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Predicting the severity of Cyclaneusma needle cast on *Pinus radiata* under future climate in New Zealand

Michael S. Watt[1,*], David J. Palmer[2], Lindsay S. Bulman[2], Duncan Harrison[2]

[1] Scion, PO Box 29237, Fendalton, Christchurch, New Zealand

[2] Scion, PO Box 3020, Rotorua, New Zealand

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*corresponding author: michael.watt@scionresearch.com

Abstract

Cyclaneusma needle cast is a very damaging foliar disease of *Pinus* species. It is particularly widespread and detrimental to the growth of planted forests in New Zealand. The influence of climate change on the spatial distribution of disease severity (S_{sev}) would provide forest managers with insight into where to deploy disease resistance planting stock in the future. Here we use an existing model of Cyclaneusma needle cast severity, developed from an extensive dataset, to spatially predict disease severity under current and future climate to 2040 and 2090.

Spatial predictions of S_{sev} under current climate varied widely throughout New Zealand. Values of S_{sev} were highest in moderately warm, wet and humid high elevation environments located in the central North Island. In contrast, relatively low values of S_{sev} were predicted in drier eastern and southern regions of New Zealand.

Projections within the North Island show relatively little change in S_{sev} from current climate over the short term and low to moderate reductions in S_{sev} within most areas over the long term. In contrast, within the South Island, S_{sev} was predicted to markedly increase over both projection periods, with more pronounced increases in S_{sev} projected by 2090. Surfaces presented here are a critical element of decision support systems that describe how climate change is likely to influence plantation productivity and vulnerability to abiotic and biotic risk factors.

Keywords: biosecurity; climate change; Cyclaneusma; disease risk assessment; disease severity; invasive species.

Introduction

Cyclaneusma needle cast is a damaging disease of *Pinus* species (Millar & Minter, 1980) caused by the pathogens *Cyclaneusma minus* (Butin) DiCosmo, Peredo & Minter and *Cyclaneusma niveum* (Pers.) DiCosmo, Peredo & Minter. The disease is present on all continents where *Pinus* spp. are grown and is characterised by yellow and brown mottling of needles that are prematurely cast (Gadgil, 1984; Stahl, 1966).

Cyclaneusma needle cast is particularly problematic within planted pine forests where significant economic losses have been recorded. The highly susceptible species *Pinus radiata* (Gadgil, 1984) is the most commonly planted species in the southern hemisphere (Lewis & Ferguson, 1993) and also comprises 90% of an economically important planted forest resource (1.7 million ha) in New Zealand (New Zealand Forest Owners Association, 2010).

A recently developed model of Cyclaneusma needle cast for New Zealand has shown that air temperature has a strong influence on the spatial distribution of the disease (Watt et al., 2012). This model was developed from an extensive national dataset and showed disease

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severity to be sensitive to mean winter air temperature, elevation, mean relative humidity during July and stand age. Analyses showed disease severity increased to a maximum at mean winter air temperatures of between 7 and 9 °C before declining. Relationships between disease severity and all other variables were linear and positive.

Given the responsiveness of the pathogen to variation in air temperature, climate change is likely to have a marked effect on disease severity and host productivity. As pathogens have shorter generation times than trees, their populations can be expected to respond more rapidly to climate change. Consequently, over the rotation interval of a forest Cyclaneusma needle cast has the potential to cause significant growth reduction in a plantation that may have been only marginally at risk at the time of establishment. The development of models that account for this variation in impact over the course of a crop life is critical for making informed decisions on where to deploy disease resistant *Pinus radiata* under increasingly rapid rates of climate change.

Using the previously developed model to spatially predict disease severity the objective of this study was to compare disease severity under current and future climate within New Zealand. Projections of disease under future climate within New Zealand were developed using a comprehensive set of 36 (12 Global Climate Models x 3 emission scenarios) climate change scenarios for both 2040 and 2090.

