

## Assessment of multiple climate change effects on plantation forests in New Zealand

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Determining the magnitude of climate change effects is crucial for informing national economic strategies, forest management and offsetting increasing carbon emissions. This study synthesizes predicted climate change impacts and future biosecurity threats to New Zealand's plantation forests. Projected productivity increases for radiata pine (*Pinus radiata* D. Don), the main commercial forest species in New Zealand, are slight due to changing climatic conditions. However including photosynthetic effects from increasing CO<sub>2</sub>, productivity gains across New Zealand averaged 19 per cent by 2040 and 37 per cent by 2090. This increased productivity results in marked increases in wind risk due to trees becoming taller and more slender. The average season length with 'very high and extreme' climatic fire risk increases by 71 per cent up to 2040 and by 83 per cent up to 2090. Currently, the most significant biotic disturbances in New Zealand plantations come from two needle cast diseases, for which climate projections show slight increases or decreases depending on the disease and region. Although insect pests currently cause little damage to New Zealand plantations, damage may increase in the future with projected increases in population and host susceptibility. It has not been possible to fully account for the effects of any new introductions of pests and pathogens and evidence from other countries with a significant resource of planted forests suggest this should not be underestimated. Potentially invasive weedy and damaging tree species are likely to expand their range under climate change and compete more strongly with plantations.

### Introduction

Climate change is emerging as one of the key influences to shape the future of natural and anthropogenic systems across the world (Cramer *et al.*, 2014). As forests cover about one quarter of the Earth's land surface area, they play a major role in current and projected future carbon budgets. Determining the influence of climate change on planted forests is of importance as these forests provide about half of the global wood supply and are a vital natural mechanism to offset future carbon emissions (Payn *et al.*, 2015). Increased disturbances to forests may reduce carbon stocks, result in substantial economic impacts and have consequences for ecosystem functioning.

Considerable research has investigated how climate change influences forest productivity. A recent review that synthesized findings from 31 studies found that 87 per cent of them identified positive changes in forest productivity when the effects of climate change and increasing CO<sub>2</sub> were combined (Reyer, 2015). Although gains in forest productivity are likely to occur as a result of climate change and CO<sub>2</sub> increases, there is some uncertainty

around the magnitude of this response. Photosynthesis of C<sub>3</sub> plants, including trees, increases strongly up to an ambient CO<sub>2</sub> concentration of about 300–400 ppm. Current observations show CO<sub>2</sub> rising above 400 ppm (Betts *et al.*, 2016), and with increasing CO<sub>2</sub> concentrations, relative photosynthetic gains by ongoing increases in CO<sub>2</sub> concentrations become progressively smaller (Kirschbaum, 2011; Hickler *et al.*, 2015).

However, while there may be gains in productivity realized through increased CO<sub>2</sub> and temperature up to the optimal value, they may be counteracted to varying degrees by changes in abiotic and biotic stressors (Reyer *et al.*, 2017). Climate change will influence the distribution and abundance of many forest pests (Unless otherwise stated (i.e. insect pest), pest refers to all agents injurious to trees or tree products (i.e. insects, pathogens and weeds)) and alter the frequency and intensity of damaging abiotic factors, such as wind and fire (e.g. Walthers *et al.*, 2009; Allen *et al.*, 2010; Anderegg *et al.*, 2015). Predicted changes in these factors under climate change have often been found to lead to reduced productivity (Kurz *et al.*, 2008; Seidl *et al.*, 2014). Although a comprehensive assessment of changes in productivity has to account

for the impacts of changes in all these factors, combined assessments such as in this paper have rarely been done in the past (e.g. [Chen et al., 2000](#); [Wolken et al., 2011](#); [Shanley et al., 2015](#)).

New Zealand provides a useful case study for examining the overall effects of climate change on plantation productivity as a single species, *Pinus radiata* D. Don, covers 90 per cent of the 1.7 million hectare plantation resource ([NZFOA, 2016](#)). There is much information describing the physiology and morphology of *P. radiata*, and how this species responds to changes in environmental factors. Using this information, previous research has modelled the growth of *P. radiata* under current ([Kirschbaum and Watt, 2011](#)) and future ([Kirschbaum et al., 2012](#)) climatic conditions within New Zealand. The major needle diseases of *P. radiata* are well known, and the spatial variation in the severity of two problematic diseases (caused by *Dothistroma septosporum* (Dorogin) M. Morelet and *Cyclaneusma minus* (Butin) DiCosmo, Peredo and Minter) has been described under both current and future climatic conditions ([Watt et al., 2011a, b, 2012a, b](#)). Spatial variation in wind risk under current and future climate has also been quantified ([Moore and Watt, 2015](#)).

The primary aim of this study was to synthesize knowledge describing the likely impacts of climate change on *P. radiata* plantations. Specifically, we summarize previously published studies describing the impact of climate change on radiata pine productivity and damage from wind and two of the major needle diseases of *P. radiata*. We complement this synthesis with additional, previously unpublished, research describing the potential impacts of fire on plantations. A general more qualitative synthesis of the literature was undertaken to describe the potential impacts of biotic factors that includes a key report describing changes in trade patterns and their effects on the origin of biosecurity risks ([Kean et al., 2015](#)). We describe the potential future impacts of key diseases, weeds and insects that are either currently in the country or could pose major incursion risks. We conclude with sections describing key sensitivities highlighted by the study and areas for further research.

## New Zealand's climate and the location of plantations

New Zealand's mean annual temperature at low-elevation sites ranges from 8°C in the south to 16°C in the north, with colder conditions at higher elevations, especially in the South Island (Figure 1a). Variation between summer and winter temperatures is generally relatively small, especially in coastal regions. Consequently, there are currently few periods with extremely hot or cold conditions in the low to moderate elevation areas of New Zealand where plantation forests are grown.

Precipitation within most of New Zealand ranges from 500–2000 mm yr<sup>-1</sup> (Figure 1b). Mountain ranges extending throughout New Zealand provide a barrier to the prevailing westerly winds, dividing the country into markedly different climatic regions. The west coast of the South Island is the wettest area of New Zealand, with a number of locations receiving over 5000 mm yr<sup>-1</sup>, whereas the area to the east of the mountains, just over 100 km away, is the driest, with annual precipitation reaching minima of 500 mm yr<sup>-1</sup>.

