New Zealand Journal of Forestry Science

41 (2011) 207-215

www.scionresearch.com/nzjfs

Predicting the severity of Dothistroma needle blight on *Pinus radiata* under future climate in New Zealand

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

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

[2] *Scion, Private Bag, 3020, Rotorua, New Zealand*

(Received for publication 9 May 2011; accepted in revised form 1 November 2011)

*corresponding author: michael.watt@scionresearch.com

Abstract

Dothistroma needle blight is a very damaging foliar disease of *Pinus* species. An existing model for predicting spatial variation in Dothistroma needle blight severity was used to predict disease severity (S_{sev}) under current and future climate.

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

Changes in S_{sev} from current climate were predicted to be low to moderate under climates projected for 2040. However, over the longer term, to 2090, projected changes in S_{sev}, resulting from climate change, ranged from moderate to high. Over both projection periods, S_{sev} was predicted to decline in the North Island and increase within the South Island. Surfaces such as those presented here are a critical element for decision support systems that provide information on site suitability for plantation species under increasing rates of global warming.

Keywords: biosecurity; climate change; disease risk assessment; disease severity; *Dothistroma septosporum*; invasive species; red band needle blight; spatial modelling.

Introduction

Climate has long been recognised as an important environmental determinant in the distribution of pathogens and development of disease (De Wolf & Isard, 2007; Hepting, 1963; Wallin & Waggoner, 1950). This is particularly the case for plant pathogens, where air temperature has been shown to influence their growth and cold season survival, while rainfall can strongly affect their ability to disperse and infect their hosts (Coakley et al., 1999; De Wolf & Isard, 2007). Process-based niche models, such as CLIMEX^{TM}, have utilised the relationship between climate and disease presence to project potential distribution of a wide range of invasive plant pathogens and disease (Desprez-Loustau et al., 2007; Ganley et al., 2009; Paul et al., 2005; Venette & Cohen, 2006; Watt et al., 2009). These projected disease distributions have predicted the likelihood that a disease could become established in a region but have not predicted disease severity. Despite the responsiveness of many diseases to climate, disease severity has been less widely predicted across broad spatial scales than potential distribution, although there are some notable exceptions (Watt, Palmer, & Bulman, 2011; Watt et al., 2010).

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

Dothistroma needle blight, also known as red band needle blight, is one of the most important foliar diseases of *Pinus* spp in the world (Barnes et al., 2004). According to the current phylogenetic understanding, the disease is caused by two distinct species of fungi, *Dothistroma septosporum* (Dorog.) Morelet and *Dothistroma pini* Hulbary (Barnes et al., 2004). *Dothistroma* spp. are known to infect over 70 pine species (Bednárova et al., 2006) and under high infection pressure and favourable conditions also infects *Pseudotsuga menziesii* (Mirb.) Franco (Dubin & Walper, 1967), *Larix decidua* Mill (Bassett, 1969) and five species of *Picea* (Gadgil 1984; Jankovský et al., 2004; Lang, 1987; Neves et al., 1986).

Although Dothistroma needle blight occurs widely on host species in their native range, it is generally most damaging as an invasive disease in exotic pine plantations (Gibson, 1974), where it is capable of causing substantial growth loss (Bulman, 2006; Hocking & Etheridge, 1967; van der Pas, 1981). In the early 1960s, outbreaks of Dothistroma needle blight in *Pinus radiata* D.Don plantations were particularly severe in East Africa, New Zealand and Chile, which led to abandonment of planting *P. radiata* in East Africa (Gibson, 1974) and India (Mehrotra, 1997), and other susceptible pine species in North America (Gibson, 1974) and central USA (Peterson, 1967). In the late 1990s and early 2000s, outbreaks were recorded on *Pinus contorta* var. *latifolia* Dougl. ex Loud. in British Columbia, which is within its native range (Woods, 2003; Woods et al., 2005) and parts of Europe (Brown, 2005; Villebonne & Maugard, 1999).

Pinus radiata, a highly susceptible species (Bulman et al., 2004), comprises 90% of an economically important plantation forest resource (1.8 million ha) in New Zealand (New Zealand Forest Owners Association, 2010). Dothistroma needle blight was first observed in New Zealand during 1962 and spread through the majority of the country over the following decades (Bulman et al., 2004; Gilmour, 1967). Currently Dothistroma needle blight is controlled by spraying of copper oxides and use of silvicultural practices that promote airflow and remove susceptible individuals (e.g. thinning (Gadgil, 1970; Marks & Smith, 1987)), and reduce inoculum (e.g. pruning (Gadgil, 1970; van der Pas et al., 1984)).