Methods

Severity dataset

Data from aerial and ground surveys of disease severity carried out between 1972 and 2006 were included in the analyses. Cyclaneusma needle cast symptoms of yellowing foliage over much of the crown in spring are unique and easily differentiated from other pine foliage diseases that are apparent at that time of year, even from the air. In total, there were 9855 records of disease from plantations across New Zealand. For each record, the proportion of trees in the stand (scale 0 to 1) affected by the disease (S_{inc}) and the severity of the infection for those affected trees (A_{sev}) (0 to 1) was estimated. Infection severity was assessed as the proportion of tree crown, in 0.05 steps, that was showing symptoms typical of the disease. The product of these measurements (S_{inc} x A_{sev}) was used to determine the severity of Cyclaneusma needle cast for each record (S_{sev}, scale 0 to 1). For each observation, location was recorded as well as the age of the stand from which the estimate was being made. To spatially consolidate the data, the 9855 records were averaged to a 5 km^2 resolution. This averaging was undertaken so that measurements of S_{sev} included a number of temporally dispersed observations. The advantage of doing this was that averaged measurements were more closely aligned to long-term average meteorological data used to model disease severity. After undertaking this averaging, 387 estimates of S_{sev} were available for the modelling. These data covered a wide environmental range and were located within almost all areas in which the current *Pinus radiata* plantation resource occurs (Figure 1). Long-term meteorological averages were used rather than meteorological data collected at the time disease severity was recorded. The former approach was used as (i) historic yearly estimates of all meteorological variables are not available by site, and (ii) changes in air temperature within sites over the years 1972 – 2006 are quite low compared to the changes between sites across New Zealand and predicted future changes.

Meteorological data

Mean monthly meteorological data from the National Institute of Water and Atmospheric Research Ltd. (NIWA) were used in this study to develop a predictive

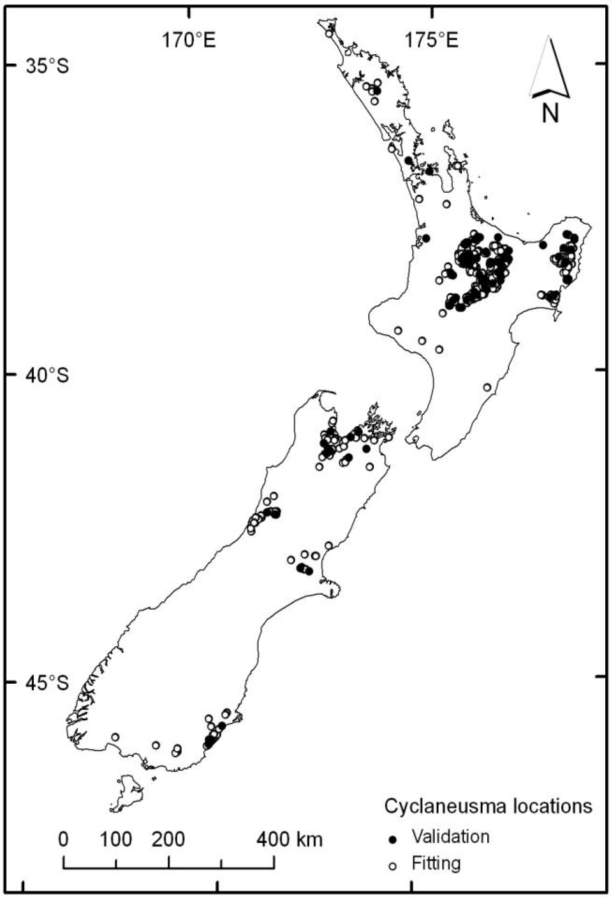

FIGURE 1: New Zealand map showing the location of the Cyclaneusma needle cast severity data used for the fitting (open circles) and validation (filled circles) of the model. Reproduced from Watt et al. (2012).

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model of S_{sev}. Data were interpolated for the whole of New Zealand on a 500 m^2 grid, using a thin-plate smoothing spline to spatially interpolate the data. This surface was derived from data collected over a 30-year period from 1971 – 2000 (mean time of 1985).