New Zealand's exotic plantation estate is distributed throughout most of the country, with the largest areas in the central North Island. Substantial areas of plantation are also found in

the far north and east coast of the North Island, the upper South Island and various locations along the east coast of the South Island, especially in the far south (Figure 1c).

## Materials and methods

### Climate change projections

Values of meteorological variables were estimated for the whole of New Zealand on a 0.05° latitude/longitude (≈5 × 5 km) grid, using a thin-plate smoothing spline to spatially interpolate daily observational data ([Tait et al., 2006](#); [Ministry for the Environment, 2008](#); [Tait, 2008](#); [Tait and Liley, 2009](#)). Climate change projections used in this study were derived from the factorial combination of 12 Global Climate Models (GCMs) and the SRES emission scenarios, B1 (low), A1B (mid-range) and A2 (high), described by [Meehl et al. \(2007\)](#). The B1, A1B and A2 scenarios approximately correspond to the newer representative concentration pathways 4.5, 6.0 and 8.5 ([Rogelj et al., 2012](#)). The 12 GCMs used in this study had been selected because of their utility in modelling 1971–2000 climatic conditions (mean sea level pressure, temperature and precipitation) over New Zealand from the widely used NCEP reanalysis ([Kalnay et al., 1996](#); [Ministry for the Environment, 2008](#)). They were as follows: CNRM, CCCma, CSIRO Mk3, GFDL CM 2.0, GFDL CM 2.1, MIROC32, ECHOG, ECHAM5, MRI, NCAR, UKMO-HadCM3 and UKMO-HadGEM1. Monthly temperature and rainfall scenarios from each GCM were statistically down-scaled to a resolution of 0.05° for 1990 (henceforth 'baseline'), 2040 and 2090, using the methods of [Mullan et al. \(2002\)](#).

### Modelling forest productivity

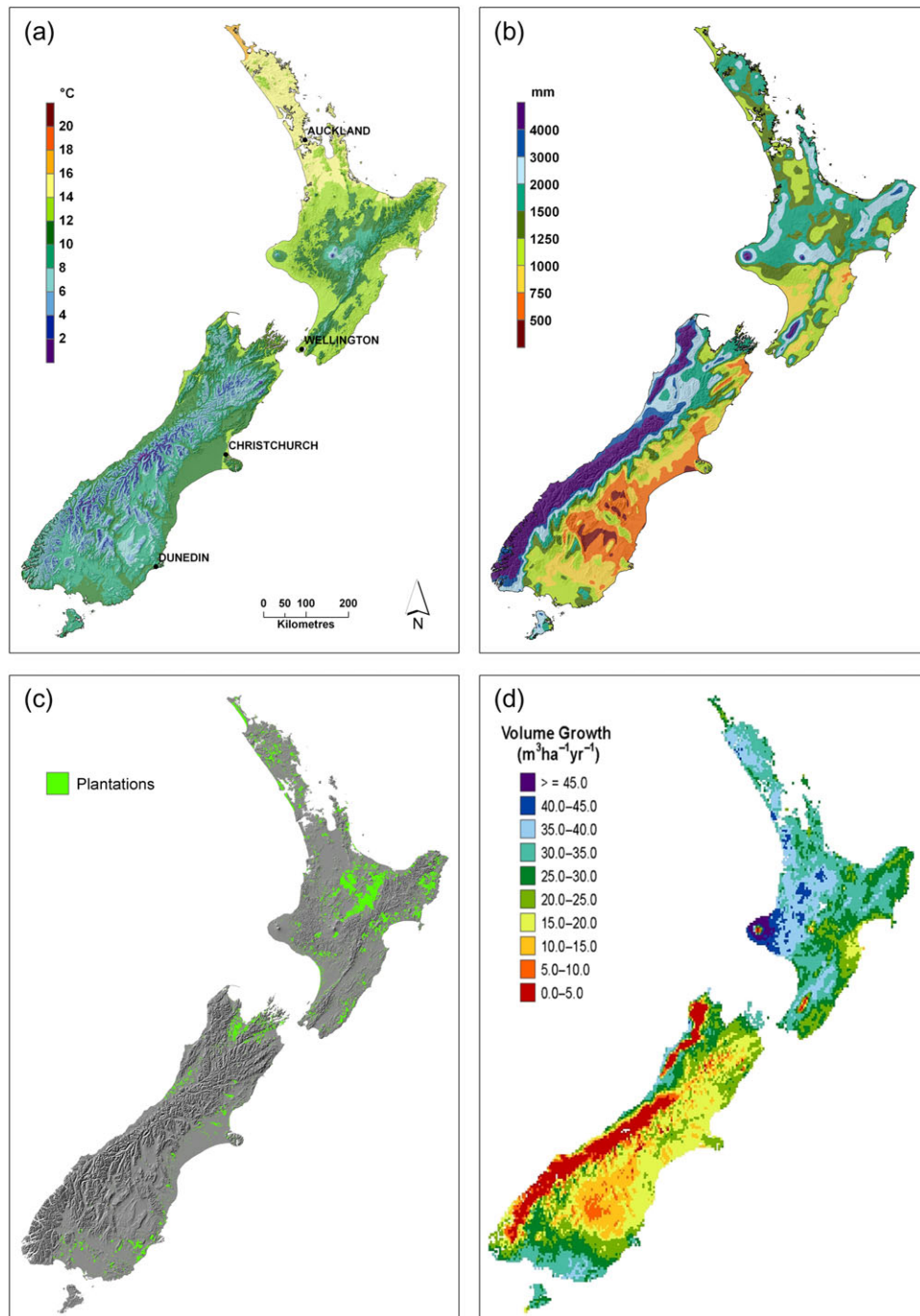
The process-based model CenW version 4.0 ([Kirschbaum, 1999](#)) was used to project productivity of *P. radiata* across New Zealand under current and future climates ([Kirschbaum and Watt, 2011](#); [Kirschbaum et al., 2012](#)). CenW has been developed primarily for climate change investigations and incorporates the key processes and feedbacks between plants and their environment that can operate on timescales ranging from daily (for water relations) to decadal and longer (for soil organic matter feedbacks and wood growth). [Kirschbaum and Watt \(2011\)](#) demonstrated that CenW can successfully model stand productivity of *P. radiata* under current climatic conditions within New Zealand, providing confidence that the model incorporates the key processes underpinning productivity.