Although *Dothistroma pini* does not occur in New Zealand the causal pathogen *D. septosporum* is present throughout New Zealand (Bulman et al., 2004). Projections of future distribution show almost the entire country remains suitable for *D. septosporum* under climate change to 2090 (Watt, Ganley, et al., 2011). Despite this, marked variation in disease severity has been reported under current climate as climate has a strong influence on disease infection rates and severity. Experimental research shows that rates of infection increase markedly as the environment becomes more warm and wet reaching a reported optimum at constant temperatures of between 16 and 20 °C when needles are continuously moist for 10 hours (Gadgil, 1974; Gilmour, 1981). Field observations concur with these observations. Disease severity has been found to be positively linked with summer rainfall in British Columbia (Woods et al., 2005) and New Zealand (Bulman, 2006).

A recently developed model of Dothistroma needle blight severity for New Zealand confirms these findings and integrates the effect of different climatic variables on severity into a single model (Watt, Palmer & Bulman, 2011). This model was developed from an extensive national dataset and showed disease severity to be sensitive to rainfall, relative humidity, air temperature and stand age. Analyses showed that optimum environmental conditions for Dothistroma needle blight were high late spring rainfall (> 150 mm month^{-1}), high relative humidity and a mean daily air temperature of 15.5 °C over late spring to mid autumn. Projections of disease severity from this model (without spatial covariance) accounted for 68% of the data in the validation dataset and agree with the observed severity pattern. Within New Zealand, highest severity is reached in wet regions with moderate to warm air temperatures while lowest severity occurs in dry areas or sub-tropical regions in the far north (Bulman et al., 2004) where air temperature exceeds the disease optimum.

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. Pathogens have shorter generation times than trees and so their populations can be expected to respond more rapidly to climate change. Consequently, over the rotation interval of a forest Dothistroma needle blight 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 site *Pinus radiata* under increasingly rapid rates of global warming.

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

Dothistroma needle blight incidence and severity data collected over a 45-year period from 1965 to 2010

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

(mean of 2000) were used in analyses. The percentage of the stand (scale = 0 to 100) affected by the disease (S_{inc}), and for those affected trees the severity (scale of 0 – 1) of the disease (A_{sev}) was estimated using the 5% step method (Bulman et al., 2004). This method was used throughout the assessment period. The stand level product of these measurements (S_{inc} x A_{sev}) was used to determine the severity of Dothistroma needle blight within the stand ($S_{sev,}$ scale = 0 – 100). For each estimate, location (easting, northing) was recorded and the stand age at which the assessment was made. The 10648 stand level observations of S_{sev} were averaged to a 25 km^2 resolution, resulting in a 169 mean estimates of S_{sev}. These data covered a wide environmental range and were located within almost all localities of the current *P. radiata* plantation resource (see Watt, Palmer, & Bulman, 2011 Figure 1 for distribution).

Meteorological data

Mean monthly meteorological data from National Institute of Water and Atmospheric Research Ltd. (NIWA) were used in this study. 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). Meteorological data include mean monthly total rainfall; mean wind speed; mean, minimum and maximum air temperature; and relative humidity. Following the procedure outlined in Watt, Palmer and Bulman (2011), these surfaces were updated to reflect current climate (defined as 2010).

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, UKMO-HadGEM1. Temperature and rainfall were statistically downscaled for each GCM to a resolution of 0.05 degree (~5 km) for two future periods 2030 – 2049 (midpoint reference year is 2040) and 2080 – 2099 (midpoint reference year is 2090). Because climate change projections are referenced to 1990, we subtracted the temperature change between 1990 and the current time (2010), from climate change surfaces before applying the climate change projections. Using a previously described rate of change in temperature over the last century of 0.009 °C year^{-1} (NIWA, 2010; Salinger, 1981) this scales to a temperature difference between 2010 and 1990 of 0.18 °C. Summary statistics describing projected future changes in air temperature and rainfall, relative to the baseline (2010), are shown in Table 1.

TABLE 1: Summary of changes in air temperature and rainfall under the climate change scenarios, in relation to current climate.

Year	Emission scenario	Temperature change (°C)			Rainfall change (%)		
		Mean	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
2040	B1	0.53	0.24	0.91	2.2	-9.3	11.7
	A1B	0.69	0.27	1.09	-0.3	7.5	11.6
	A2	0.69	-0.08	0.96	-0.7	-5.7	7.6
2090	B1	1.21	0.44	2.16	0.1	-9.7	11.5
	A1B	1.89	0.84	2.97	-2.6	-18.1	14.1
	A2	2.46	1.31	3.14	1.0	-17.0	14.9

Values shown give the mean New Zealand change pooled across the 12 Global Climate Models (GCMs), within each emission scenario. The lowest and highest mean New Zealand change (in rainfall and temperature) from the 12 GCMs are represented by the Min. and Max.