Analyses

A previously described model (Watt et al., 2012) was used to describe S_{sev} under future climate. A brief summary of this model follows. In total 80% of the 387 available observations were used for model development while the remaining 20% (n = 77 randomly selected observations) were withheld for model validation. The final model of disease severity was developed from transformed values of stand severity [tS_{sev} = ln (S_{sev} + 1)] using the regression kriging approach, that is fully described in Watt et al. (2012). The predictive variables included mean winter air temperature (T_{win}), mean July relative humidity (RH_{July}), elevation (E) and stand age (A) in the following formula:

$$tS_{sev} = \beta_0 + \beta_1 T_{win} + \beta_2 T_{win}^2 + \beta_3 E + \beta_4 RH_{July} + \beta_5 A \quad [1]$$

where β_0 to β_5 represent empirically fitted parameters. Parameter values and summary statistics for the model are described in Table 1. Spatial covariance in the dataset was found to be highly significant (P< 0.001). After testing a wide range of structures this covariance was found to be best represented using an isotropic spatial covariance structure. Estimated covariance parameters within this structure for the partial sill, range and nugget were 0.0014, 29 km and 6.7 x 10^{-4}. The sill, which represents the sum of the partial sill and nugget was 0.002. The effective range, the distance at which the spatial auto-correlation in the dataset declined to less than 0.05, was determined as 3 x range = 87 km. For distances greater than or equal to the range (87 km), spatial correlation between observations was effectively zero. The final model with spatial covariance accounted for 72.8% of the variance in the validation data.

Model projections

Spatial projections of S_{sev} were developed from the described model under current and future climate using 36 described climate change scenarios for both 2040 and 2090. Climate change projections used in this study were derived from the factorial combination of 12 Global Climate Models (GCMs) and the B1 (low), A1B (mid-range) and A2 (high) emission scenarios, that have been fully described, previously (Ministry for the Environment, 2008). The 12 GCMs used in this study, which cover the expected range in climate change for New Zealand, are abbreviated to: CNRM, CCCma, CSIRO Mk3, GFDL CM 2.0, GFDL CM 2.1, MIROC32, ECHOG, ECHAM5, MRI, NCAR, UKMO-HadCM3 and UKMO-HadGEM1. Temperature was statistically downscaled for each GCM to a resolution of 0.05 degree (~5 km) for two future periods 2030 – 2049 (midpoint reference year = 2040) and 2080 – 2099 (midpoint reference year = 2090). Summary statistics describing projected future changes in air temperature are shown in Table 2.

Compared to current climate, predicted changes in mean S_{sev} under climate change were very different between the North and South Island. Consequently, mean values of S_{sev} for the 36 climate change scenarios are displayed by island. The two GCMs representing the extremes were determined as those with the lowest and highest average absolute changes in S_{sev} from current climate, for New Zealand. Projections of S_{sev} for these extreme climate change scenarios are displayed with current climate, for both projection periods.

Results

Model projections under current climate

As previously reported (Watt et al., 2012), spatial projections developed using the regression model at a constant age of 16 years (mean age in the fitting dataset) clearly highlight the importance of

TABLE 1: Summary of statistics for the regression model of Cyclaneusma needle cast severity. All statistics relate to the log-transformed dependent variable (i.e. tS_{sev}), which represents a natural log transformation of S_{sev} determined as tS_{sev} = ln (S_{sev}+1). For the significance category, the F values and P categories from an F-test are shown with asterisks *** representing significance at P < 0.001.

Parameter	Value	Variable	Units	Significance
β_0	-0.7306	Intercept		
β_1	0.08144	Mean winter air temperature (T_{win})	°C	30.9***
β_2	-0.00481	T_{win}^2		24.2***
β_3	1.60 x 10^{-4}	Elevation	m	42.8***
β_4	4.259 x 10^{-3}	Mean relative humidity during July	%	9.1***
β_5	3.326 x 10^{-3}	Stand age	years	30.5***

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environment on S_{sev}. Values of S_{sev} were highest in moderately warm and relatively wet regions, with high relative humidity, in the central North Island (Figure 2A). Reductions in S_{sev} occurred in warm temperate northern regions of the North Island as air temperature increased beyond the optimum. S_{sev} was relatively low in moderately warm but drier eastern regions and in cooler dry southern areas of the North Island (Figure 2A). Average S_{sev} within the North Island was 0.064.