CenW was parameterized for current climatic conditions using growth data from permanent sample plots covering almost the complete environmental range across which *P. radiata* is grown in New Zealand. These data consisted of 101 sites with 1297 individual observations of height and/or basal area from which diameters and volumes were calculated. Using the parameter values determined by [Kirschbaum and Watt \(2011\)](#), there was excellent correspondence between model predictions and measurements of a range of tree dimensions.

Simulations were run under both current and future climatic conditions using projections from the 12 GCMs and the three emission scenarios described previously. Future climate scenario outputs were used in CenW with both constant and increasing CO<sub>2</sub> to isolate tree responses to changing climatic conditions and elevated CO<sub>2</sub>. The results presented hereafter are the mean of the 12 GCMs unless otherwise stated.

### Wind damage

The risk of wind damage was quantified using the approach described by [Moore and Watt \(2015\)](#). They investigated both the direct effects of increasing wind speeds and the indirect effects of changes in stand structure, which affects the underlying susceptibility to wind damage. These impacts were investigated using representative growth rates and climatic conditions for seven bio-geo-climatic zones for *P. radiata* in New Zealand ([Goulding, 1994](#)). Site productivity metrics for these zones were



**Figure 1** New Zealand maps of current (1980–1999) (a) mean annual temperature and (b) mean annual rainfall (after Wratt *et al.* (2006)), (c) the current location of plantation forests and (d) modelled wood productivity (as volume growth) of *P. radiata* under current climatic conditions (redrawn from Kirschbaum & Watt, 2011).

used to predict the stand structure (diameter, height, volume and spacing) for three contrasting silvicultural regimes (pruned, unpruned and carbon) under current and future climatic conditions. Stands grown under a carbon regime are planted at a very high stand density and left in perpetuity with the sole purpose of maximizing carbon sequestration. This information was then input into a mechanistic wind damage model, ForestGALES (Gardiner *et al.*, 2000), in order to predict the critical wind

speed required to damage mean trees within a stand. The average annual probability that these critical wind speeds were exceeded was estimated from frequency distributions of extreme wind speeds calculated from time series of observations from long-term meteorological stations in each zone.

Although there is still considerable uncertainty around New Zealand's future extreme wind climate, an analysis carried out by Mullan *et al.* (2011)

has indicated that extreme wind speeds are only likely to increase by between 1 and 5 per cent under the A1B scenario, with no predictions of any changes available under other future scenarios. We accounted for these potential increases through increasing the mode of the extreme wind speed distribution by 5 per cent for all simulated time periods (Quine and Gardiner, 2002). All results are expressed at the age of 30 years as an annual exceedance probability (AEP) which is defined as the likelihood of a damaging wind event occurring in a given year, with values ranging from 0 to 1.

### Fire risk

Fire danger ratings (using 1970–1999 as a baseline) were computed using temperature, humidity, wind speed and rainfall data from the A1B emissions scenario, previously described. These changes were applied to 20 weather station sites across New Zealand with at least 20 years of observations to calculate future daily Fire Weather Index (FWI) and fire danger class values (Anderson, 2005). Fire risk is classified as being Low, Moderate, High, Very High, or Extreme. The fire climate severity is quantified here as the frequency of days in each fire season that had Very High or Extreme (VH + E) fire danger. Further details of the methods used in this study are described by Pearce *et al.* (2011) and Simpson *et al.* (2014).

Projected changes in fire danger for the whole of New Zealand were produced by spatially interpolating the changes predicted at each of the 20 station locations using the co-kriging technique (Goovaerts, 1999). The co-kriging technique allowed inclusion of additional surface prediction variables for station location (latitude/longitude), elevation and information from additional stations in data sparse locations (Pearce *et al.*, 2011).

### Disease damage

Damage from foliar pathogens is currently the most costly natural disturbance to New Zealand plantation forests (Watt *et al.*, 2008). *Dothistroma septosporum*, which causes dothistroma needle blight is currently the most damaging forest pathogen of *P. radiata* plantations. *Phytophthora pluvialis* (Reeser *et al.*, 2013), which is associated with red needle cast, was detected in 2008 and has the potential to cause significant damage within plantations (Scott and Williams, 2014). *Cyclaneusma minus* which results in cyclaneusma needle cast is also important but of lesser concern. Other pine pathogens currently within New Zealand may cause sporadic or localized damage but their national impact is not significant (Watt *et al.*, 2008).

The approach used to determine damage from *D. septosporum* and *C. minus* has been described in detail previously (Watt *et al.*, 2011a, b, 2012a, b) and is briefly summarized in the following. Disease incidence and severity data were collected from plantations throughout New Zealand over a 45-year period for dothistroma needle blight and over a 34-year period for cyclaneusma needle cast. Disease severity,  $S_{sev}$ , was determined at the stand level by multiplying the percentage of trees in the stand affected by mean severity (percentage of needles affected) on affected trees (scale = 0 – 100). Growth reduction generally occurs when disease severity exceeds 20 per cent, whereas disease severity values of 2–10 per cent (Table 3) are not likely to significantly impair growth. However, stands and individual trees growing in disease-prone regions may have values at which significant growth loss occurs. Multiple regression models of  $S_{sev}$  were developed for both diseases from meteorological data, described above, using the methods described fully by Watt *et al.* (2011b, 2012b). Using these multiple regression models, spatial predictions of  $S_{sev}$  were made under current climate and to 2040 and 2090 using the climate change scenarios previously described.

## Impacts

### Climate change projections

Averaged across the 12 GCMs, mean air temperature in New Zealand was projected to increase between the three emission

**Table 1** Summary of the mean simulated changes in temperature, precipitation and CO<sub>2</sub>. GCM minimum (min) and maximum (max) refer to the GCM with the lowest and highest spatially averaged changes. Variation of simulated changes between the GCMs is also expressed as a standard deviation (SD) which expresses the variation between the average NZ values between the 12 GCMs.