Analyses

All analyses were undertaken using SAS (SAS-Institute-Inc., 2000). Current climate and stand age was linked to S_{sev} at the resolution of these surfaces and these data were then averaged to a 25 km^2 resolution for analyses. As described in Watt, Palmer and Bulman (2011), 20% of the 169 measurements available for modelling were randomly selected and withheld from the model fitting for later validation. S_{sev} was log transformed for the modelling [ln (S_{sev} + 1)] which corrected the non-normal distribution of residuals evident in later analyses.

The multiple regression model of S_{sev} outlined in Table 2 was developed from the fitting dataset by using the methods described fully in Watt, Palmer and Bulman (2011). We chose not to use a model with spatial covariance as it is unknown whether this spatial covariance will remain constant under climate change. Consequently, the precision of the multiple regression model used here (R^2 = 0.68) was slightly lower than that of the final model cited in Watt, Palmer and Bulman (2011) (R^2 = 0.72) that included spatial covariance for projections under current climate. The final regression model included stand age (A), mean total November rainfall (P_{Nov}), mean relative humidity from October to April ($RH_{Oct-Apr}$) and mean air temperature from November to April ($T_{Nov-Apr}$). All four variables were highly significant (Table 2). Diagnostics describing the model fit and partial response functions between all four variables and S_{sev} are described in detail in Watt, Palmer and Bulman (2011).

TABLE 2: Summary of statistics for the final predictive model of Dothistroma needle blight severity. Parameter values and variable partial R^2 (in brackets) and cumulative R^2 values are shown. For the significance category, the *F* values and *P* categories from an *F*-test, are shown, with asterisks *** representing respective significance at $P < 0.001$. Reproduced from Watt, Palmer and Bulman, (2011).

Equation: $\ln (S_{sev} + 1) = \alpha_1 + \alpha_2 A + \alpha_3 A^2 + \alpha_4(1-\exp(-\alpha_5 P)) + \alpha_6 T + \alpha_7 T^2 + \alpha_8(1-\exp(-\alpha_9 RH))$

Parameter	Value	Variable	Units	R^2	Significance
α_1	-14876.0				
α_2	0.22480	Stand age (A)	years	0.14 (0.14)	10.5***
α_3	-0.00940				
α_4	5.03981	November rainfall (*P*)	m	0.47 (0.33)	39.8***
α_5	0.03176				
α_6	3.36750	Mean air temp. Nov. - April (*T*)	°C	0.55 (0.08)	11.7***
α_7	-0.10847				
α_8	14846.9	Mean relative humidity at 9am Oct. - April (*RH*)	%	0.60 (0.05)	16.2***
α_9	0.13136				

Model projections

Spatial projections of S_{sev} were developed from the described model under current and future climate using the 36 described climate change scenarios for both 2040 and 2090. For these projections the stand age used in the model was held at a constant value of 9 years which was the mean value in the fitting dataset. As mean S_{sev} responds differentially between the North and South Island under climate change, mean values of S_{sev} for the 36 climate change scenarios were determined 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 under the A1B emission scenario are displayed with current climate, for both projection periods (Figure 1).

Results

Model projections under current climate

As previously reported (Watt, Palmer, & Bulman, 2011) spatial projections, developed using the regression model at a constant age of 9 years (mean age in the fitting dataset) clearly highlight the importance of environment on S_{sev} in the North Island. Values of S_{sev} were highest in moderately warm and relatively wet regions in the central North Island (Figure 1A). Reductions in S_{sev} occurred with decreasing latitudes in warm temperate northern regions of the North Island as air temperature increased and rainfall declined. S_{sev} was relatively low in moderately warm but drier eastern regions and in cooler dry southern areas of the North Island (Figure 1A). Average S_{sev} within the North Island was 10.9.

Compared to the North Island, the mean S_{sev} within the South Island of 4.3 was markedly lower (Figure 1A). However, there was wide spatial variation that was particularly marked from west to east as the main axial ranges have a substantial influence on rainfall distribution. In regions west of the main axial ranges, where rainfall exceeds 2000 mm, and temperatures are moderate, values of S_{sev} ranged from 14 to 20. In contrast, east of the main divide, where rainfall ranges from 500 to 1250 mm, S_{sev} was lower than 8 (Figure 1A). On the South Island east coast there was a gradual decline in S_{sev} from east to west, caused by reductions in air temperature that occurred with increasing altitude and proximity to the main axial ranges (Figure 1A).

