectar, as it is for mānuka to grow and produce flowers that are not affected by weather conditions.

A substantial part of the Hawke's Bay region is suitable for the establishment of tōtara. We have used tōtara as an example to demonstrate the connection between the characteristic response curves and the spatial information developed from them to represent site suitability spatially. Figure 2 illustrates the effect of elevation, total annual rainfall, and mean annual temperature for the site suitability of tōtara. Elevation is important, with sites over 500 m elevation considered unsuitable. Mean annual temperature also limited site suitability for tōtara, with values less than 9.8°C considered unsuitable. Total annual rainfall was also important, with sites between 1, 000 mm and 1,200 mm considered optimal for tōtarasite suitability, and those with less than 750 mm rainfall unsuitable. Rainfall values above 1,200 mm also reduce site suitability.

Discussion

Response curves and fuzzy membership have been used to develop tree species site suitability maps

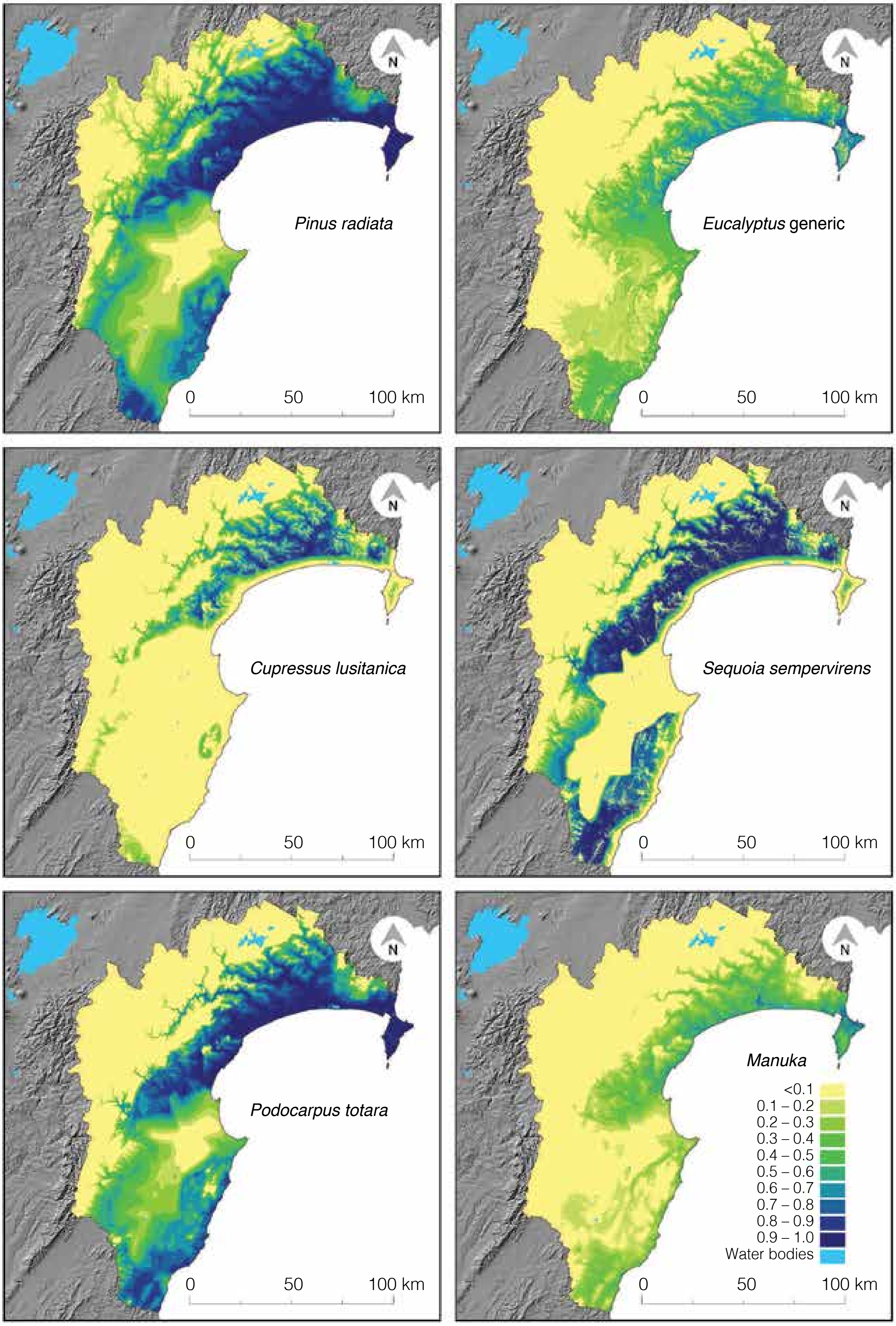

Figure 1: Tree species site suitability for *Pinus radiata*, *Eucalyptus* spp, *Cupressus lusitanica*, *Sequoia sempervirens*, *Podocarpus totara* and *Leptospermum scoparium*. The scale is applicable to all maps and shows site suitability from unsuitable (<0.1) to optimal (1.0)