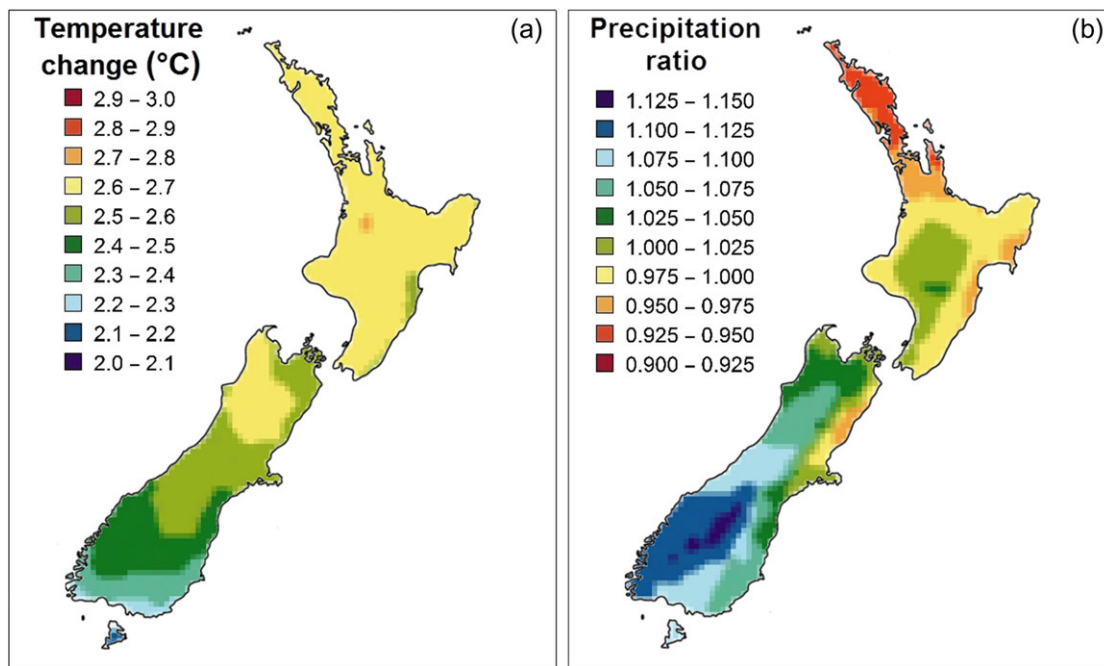
Year	Emission scenario	CO <sub>2</sub> (ppm)	Temperature change (°C)				Rainfall change (%)			
			Mean	GCM		SD	Mean	GCM		SD
				Min	Max			Min	Max	
2040	B1	457	0.7	0.4	1.2	0.3	1.6	-2.1	5.6	2.3
	A1B	483	0.9	0.4	1.3	0.3	2.1	0.0	5.0	1.6
	A2	481	0.9	0.3	1.3	0.3	0.9	-5.6	4.3	2.6
2090	B1	538	1.3	0.7	2.3	0.4	2.6	-4.7	7.9	3.8
	A1B	674	2.1	1.2	3.4	0.6	3.2	-1.5	12.9	3.9
	A2	754	2.6	1.6	3.6	0.5	3.0	-3.8	11.5	5.6

scenarios by 0.7–0.9°C by 2040 and by 1.3–2.6°C by 2090, although the inter-model uncertainty outweighs the scenario uncertainty (Table 1). Projected multi-model mean increases in rainfall for New Zealand under the three emission scenarios were between 0.9 per cent – 2.1 per cent by 2040 and 2.6 per cent – 3.2 per cent by 2090, with significant inter-model variation with even the sign of the change differing between GCMs implying considerable uncertainty in regional and national precipitation projections (Table 1). However, a consistent pattern in these simulations was the absence of any extreme changes, with all model projections falling within the range between –5.6 and +12.9 per cent. Changes under the A1B scenario showed the largest increases in rainfall by 2090, with changes under the A2 scenario falling between those under the B1 and A1B scenarios.

The mean 2090 projections for the A2 scenario (Figure 2) illustrate the regional patterns of the expected changes in temperature and precipitation. Expected temperature changes broadly correlated with latitude, with expected warming ranging from 2.7°C in the north to 2.2°C in the far south. Variation in precipitation also showed a latitudinal correlation, with rainfall increasing in the already wet south-western and elevated areas, while relatively drier areas along the east coast and in the north are projected to become drier (Figure 2b).

### Modelling forest productivity

Under baseline climatic conditions, there was wide regional variation in predicted stem volume growth (Figure 1d). Values were highest in the warm and moderately wet northern and western areas of the North Island, reaching maximum growth rates of >40 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup> in the fertile Taranaki region. Productivity was considerably lower within the South Island, partly attributable to cooler temperatures that were generally sub-optimal. Reduced productivity was also attributable to excessively high rainfall (>3000 mm yr<sup>-1</sup>) on the west of the main axial mountain ranges and relatively low rainfall (<750 mm yr<sup>-1</sup>) on the eastern side. In contrast, in the most southerly regions, where there is moderate



**Figure 2** Projected changes in temperature (a) and precipitation (b) for 2090 from baseline under the A2 emission scenario.

rainfall (Figure 1b) and little seasonal water deficit, productivity was predicted to be higher than in regions with greater rainfall extremes (Figure 1d) but still considerably lower than in the North Island, owing to the much lower temperatures.