TABLE 2: Summary of changes in air temperature under the three climate change scenarios, in relation to current climate.

Year	Emission scenario	Temperature change (°C)[1]		
		Mean	**Min.**	**Max.**
2040	B1	0.53	0.24	0.91
	A1B	0.69	0.27	1.09
	A2	0.69	-0.08	0.96
2090	B1	1.21	0.44	2.16
	A1B	1.89	0.84	2.97
	A2	2.46	1.31	3.14

[1] Values shown give the mean New Zealand change pooled across the 12 Global Climate Models (GCMs), within each emission scenario. Min. and Max. represent the lowest and highest mean New Zealand change from all of the 12 GCMs respectively.

Compared to the North Island, the mean S_{sev} within the South Island of 0.021 was markedly lower (Figure 2A). However, there was wide spatial variation that was particularly marked from west to east as the main axial ranges (Southern Alps) have a substantial influence on rainfall distribution and relative humidity. In regions west of the Southern Alps, where relative humidity is high and temperatures are moderate, values of S_{sev} ranged from 0.05 to 0.1. In contrast, east of the main divide, where conditions are drier and relative humidity is low, S_{sev} was lower than 0.05 in most areas (Figure 2A).

Projections under climate change

Changes in S_{sev} from current climate projected to 2040 ranged widely between the North and South Island. Within the North Island there was a slight increase in S_{sev} but this was limited to a maximum gain of 2.5% (S_{sev} = 0.0651 *vs*. 0.0635) across the 36 scenarios (Figure 3A). In contrast, increases in the South Island averaged 75% (S_{sev} = 0.0380 *vs*. 0.0217) (Figure 3B), with the greatest increases of 121% (S_{sev} = 0.0480 *vs*. 0.0217) occurring under the UKMO HadGEM1 model coupled with the A1B emission scenario (see Figure 2C for spatial variation in S_{sev} under this scenario).

Compared to current climate, changes in S_{sev} were more marked by 2090. Within the North Island there were in general slight reductions in S_{sev} that averaged 7% (S_{sev} = 0.0592 *vs*. 0.0635) (Figure 3C). Despite these overall reductions, there was a considerable increase in S_{sev} within the central North Island (Figures 2E & 2F). More marked overall changes were noted within the South Island, with S_{sev} increasing by on average 162% (S_{sev} = 0.0569 *vs*. 0.0217) (Figure 3D), with maximum increases of 214% (S_{sev} = 0.0681 *vs*. 0.0217) noted for the UKMO HadGEM1 model using the A2 emission scenario. Predicted gains in severity were similar for the UKMO HadGEM1 model when combined with the A1B emission scenario. Under this scenario increases in S_{sev} occurred in almost all regions of the South Island and were particularly marked in high elevation regions (Figure 2F).

Discussion

Cyclaneusma needle cast is a very damaging disease of *Pinus radiata* within New Zealand, where it is widely distributed. Volume losses have been shown to scale linearly with disease severity, reaching mean volume increment reductions of ca. 60% at disease severities of 80% (van der Pas et al., 1984). Although fungicides do provide some control of the disease it is not economic to use these chemicals to treat the disease on a commercial basis (Vanner, 1986). Tree breeding has resulted in improvements in disease resistance in younger stands through development of a *Pinus radiata* provenance with high needle retention. Given the difficulty in controlling the disease, it is important to understand how climate change is likely to influence spatial variation in disease severity. Such knowledge could influence the deployment of resistant trees in the future.