Projections under climate change

Changes in S_{sev} from current climate were predicted to be low to moderate under projections during 2040 (Figures 2A & 2B), with S_{sev} values in the North Island declining on average by 10% (10.9 vs. 9.8) and increasing by an average of 31% in the South Island (5.6 vs. 4.3). Variation in S_{sev} was relatively low between emission scenarios (Figures 2A & 2B). Changes in S_{sev} from current climate for GCMs representing extremes, ranged widely from -1.8% (for MRI) to -25% (for MIROC 32) for the North Island and from 2% (for ECHAM 5) to 55% (NCAR) for the South Island (see Figures 1B & 1C for projections from contrasting GCMs under the AIB scenario).

Over the longer term, to 2090, projected reductions in foliage retention resulting from climate change, ranged from moderate to high (Figures 2C & 2D). Compared to current climate, mean S_{sev} were reduced by 18%, 31%, and 48%, respectively, under the B1, A1B and A2 emission scenarios for the North Island

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)

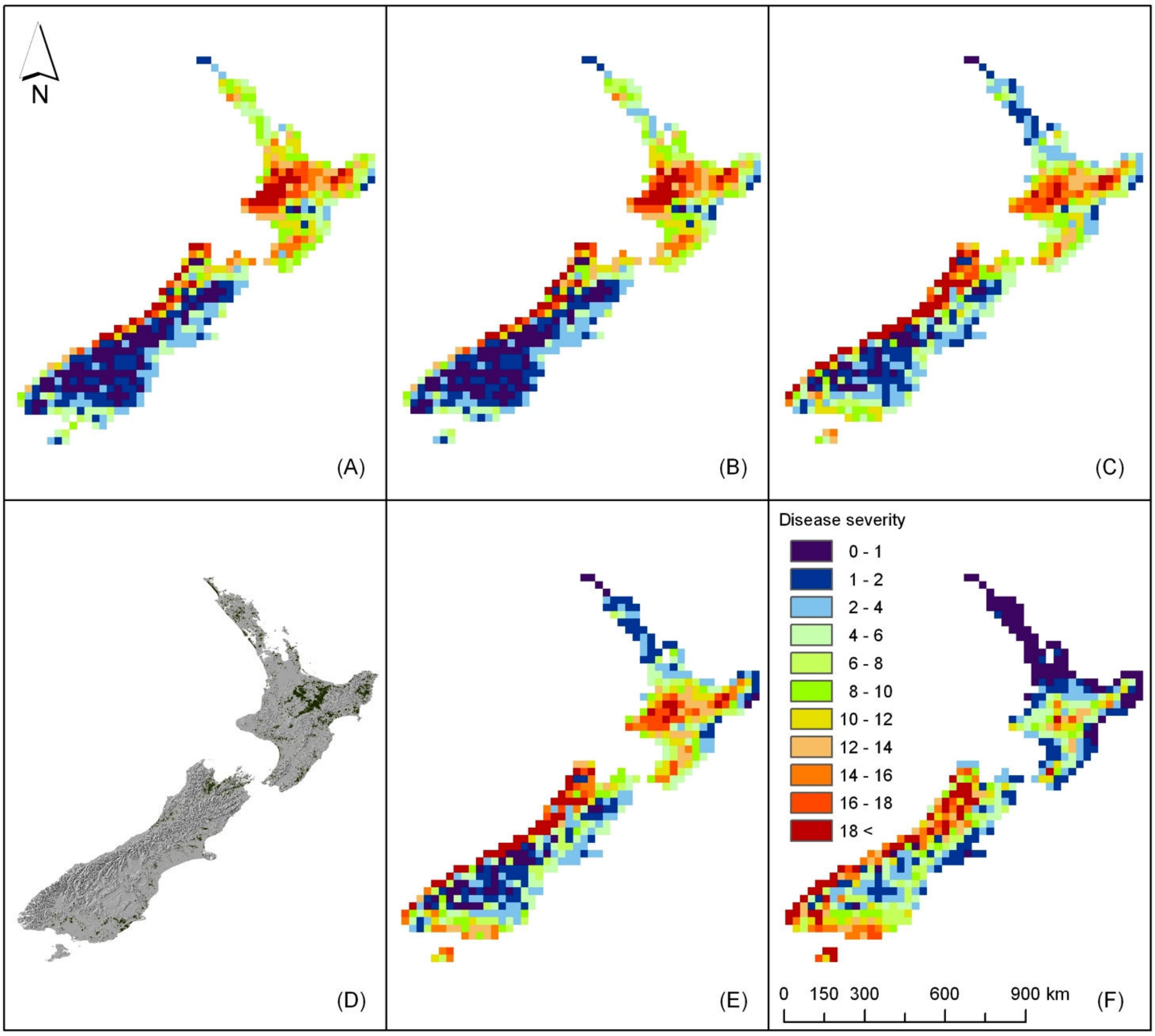

FIGURE 1: Variation in disease severity under current climate (A), and future climate during 2040 projected by scenarios representing extreme changes in stand severity, S_{sev}. These are: (B) ECHAM5 (least change in S_{sev}); and (C) NCAR (greatest change in S_{sev}), and during 2090 projected by: (E) UKMO-HadCM3 (least change in S_{sev}); and (F) MIROC 32 (greatest change in S_{sev}).