for radiata pine, coast redwood, *Cupressus lusitanica*, a *Eucalyptus* generic scenario, tōtara and mānuka. This approach not only gives us a useful prediction of where a species can be planted, survive, and grow from low to high productivities (i.e. low to high suitability), but also provides an estimation of suitability between species. The modelling framework is dynamic and can be easily updated as the thinking changes around what constitutes tree species characteristics that affect site suitability. The tree species site suitability maps can also be redeveloped as new information becomes available. This includes, for example, the collection of more observations to represent the full environmental regimes of potential growth sites for different tree species.

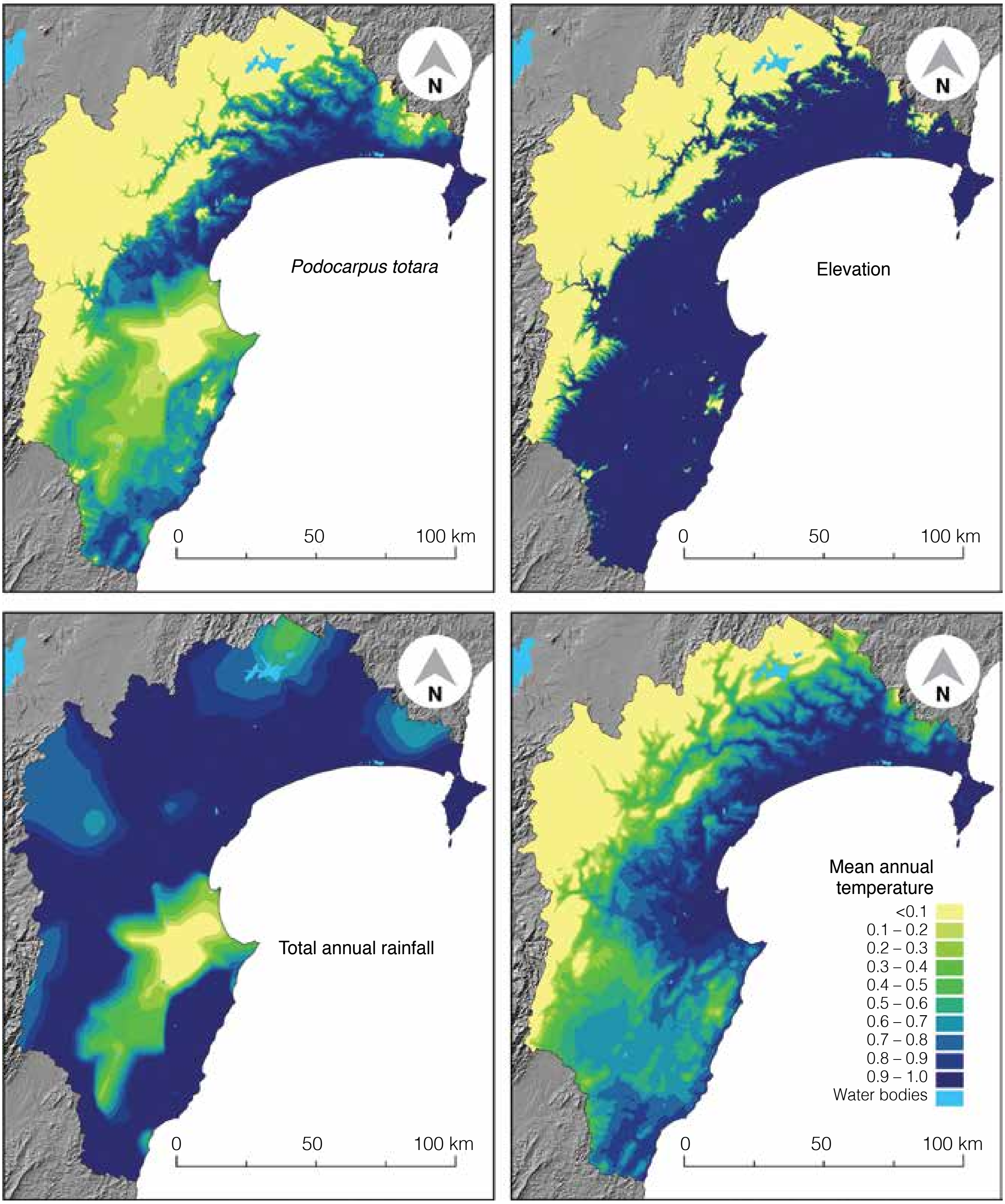

Figure 2: *Podocarpus totara* site suitability characteristic maps for elevation, total annual rainfall, and mean annual temperature across Hawke's Bay. The scale is applicable to all maps and shows site suitability from unsuitable (<0.1) to optimal (1.0)

The fuzzy membership approach assumes we have selected the best upper and lower limits, and the optimal response curve to represent each of the tree species. By choosing limits that are logical, and applying these consistently across all the tree species characteristics, we hope to have provided a level playing field across all the tree species we have modelled.

Productivity and/or a site index could be added to the modelling system in the future. They were not included in this work as values were not available for all species considered in this project and their use may have introduced bias. Further, productivity encompasses many of the characteristics used in the current modelling, and the national spatial datasets used in the development of productivity surfaces are from the same sources and have similar uncertainties.

Looking at the radiata pine productivity (standing volume) or site index (tree height) (Palmer et al., 2009) across Hawke's Bay, radiata pine is reasonably tolerant of high elevation and cooler sites compared to *S. sempervirens* (Palmer et al., 2012) and *C. lusitanica* (Watt et al., 2009), which is very similar to the site suitability maps developed. Also, in keeping with site suitability maps, radiata pine volume and tree height are substantially higher in the northern regions and along the coastal Hawke's Bay regions.

Making comparisons between species at a given location should be approached with care. We believe that separating the data into unsuitable, poor, medium, high and optimal would provide a practical (coarse) interval of comparison. In reality, there is currently no method of validating these results except by expert knowledge. Even with expert knowledge, we seldom find an abundance of tree species growing across the region, let alone a range of species planted at the same locations. From this perspective, using empirical data from PSP locations across New Zealand provides insights that are not otherwise available.