Spatial projections of future disease severity to 2090 were found to vary widely between both the GCMs and emission scenarios. When interpreting the results, it is worthwhile considering the findings of Rahmstorf et al. (2007) who showed that recent trends in recorded climate change and sea level rise are effectively beyond the upper end of the emission scenarios considered by the International Panel on Climate Change (IPCC). Therefore, the GCMs that project moderate to high temperature increases, and scenarios that project moderate (A1B) to high (A2) emissions should be given more weight as indicators of future climatic conditions.

Results suggest changes in disease severity, from those noted under current climate, are likely to be far more marked within the South Island than the North Island. Over the short term little change in S_{sev} is noted within the North Island while only minor reductions occur over the long term to 2090 as most of the North Island remains close to or slightly above the optimum air temperature for the disease. In contrast,

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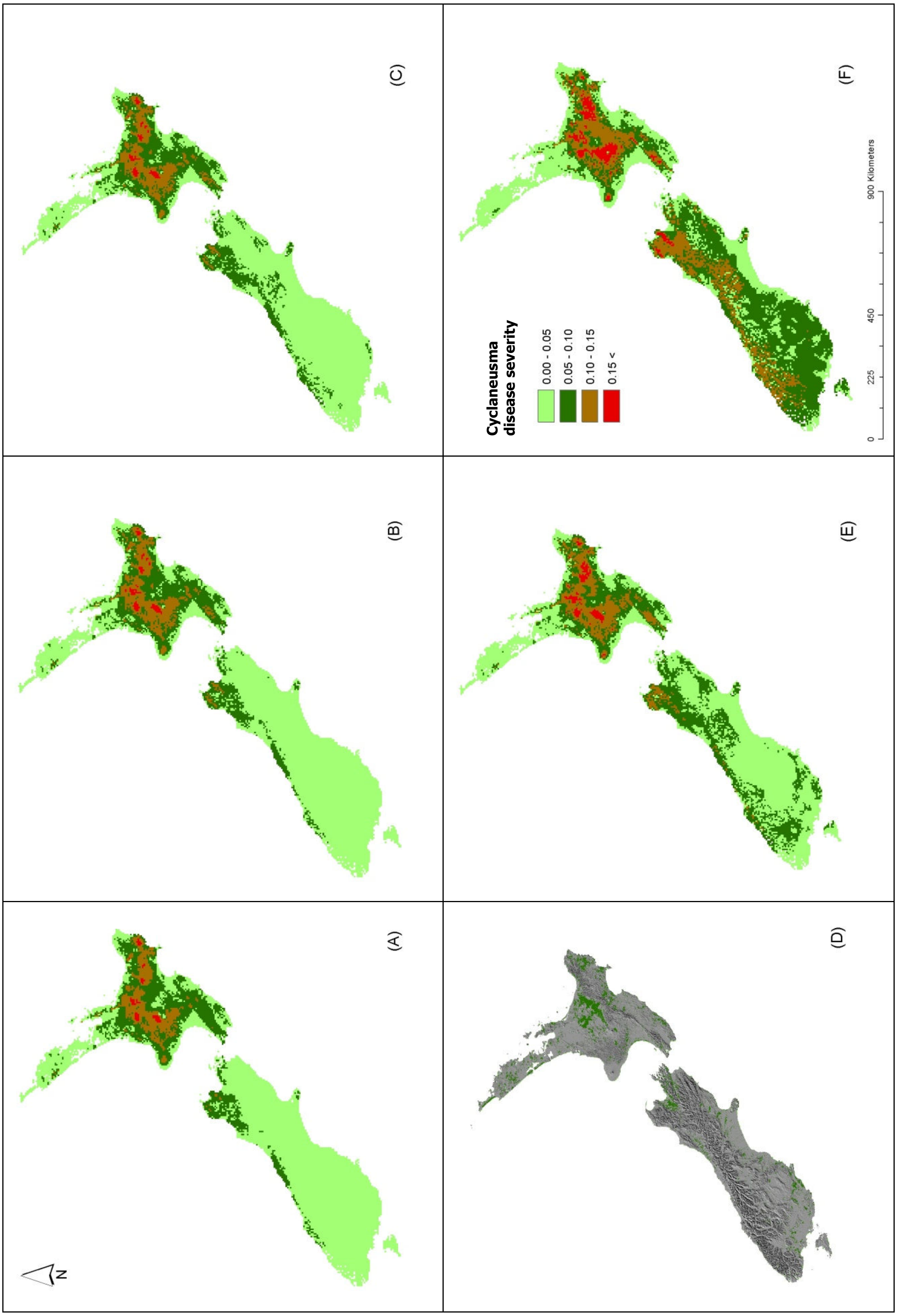