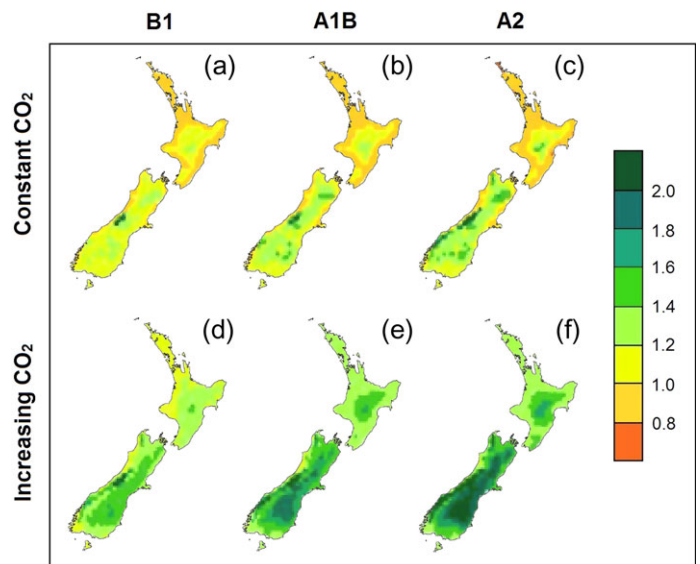
Neglecting future increases in CO<sub>2</sub> isolates the effect of expected climatic changes on future volume productivity. Projections to 2090 showed reduced productivity in northern and low-elevation regions and increased productivity in southern and upland regions (Figure 3a-c), likely due to shifts in temperature towards the optimum range for *P. radiata*, which Kirschbaum and Watt (2011) found to be at a mean annual air temperature of 12–15°C. These changes in climatic conditions resulted in growth gains for about half of all plantations (Kirschbaum et al., 2012), with mean changes in volume productivity within plantation forests averaging +3 per cent by 2090.

Simulations with increasing CO<sub>2</sub> led to productivity increases during 2090 for all regions and under all emission scenarios (Figure 3d-f). Increasing CO<sub>2</sub> completely reversed the losses in low-lying and northerly regions that had been modelled due to climatic shifts. Productivity gains were predicted throughout New Zealand and reached increases exceeding 100 per cent within parts of the South Island (Figure 3d-f). Within the current plantation estate, simulations showed mean productivity increases to 2040 and 2090 of 19 per cent and 37 per cent, respectively (Kirschbaum et al., 2012).

## Abiotic impacts

### Wind damage

The AEP, which is defined as the likelihood of a damaging wind event occurring in a given year, at the age of 30 years is given for each silvicultural regime and emission scenario in Table 2.



**Figure 3** Mean volume productivity ratio in 2090 compared to current productivity with constant (top row) and increasing CO<sub>2</sub> (bottom row) under the B1 (a, d), A1B (b, e) and A2 (c, f) emission scenarios.

For a 30-year-old stand, i.e. at typical harvest age, the risk of wind damage was relatively low under the baseline climate. Under this baseline, AEP ranged from 0.094 for the unpruned regime to 0.166 for the carbon regime (Table 2). Projections to 2040 for the pruned regime show that AEP was less than 0.2 for all scenarios apart from the A2 emission scenario with CO<sub>2</sub> held constant at 1990 levels where the AEP was 0.286. Projections to

2090 showed that the AEP increased on average by 0.066, and for four of the six scenarios, the AEP was >0.2 (Table 2).

The risk of wind damage for the unpruned regime was very similar to the risk for pruned stands in both 1990 and 2040. However, for projections to 2090, the risk of wind damage for the unpruned regime was substantially higher than for the pruned regime due to the higher ratio of height to diameter for this regime. These increases were particularly marked for emission scenarios that assumed a full response to increasing CO<sub>2</sub> (Table 2). The risk of wind damage was markedly higher for the carbon regime than for the other two regimes due to the higher height to diameter ratio of trees. The carbon regime had very high sensitivity to increasing CO<sub>2</sub>. For projections made to 2090, scenarios that assumed a full response to increasing CO<sub>2</sub> had an AEP that was on average 0.33 higher than those that assumed no response, and the AEP of these three scenarios ranged from 0.639 for the B1 to 0.922 for the A2 emission scenario (Table 2). Stands grown on a carbon regime tended to be overstocked, particularly in the latter part of the rotation and the increased risk of wind damage in such situations is consistent with experiences in other regions of the world (Mitchell, 2000; Cameron, 2002).

The relative contributions of different factors on AEP at 2040 and 2090 were determined using previously described methods (Hawkins and Sutton, 2009, 2011; Melia *et al.*, 2015). Figure 4 shows that currently, most of the variation in AEP is attributable to location, with stand age and silvicultural regime also being important. Under future climates, mean values of AEP for a 30-year-old stand ranged from 0.18 to 0.79 across locations (data not shown). Stand age accounted for 27 per cent of the variance in AEP under future climates (Figure 4). The change in mean AEP for increasing stand age from 20 to 30 years ranged from 0.09 to 0.33 in 2040 and from 0.12 to 0.49 in 2090.

Silvicultural regime was relatively important (Figure 4) under future climates, accounting for 19 per cent of the variance in

AEP (Figure 4). Mean AEP ranged from 0.21 under the pruned regime to 0.24 under the unpruned regime and 0.50 under the carbon regime (Table 2). The growth response to increasing CO<sub>2</sub> had relatively little impact on AEP in 2040 but a greater impact in 2090 at which time it was equal in importance to the silvicultural regime. Relative to other factors, both emissions uncertainty and increasing wind speed had very little effect on AEP, and together, they accounted for less than 4 per cent of the total variance during both 2040 and 2090 (Figure 4).

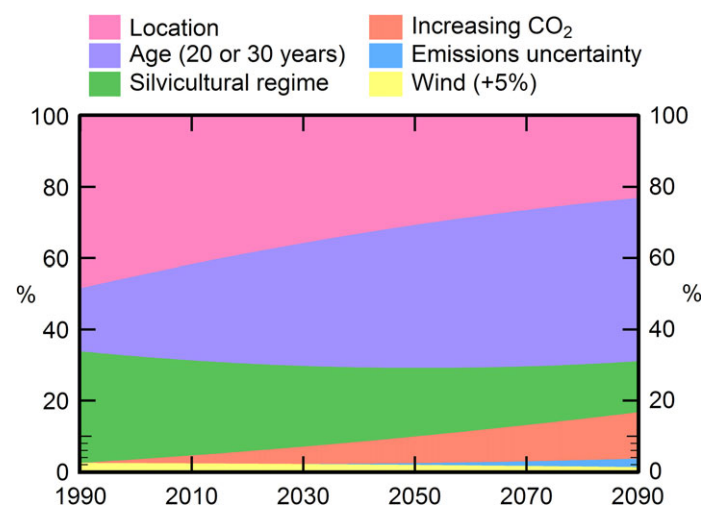
## Fire risk

Under the baseline climate, dryland areas on the east coast had the highest average number of VH + E fire danger days per year, while many areas on the west coast had a very few, or no VH + E days. There was widespread spatial variation in the degree of change in frequency of VH + E days between baseline and future climate (Figure 5). The regions with the most notable VH + E increases were located on the eastern coast in the southern half of both islands.