Conclusions

We have developed the tree species site suitability maps to provide a high-level view of where in the landscape a species could be established and grow. An estimate of site suitability, where a tree species finds site characteristics unsuitable (zero) through to optimal (one) across the landscape, can be modelled using fuzzy logic. The site suitability maps are dynamic and can be updated and improved as new information or knowledge becomes available.

Elevation, rainfall and temperature are the main contributors across all the tree species site suitability maps developed here. Overall, the modelling suggests that radiata pine is the most versatile, closely followed by tōtara, albeit at lower elevations. Coast redwood and cypress species are more suited to lower elevations, with redwoods more suited to the southern regions of Hawke's Bay. Neither species are suited to coastal regions due to intolerance to sea spray. The *Eucalyptus* generic scenario and mānuka occupy similar environmental envelopes and site characteristics.

Most species could be grown on highly erosion-prone sites. However, site fertility will be a major consideration for many of the species. In using these broad-level tree species site suitability data, it would be useful to consider each of the characteristic layers independently, to highlight limitations and optimal conditions.

Our tree species site suitability maps provide information across productive agriculture areas where trees are unlikely to be established because of the high cost of land. Conversely, information is provided on areas were the landscapes are eroded, with skeletal soils that would suit the establishment of trees. In these marginal land areas the retirement of the land for reducing erosion and gaining other ecosystem services benefits would be beneficial.

The information provided here can help stakeholders in the decision-making process around the establishment of trees. The next stage of the process would be to engage a forest specialist who can walk across the landscape and assess the terrain, and its climate, and provide the fine-level detail that is required for the establishment and management of trees. It is hoped this work will encourage discussion and conversation about the right species in the right place in the landscape.

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David Palmer is a Spatial Scientist and Les Dowling is a Research Scientist at Scion based in Rotorua. Andrew Clarke is Consulting Manager and Kit Richards is Environment Manager at PF Olsen Limited in Rotorua. Tim Payn is a Principal Scientist at Scion and Professor of Sustainable Forestry at the Toi Ohomai Institute of Technology in Rotorua. James Powrie is Project Manager at RedAxe Forestry Intelligence in Napier. Corresponding author: david.palmer@scionresearch.com