All GCMs presented use the moderate emission scenario, A1B.

Also shown are the location of New Zealand *Pinus radiata* plantations in panel (D).

(Figure 2C). Conversely, S_{sev} increased, on average, by 50%, 67%, and 92%, respectively, under the B1, A1B and A2 emission scenarios for the South Island (Figure 2D). Similarly, there was wide variation in changes in S_{sev} between the 12 GCMs. Changes in S_{sev} ranged from -17% (for CNRM) to -61% (for MIROC 32) for the North Island and from 46% (for UKMO-HadCM3) to 108% (MIROC32) for the South Island (see Figures 1E & 1F for contrasting GCMs under the AIB scenario). Compared to current climate, reductions in S_{sev} occurred throughout most of the North Island in the future, with the most marked reductions occurring in coastal and northern regions (Figures 1E & 1F). In contrast, with the exception of the northern areas, increases in S_{sev} were projected within most South Island regions, with gains most pronounced in southern regions (Figures 1E & 1F).

Discussion

Dothistroma needle blight is one of the most damaging diseases of *Pinus radiata* within New Zealand. Volume loss has been shown to scale linearly with average disease level. For instance, over a seven-year period trees with a 50% infection rate had a 50% volume growth loss, compared to trees with little infection (van der Pas, 1981). In many east coast and southern regions that have low disease severity no treatment is required, while repeated treatments are required in areas with high disease severity. From 2005 to 2010, over 90% of the area sprayed for Dothistroma needle blight control was located in the central North Island (see Figure 1D for location of these forests) with the remainder being treated within the northern and western regions of the South Island (Nelson and