FIGURE 2: Variation in disease severity under current climate (A), and future climate during 2040 projected by scenarios representing extreme changes in stand severity, S_{sev}. These are for 2040 (B) ECHAM5 under A2 (least change in S_{sev}) and (C) UKMO HADGEM1 under A1B (greatest change in S_{sev}), and during 2090 projected by (E) CSIRO Mk3 under B1 (least change in S_{sev}), and (F) UKMO HADGEM1 under A1B (greatest change in S_{sev}). Also shown are the locations of New Zealand *Pinus radiata* plantations in panel (D).

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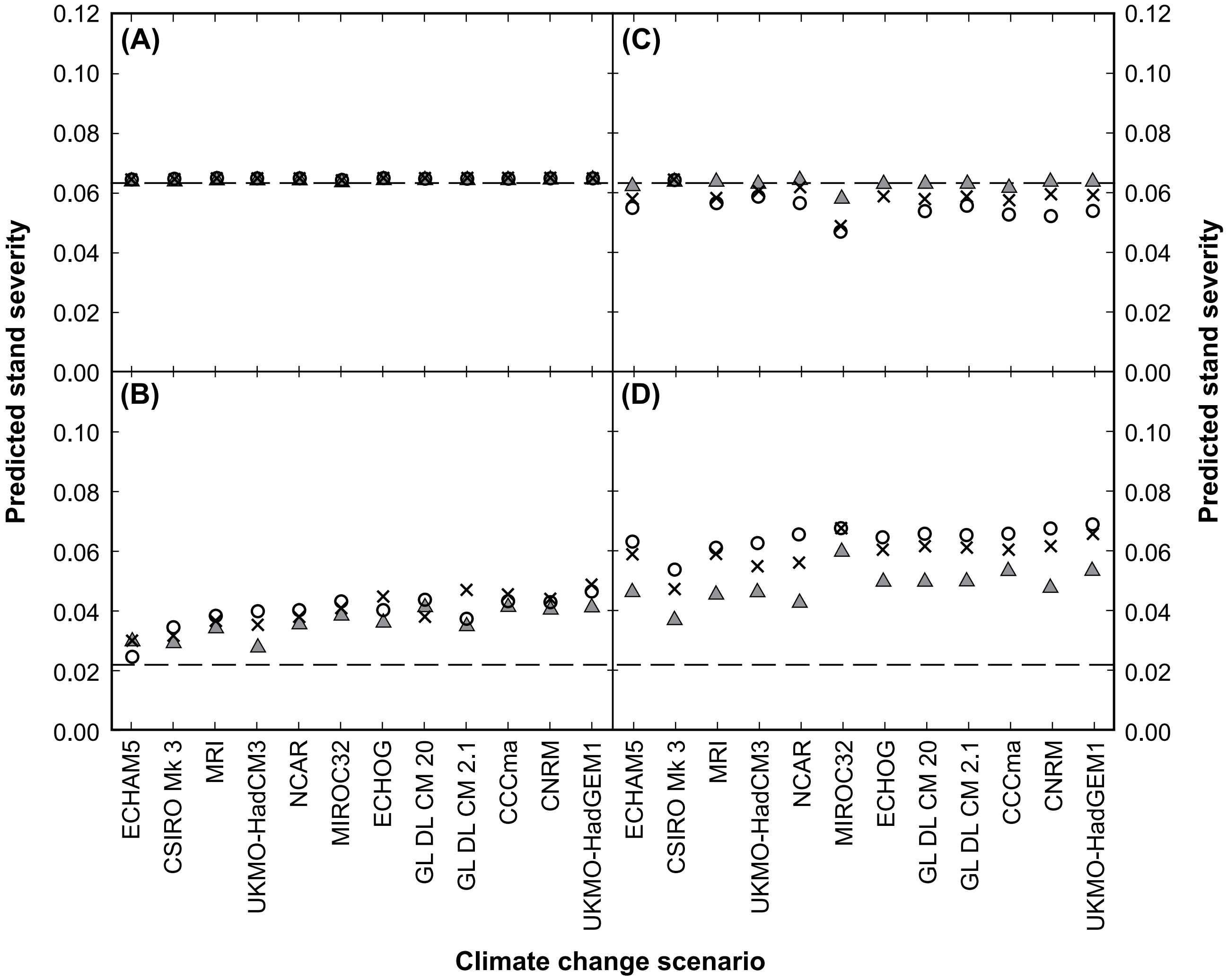