Examination of the fire risk by location demonstrates the high variation between sites with the frequency of VH + E fire risk under the baseline climate ranging from 0 to 40 days (Figure 6). When averaged over all sites, the number of days with VH + E fire risk was projected to increase by 71 per cent by 2040, and by a further 12 per cent by 2090. All sites on the east coast showed increases under climate change. The locations with highest current fire risk, Christchurch and Gisborne, had significant further increases in VH + E fire risk by 2090 to 44 and 48 days, respectively. However, the most marked relative changes occurred in Wellington (lower North Island) and Dunedin (south-eastern South Island) where VH + E fire risk increased to 2090 by, respectively, 89 per cent to 32 days and 207 per cent to 18 days (Figure 6).

**Table 2** AEP of wind damage in 30-year-old stands as a function of simulation year, emission scenario and CO<sub>2</sub> concentration for three silvicultural regimes. Values shown represent the means across seven bio-geo-climatic zones defined by their current wind climate. Values of AEP are differentiated by colour into the categories of AEP < 0.20 (green), 0.2–0.5 (orange) and >0.5 (red).

Year	Emission scenario	Inc. CO <sub>2</sub>	Silvicultural regime		
			Pruned	Unpruned	Carbon
1990			0.110	0.094	0.166
2040	B1	N	0.152	0.141	0.262
2040	A1B	N	0.164	0.155	0.291
2040	A2	N	0.286	0.154	0.286
2040	B1	Y	0.150	0.172	0.419
2040	A1B	Y	0.164	0.201	0.507
2040	A2	Y	0.164	0.197	0.495
2090	B1	N	0.186	0.182	0.344
2090	A1B	N	0.238	0.242	0.443
2090	A2	N	0.272	0.278	0.483
2090	B1	Y	0.191	0.256	0.639
2090	A1B	Y	0.267	0.423	0.850
2090	A2	Y	0.321	0.522	0.922

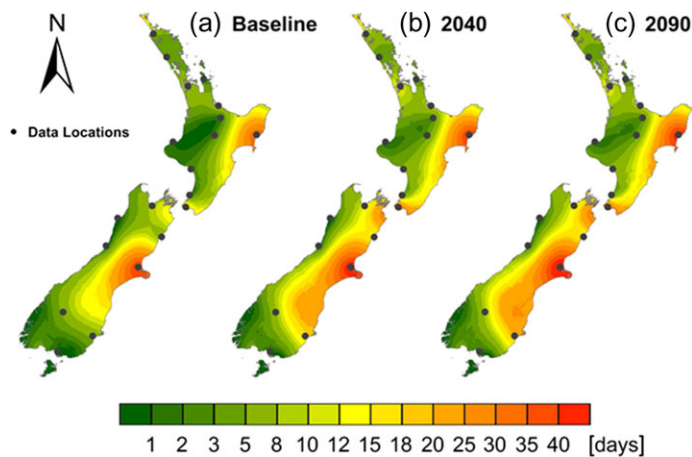


**Figure 4** Relative contribution of location, stand age, silvicultural regime, increasing CO<sub>2</sub>, emissions scenario and wind speed to AEP. Values of relative importance used in the figure were extracted from Table 2 and relative importance was interpolated between years using second-degree polynomials.

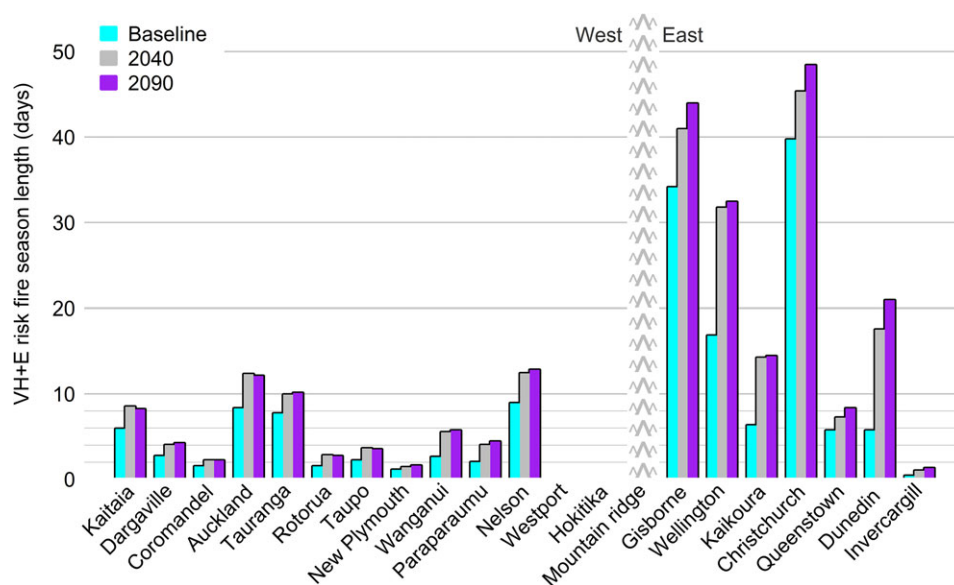
## Biotic impacts

### Distribution of pests

One of the most important changes likely to result from climate change is a shift in suitable habitats for certain pests, which is mainly linked to changing temperatures. Temperature influences thresholds for pest growth and survival through events such as frost frequency and the requirement for reproduction as determined through accumulation of thermal units. A benchmark for the effects of temperature on changes in distribution is provided by the relationship of temperature with elevation and latitude (Linacre, 1992). Average warming over the past century has



**Figure 5** Multi-model-mean projections of annual frequency of Very High and Extreme (VH + E) forest fire danger over fire season months (Oct–Apr). Note the non-linear colour scale. The locations used to construct this figure are shown as black dots, and actual fire risks for these locations is given in Figure 6.