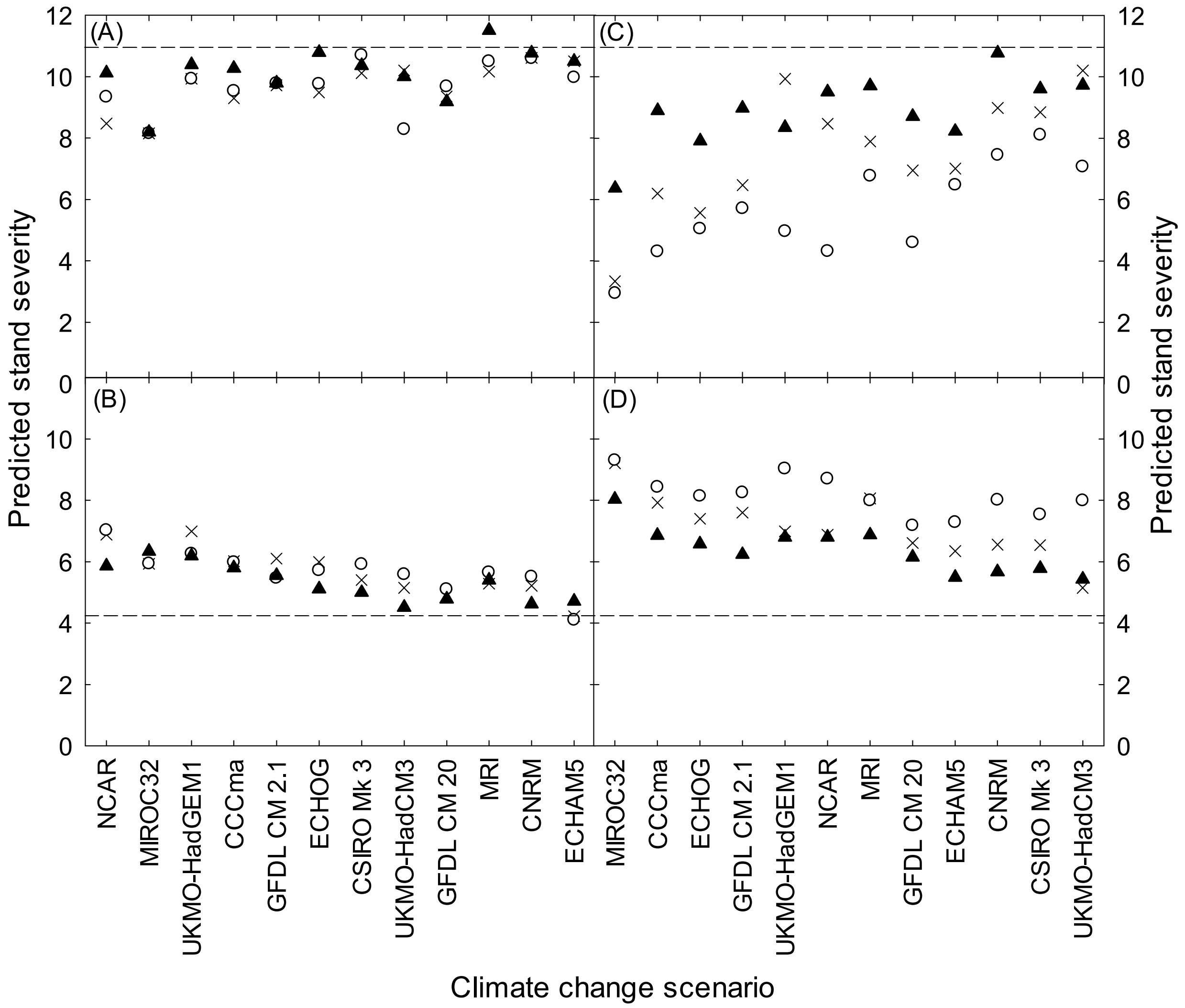

FIGURE 2: Variation in mean predicted foliage retention for New Zealand under 12 models using the B1 (triangles), A1B (crosses) and A2 (open circles) emission scenarios, projected to 2040 within the (A) North Island and (B) South Island and to 2090 within the (C) North Island and (D) South Island.

The mean predicted foliage retention under current climate is shown on both figures as a dashed line.

Scenarios are sorted in descending order of mean stand severity, averaged across New Zealand for both 2040 and 2090.

Westland). Forests located on the west and east coasts of the North Island are treated occasionally (Bulman, L., unpub. data).

Spatial projections of regional variation in disease severity under current climate presented both here and in Watt, Palmer and Bulman (2011) are consistent with previous empirical observations describing regional variation in severity (Bulman et al., 2004). For example, in the North Island, infection levels tend to be low in Northland and along the east coast (Hawke's Bay and Wairarapa), whereas the central North Island, Waikato and Taranaki are the most severely affected regions. In the South Island, both modelled and empirical data indicate that infection is most severe west of the main axial ranges, with low infection levels generally found throughout the remainder of the South Island. Currently, the disease is particularly problematic to the forest industry as a large proportion (ca. 30%) of the *Pinus radiata* estate is located in the severely affected central North Island region (Figure 1D), where rainfall is high and air temperature is close to optimum for the pathogen.

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 also 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 Intergovernmental Panel on Climate Change. Therefore, the GCMs that project moderate to high temperature increases (e.g. MIROC32), and scenarios that project moderate (A1B) to high (A2) emissions should be given more weight as indicators of future climatic conditions.

Our results suggest that climate change is likely to have a significant effect on severity of Dothistroma needle blight over the long term. Projections of disease severity to 2040 show low to moderate change from projections under current climate, as air temperature is not forecast to increase substantially within New Zealand over the medium term. However, by 2090, reductions in disease severity are relatively marked within the North Island, particularly under the AIB and A2 emission scenarios, as air temperature surpasses the disease optimum in most regions. These reductions are particularly pronounced in the far north where increases in temperature make the environment largely unsuitable for the expression of the disease. In contrast, there are relatively substantial increases in disease severity within most of the South Island, particularly within relatively wet southern regions under the more extreme A2 scenarios. Under the most extreme climate change scenarios disease severity in the lower South Island is predicted to be broadly similar to that of the worst affected central North Island regions under current climate.

It is worth noting that within northern areas of the North Island projections of severity under climate change are extrapolated above the air temperature range used to construct the model. However, as both the raw data (not shown) and model show markedly lower disease severity within these regions under current climate we have a reasonable level of confidence in these low extrapolated values. In addition, the degree of extrapolation is relatively small (maximum of 2.46 °C), compared to the total range of mean annual air temperatures over which the model was developed (ca. 8 °C).

Although *Pinus radiata* has the highest general growth rate of plantation species cultivated in New Zealand, there are a number of potential alternative species with relatively good growth rates that are not currently subject to serious diseases (e.g. *Sequoia sempervirens* (D.Don) Endl.). Decisions around species selection are usually based on a relatively 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 likely to be at least as important as defining how biotic risk changes. For instance, in the central North Island disease severity of Dothistroma needle blight is projected to markedly reduce over the long term. However, as the temperature optimum for *P. radiata* growth closely matches that of disease severity these reductions in disease severity are likely to be accompanied by growth responses that are far lower than the substantial growth gains predicted throughout the South Island (Kirschbaum et al., in press). 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.

Acknowledgements

We thank the Ministry of Agriculture and Forestry (Contract No. C04X0901) for funding this research. The data were collected during forest health surveys funded from 1970 to 1987 by the New Zealand Forest Service and thereafter primarily by members of the New Zealand Forest Owners' Association.