FIGURE 3: Variation in mean predicted stand severity for New Zealand under 12 models using the B1 (triangles), A1B (crosses) and A2 (open circles) emission scenarios, projected to 2040 within the (A) North Island and (B) South Island and to 2090 within the (C) North Island and (D) South Island. The mean predicted stand severity under current climate, by island, is shown on both figures as a dashed line. Scenarios are sorted in ascending order of mean stand severity, after averaging across New Zealand for both time periods.

increases in S_{sev}, from values noted under current climate, are quite pronounced within the South Island reaching mean S_{sev} for the most extreme scenario of 0.0681. This occurs as the currently sub-optimal air temperature for the disease within most of the South Island shifts upwards under climate change towards the optimum air temperature. To place this in context the mean predicted S_{sev} during 2090 in the South Island is broadly equivalent to mean S_{sev} within the North Island under current climate (S_{sev} = 0.0569 vs. 0.0635).

Areas currently most affected by the disease are located in central (central North Island) and north-eastern regions (East Cape) of the North Island. Although changes in S_{sev} within the North Island are not overall as marked as the South Island, it is worth noting that S_{sev} does increase within the central North Island over the long term (2090), particularly under the most extreme scenario (Figure 2F). Within north-eastern regions, little change in S_{sev} from current climate is noted under climate change (Figure 2).

Threshold and optimum temperature requirements for other needle diseases such as Dothistroma needle blight have been determined experimentally (Gadgil, 1974, 1977; Gilmour, 1981; Peterson, 1973). However, there has been little experimental research describing how air temperature regulates infection and disease development for Cyclaneusma needle cast. Despite this, previous research does broadly agree with model predictions. The main infection period for *Cyclaneusma* is autumn and winter and Gadgil (1984) suggested wet and mild conditions with temperatures above 10 °C were conducive to disease development. Further research should be undertaken to more accurately characterise the pathogen response to air temperature.

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It is possible that *Cyclaneusma* spp. may adapt to climate change but there is little historical evidence of this occurring. *Cyclaneusma* spp. reproduce sexually and have been present in New Zealand for a long time. Introduction of the pathogen probably occurred with the first *Pinus radiata* importations in the 19th century. Since then, adaptation has not been observed. For instance, the pathogen has not become more damaging in parts of New Zealand that have remained cool and/or dry.

There are potential alternative species to *Pinus radiata* with relatively good growth rates that do not currently suffer from serious diseases. However, decisions around species selection should be based on a broad set of criteria that, in addition to susceptibility to biotic and abiotic risk factors, include factors affecting profitability (e.g. growth rates, product value, and rotation length). Accounting for direct growth responses of plantation species to climate change is therefore likely to be at least as important as defining how biotic risk changes. Spatial models and decision support systems that integrate these complexities and appropriately weight risk factors should be developed to determine how climate change is likely to influence the future distribution of New Zealand plantation species. As *P. radiata* can be harvested within 30 years and most change is predicted to occur over the next 80 years, it may be prudent to defer decisions on species selection until more is known about the risk posed by climate change.

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