**Figure 6** Projected average number of days of the fire season with Very High and Extreme (VH + E) forest fire danger under current conditions and in 2040 and 2090, at individual station locations and averaged for New Zealand across the 12 GCMs. Locations were grouped with respect to New Zealand's main mountain ranges, then ordered by latitude (northern-most left).

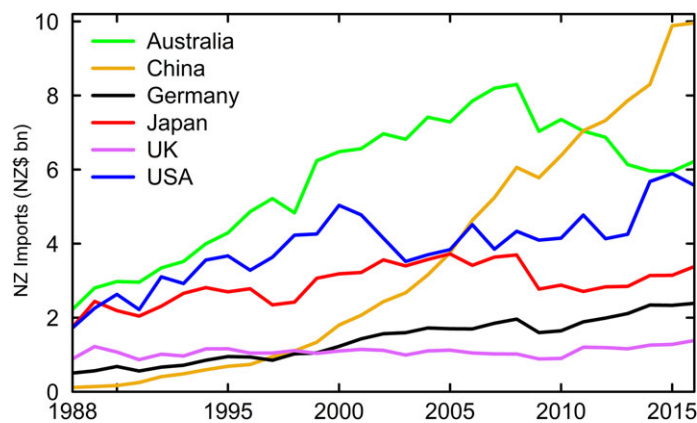
been about 0.85°C (IPCC, 2013), with 2015 having been the first year with temperatures more than 1°C above pre-industrial temperatures (Hawkins *et al.*, 2017). Global meta-analyses have documented significant range-boundary changes for 279 species, which, on average, have shifted poleward by 40 km over an average timespan of 66 years (Parmesan and Yohe, 2003).

### Geographic source of future pests

The main pathways for the arrival of pests and pathogens are associated with international trade. This section reviews recent changes in trade patterns and considers future trends based on trade agreements and expert opinion. New Zealand-specific import data were obtained from Statistics New Zealand (2017) and for data going back to 1988, from Statistics NZ Infoshare (2017).

Since the 1980s, imports have increased from the established trading countries of Australia, Europe, US and Japan. However, the most significant change has been the dramatic rise of China as the dominant importer to New Zealand (Figure 7). In 1988, only 1 per cent of New Zealand's imports originated from China, but in 2016 these imports represented more than 16 per cent.

Changes in the origins of imported goods and passengers are expected to result in changes in the profile of pest threats. In fact, this has already been observed in several regions. For example, in North America and Europe there has been an increase in insect pest and pathogen incursions originating from north-east Asia (Brockhoff and Liebhold, 2017). Historically, the majority of forest insects invading North America originated from Europe but in the last two decades, north-east Asian species, including some high-impact invaders, such as the Asian Longhorned beetle (detected in 1998) and Emerald Ash Borer (detected in 2002), have become more prominent (Aukema *et al.*, 2010).



**Figure 7** Imports from New Zealand's main trading partners, 1988–2016 (Statistics New Zealand, 2017).

Based on import trends and bilateral/multilateral trade agreements, one can assume that New Zealand's imports from east Asia will continue to increase. New Zealand's traditional trading partners in Europe and North America are likely to remain important sources of imports, even though their relative share may decrease, and Australia is likely to remain a key source of imports owing to its physical proximity. While trade may arguably present the greatest risk of introducing unwanted pests and diseases, the increasing number of international passenger arrivals to New Zealand presents another important pathway for possible pest incursion.

The volume of imports and the number of international visitors may be primary drivers of pest propagule pressure, but several other factors will also affect future biosecurity risks. For example, rapidly growing trade with new trading partners may have a disproportionate effect on biosecurity risks because they may host pests that have not previously had access to New Zealand. Many of the potentially most invasive species from New Zealand's long-standing trading partners have either established themselves in New Zealand already or have been excluded by effective border biosecurity measures targeted at specific species or to mitigate specific entry pathways. Such measures include, for example, requirements for pest monitoring, control and treatment by overseas growers and exporters, border inspection and additional treatment requirements for imports, and post-border pest surveillance and incursion response capability (Gordh and McKirdy, 2013). Pest-specific measures are not necessarily in place for pests from newer non-traditional trading partners, although many pests may be excluded by generic measures to prevent pest entry. The greatest threat may be from new 'hitchhiker' species (i.e. species that are transported inadvertently on inanimate objects such as sea containers or vehicles) that are difficult to manage because they are not necessarily associated with particular pathways in a predictable way (Toy and Newfield, 2010).

Climatic similarities between New Zealand and the potential incursion species' native habitat will also be important for the ability of pests and plant weeds to establish and develop pest potential in New Zealand. In this respect the southeast Asian countries will probably pose smaller risks due to their fundamentally different climatic zones. However, pests from temperate and some subtropical regions are of greater concern.

**Table 3** Variation in mean predicted stand severity,  $S_{sev}$ , of cyclaneusma needle cast and dothistroma needle blight for New Zealand under current climate and the B1, A1B and A2 emission scenarios, projected for 2040 and 2090 within the North (NI) and South (SI) Islands.

Year	Emission scenario	Cyclaneusma		Dothistroma	
		NI	SI	NI	SI
Baseline		6.40	2.17	10.9	4.26
2040	B1	6.18	3.56	10.0	5.04
	A1B	6.16	3.96	9.52	5.44
	A2	6.17	3.85	9.54	5.47
2090	B1	6.03	4.76	8.69	6.13
	A1B	5.62	5.76	7.51	6.83
	A2	5.25	6.17	5.82	7.89

Climate matching of current and future climates suggests that parts of north-east Asia, southern South America, western Europe, and southern Africa, as well as cooler (e.g. montane) regions in subtropical countries may represent sources of species of growing biosecurity concern (Ridley *et al.*, 2000; Peacock and Worner, 2006; Bertheau *et al.*, 2010; Kriticos, 2012).