References

Barnes, I., Crous, P. W., Wingfield, B. D., & Wingfield, M. J. (2004). Multigene phylogenies reveal that red band needle blight of *Pinus* is caused by two distinct species of Dothistroma, *D. septosporum* and *D. pini*. *Studies in Mycology, 50*, 551-565.

Bassett, C. (1969). *Larix decidua* a new host for *Dothistroma pini*. *Plant Disease Reporter, 53*, 706.

Bednárová, M., Palovcíková, D., & Jankovský, L. (2006). The host spectrum of Dothistroma needle blight *Mycosphaerella pini* E. Rostrup - new hosts of Dothistroma needle blight observed in the Czech Republic. *Journal of Forest Science, 52*(1), 30-36.

Brown, A. (2005). Seeing red! *Forestry & British Timber, 34*(7), 16-18.

Bulman, L. S. (2007). Foliar diseases of pine - the New Zealand experience. In M. B. Jackson (Comp.), *Proceedings of the 54th annual western international forest disease work conference, Smithers, BC, 2-6 October 2006,* (pp. 57-60). Missoula, MT, USA: US Department of Agriculture, Forest Service, Forest Health Protection.

Bulman, L. S., Gadgil, P. D., Kershaw, D. J., & Ray, J. W. (2004). *Assessment and control of Dothistroma needle-blight.* (Forest Research Bulletin No. 229). Rotorua, New Zealand: New Zealand Forest Research Institute Ltd.

Coakley, S. M., Scherm, H., & Chakraborty, S. (1999). Climate change and disease management. *Annual Review Phytopathology, 37*, 399-426.

De Wolf, E. D., & Isard, S. A. (2007). Disease cycle approach to plant disease prediction. *Annual Review of Phytopathology, 45*, 203-220.

Desprez-Loustau, M. L., Robin, C., Reynaud, G., Deque, M., Badeau, V., Piou, D., Husson, C, & Marcais, B. (2007). Simulating the effects of a climate-change scenario on the geographical range and activity of forest-pathogenic fungi. *Canadian Journal of Plant Pathology, 29*, 101-120.

Dubin, H., & Walper, S. (1967). *Dothistroma pini* on *Pseudotsuga menziesii*. *Plant Disease Reporter 51*, 454.

Gadgil, P. D. (1970). Survival of *Dothistroma pini* on fallen needles of *Pinus radiata*. *New Zealand Journal of Botany, 8*, 303-309.

Gadgil, P. D. (1974). Effect of temperature and leaf wetness period on infection of *Pinus radiata* by *Dothistroma pini*. *New Zealand Journal of Forestry Science, 4*(3), 495-501.

Gadgil, P. D. (1984). *Dothistroma needle blight.* (Forest Pathology in New Zealand No. 5). Rotorua, New Zealand: New Zealand Forest Service.

Ganley, R. J., Watt, M. S., Manning, L., & Iturritxa, E. (2009). A global climatic risk assessment of pitch canker disease. *Canadian Journal of Forest Research, 39*, 2246-2256.

Gibson, I. A. S. (1974). Impact and control of dothistroma blight of pines. *European Journal of Forest Pathology, 4*(2), 89-100.

Gilmour, J. W. (1967). Distribution impact and control of *Dothistroma pini* in New Zealand. In *Proceedings of the 14th IUFRO Congress, Munich Pt V,* (Sect. 24, pp. 221-248). Germany: Deutscher Verband Forstlicher Forschungsanstalten.

Gilmour, J. W. (1981). The effect of season on infection of *Pinus radiata* by *Dothistroma pini*. *European Journal of Forest Pathology, 11*, 265-269.

Hepting, G. H. (1963). Climate and forest diseases. *Annual Review of Phytopathology, 1*, 31-50.

Hocking, D., & Etheridge, D. (1967). Dothistroma needle blight of Pines. I. Effect and etiology. *Annals of Applied Biology, 59*, 133-141.

Jankovský, L., Bednářová, M., & Palovčíková, D. (2004). Dothistroma needle blight *Mycosphaerella pini* E. Rostrup, a new quarantine pathogen of pines in the CR. *Journal of Forest Science 50*(7), 319-326.

Kirschbaum, M. U. F., Watt, M. S., Tait, A., & Ausseil, A. E. (in press). Future productivity of *Pinus radiata* in New Zealand under expected climatic changes. *Global Change Biology*.

Lang, K. (1987). *Dothistroma pini* on young Norway spruce (*Picea abies*). *European Journal of Forest Pathology 17*, 316-317.

Marks, G., & Smith, I. (1987). Effect of canopy closure and pruning on *Dothistroma septospora* needle blight of *Pinus radiata* D. Don. *Australian Forest Research, 17*, 145-150.

Mehrotra, M. (1997). Diseases in the Forest. India. In E. M. Hansen, & K. J. Lewis (Eds.), *Compendium of Conifer Diseases (*pp. 83-85). St Paul, MN,, USA: APS Press.

Ministry for the Environment. (2008). *Climate change effects and impacts assessment. A guidance manual for local government in New Zealand.* 2nd Edition. (MFE Publication ME 870). Retrieved April 2010 from http://www.mfe.govt.nz/publications/climate/climate-change-effect-impacts-assessments-may08/climate-change-effect-impacts-assessment-may08.pdf.

National Institute of Water and Atmospheric Research Ltd (NIWA). (2010). *New Zealand temperature record.* Retrieved 25 June, 2010 from http://www.niwa.co.nz/our-science/climate/news/all/nz-temp-record.

Neves, N., Moniz, F., De Azevedo, N., Ferreira, M., & Ferreira, G. (1986). Present phytosanitory situation in Portuguese forests. *EPPO Bulletin 16*, 505-508.

New Zealand Forest Owners Association. (2010). *New Zealand plantation forest industry facts and figures.* Wellington, New Zealand: New Zealand Forest Owners Association.

Paul, I., Van Jaarsveld, A. S., Korsten, L., & Hattingh, V. (2005). The potential global geographical distribution of citrus black spot caused by *Guignardia citricarpa* (Kiely): Likelihood of disease establishment in the European Union. *Crop Protection, 24*(4), 297-308.

Peterson, G. (1967). Dothistroma needle blight of Pines in North America. *Proceedings of the 14th IUFRO Congress, Munich Pt V,* (Sect. 24, pp. 269-278). Germany: Deutscher Verband Forstlicher Forschungsanstalten.

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R. F., Parker, D. E., et al. (2007). Recent climate observations compared to projections. *Science, 316*(5825), 709.

Salinger, M. J. (1981). *New Zealand Climate: The instrumental record.* PdD Thesis, Victoria University of Wellington, New Zealand.

SAS-Institute-Inc. (2000). SAS/STAT User's Guide: Version 8. *Volumes 1, 2 and 3.* Cary, NC, USA: SAS Institute Inc.

van der Pas, J., Bulman, L., & Horgan, G. (1984). Estimation and cost benefits of spraying *Dothistroma pini* in tended stands of *Pinus radiata* in New Zealand. *New Zealand Journal of Forestry Science, 14*, 23-40.

van der Pas, J. B. (1981). Reduced early growth rates of *Pinus radiata* by *Dothistroma pini*. *New Zealand Journal of Forestry Science, 11*(3), 210-220.

Venette, R. C., & Cohen, S. D. (2006). Potential climatic suitability for establishment of *Phytophthora ramorum* within the contiguous United States. *Forest Ecology and Management, 231*, 18-26.

Villebonne, D., & Maugard, F. (1999). Rapid development of Dothistroma needle blight (*Scirrhia pini*) on Corsican pine (*Pinus nigra* subsp. *laricio*) in France. In *Annual Report 1998* (pp. 30–32). Paris, France: Le Département De La Santé des Forêts.

Wallin, J. R., & Waggoner, P. E. (1950). The influence of climate on the development and spread of *Phytophthora infestans* in artificially inoculated potato plots. *Plant Disease Reporter Supplement, 190*, 19-33.

Watt, M. S., Ganley, R. J., Kriticos, D. J., & Manning, L. (2011). Dothistroma needle blight and pitch canker: the current and future potential distribution of two important diseases of *Pinus* species. *Canadian Journal of Forest Research, 41*, 412-424.

Watt, M. S., Kriticos, D. J., Alcaraz, S., Brown, A. V., & Leriche, A. (2009). The hosts and potential geographic range of Dothistroma needle blight. *Forest Ecology and Management, 257*, 1505-1519.

Watt, M. S., Palmer, D. J., & Bulman, L. S. (2011). Predicting the severity of Dothistroma on *Pinus radiata* under current climate in New Zealand. *Forest Ecology and Management, 261*, 1792-1798.

Watt, M. S., Stone, J. K., Hood, I. A., & Palmer, D. J. (2010). Predicting the severity of Swiss needle cast on Douglas fir under current and future climate in New Zealand. *Forest Ecology and Management, 260*, 2232-2240.

Woods, A. (2003). Species diversity and forest health in northwest British Columbia. *Forestry Chronicle, 79*, 892-897.

Woods, A., Coates, K., & Hamann, A. (2005). Is an unprecedented Dothistroma needle blight epidemic related to climate change? *BioScience, 55*, 761-769.

ISSN 0048-0134 (print)
ISSN 1179-5395 (on-line)