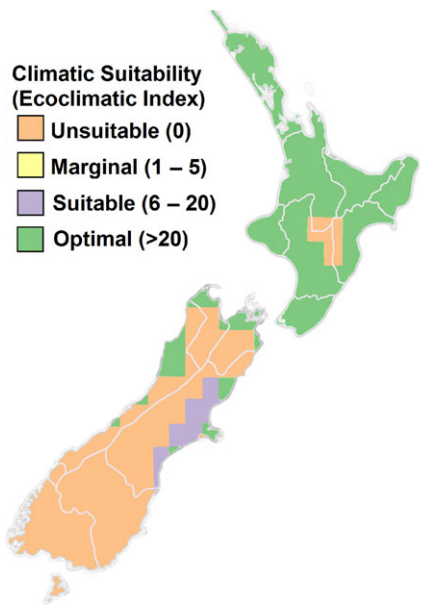
### Damage from tree pathogens

Within the major plantation areas in the North Island, simulations showed that the severity of dothistroma needle blight and cyclaneusma needle cast are likely to decline throughout the 21<sup>st</sup> century under all emission scenarios; however, increases in disease severity were predicted for large areas of the South Island (Table 3). With the exception of the west coast of the South Island, the actual predicted severity remains relatively low compared to the damaging levels currently found within the North Island. Although high disease severity is predicted within the west coast of the South Island under both projection periods (2040 and 2090), it causes little concern in the national context because this area currently constitutes only 1.8 per cent of the total New Zealand plantation area (Watt *et al.*, 2011a, 2012a).

There are also a number of other pathogens that could cause considerable damage to plantation forests should they establish within New Zealand. Pitch canker is a devastating disease of *Pinus* spp., and *P. radiata* is known to be highly susceptible to the disease (Ganley *et al.*, 2011). Projections using process-based distribution models show that the potential New Zealand distribution of this disease could expand from coastal areas of the North Island under baseline climate to almost all of the North Island and eastern parts of the South Island by 2080 (Figure 8) (Ganley *et al.*, 2011).

Red needle cast caused by *Phytophthora pluvialis* causes periodic episodes of defoliation in New Zealand's *P. radiata* plantations, particularly in locations exposed to frequent wet days and fog over the cooler months. *Phytophthora pinifolia* causes similar problems in Chile (Durán *et al.*, 2008) and could be problematic in New Zealand if it were introduced. Perhaps a greater threat is posed by pathogens that are new to science (e.g. *P. pluvialis* was





**Figure 8** Pitch canker Ecoclimatic Index for 2080 derived from NCAR-CCSM for the A1B emissions scenario. Based on [Ganley et al., 2011](#). The squares evident in the figure reflect the resolution of the underlying climate change scenario.

unknown when the pathogen was first isolated from diseased *P. radiata* foliage in 2008), or by those that behave in unexpected ways in a new environment. For instance, *Neonectria fuckeliana* (C. Booth) Castl. & Rossman was well known in the Northern Hemisphere as a wound-invading fungus that was found only on spruce (*Picea* spp.) and fir (*Abies* spp.) and caused little or no damage. When it first established in the Southern Hemisphere on *P. radiata*, it caused severe damage to some plantations in the lower half of the South Island ([Crane et al., 2009](#)) until a successful control strategy was developed.

### Damage from tree-feeding insects

Although climate change effects on tree-feeding insects are relatively well known in several countries, and have been the subject of a considerable research effort, little research on this topic has been carried out in New Zealand. However, several general reviews specific to New Zealand exist, and one specific study on effects by a potentially invasive defoliator was undertaken.

Climate change can affect problems related to insect pests through several mechanisms including (i) changing the severity of damage by native or non-native insects due to changes in climatic suitability for the pest or the host tree ([Battisti et al., 2005](#); [Marini et al., 2012](#)), (ii) changing the likelihood of establishment of invasive species that are not yet present in New Zealand ([Sutherst et al., 2007](#); [Kriticos et al., 2013](#)), and (iii) as an indirect consequence through interactions with other disturbance factors, such as increases in fire hazards due to tree mortality or pest susceptibility of stands through increasing wind damage ([Stinson et al., 2011](#); [Hickey et al., 2012](#); [Jenkins et al., 2012](#)).

Currently, only a few insect pests affect *P. radiata* plantations in New Zealand. As there are no native *Pinaceae* in New

Zealand, most insects feeding on these trees are non-native species that were introduced accidentally, but see [Berndt et al. \(2004\)](#) for a description of a native defoliator that has adapted to feeding on pines. Fortunately, most of these species cause little or no damage at present. An exception is the woodwasp *Sirex noctilio* that was a concern in the past, but is now largely controlled through the introduction of biological control agents and changes in forest management that reduce stand susceptibility to *S. noctilio* ([Bain et al., 2012](#)). However, the pest status of some of these species could change as a result of climate change, and in other countries, there are many pests of conifers that could represent serious threats to plantation forests in New Zealand if they should ever become established in the country ([Brockerhoff and Bulman, 2014](#)). These threats could potentially become even more severe in the future.

There are hundreds of damaging pests associated with conifers that are not yet present in New Zealand ([Brockerhoff and Bulman, 2014](#)). For example, the Eurasian nun moth, *Lymantria monacha*, and the European pine processionary moth, *Thaumetopoea pityocampa*, would probably cause considerable defoliation if they became established in New Zealand ([Withers and Keena, 2001](#); [Kriticos et al., 2013](#)). A climate-matching study has indicated that there are also a number of North American bark beetles that attack pines and could present threats to New Zealand's plantation forests. They include *Dendroctonus valens* and *Ips calligraphus* ([Lantschner et al., 2017](#)).

Most of the regions in New Zealand where conifer plantation forests occur are expected to be climatically suitable for the pine processionary moth, and estimates of its impacts on pine productivity suggest that significant growth losses would occur if it were introduced ([Kriticos et al., 2013](#)). In Europe, the main limiting factor for most insect pests is cold stress ([Robinet et al., 2007](#); [Kriticos et al., 2013](#)). Hence, for many species, climate change is expected to increase the area with suitable climate ([Robinet et al., 2007](#)). The situation in New Zealand is likely to be similar. This effect of climate change on climatic suitability is likely to have more far-reaching implications for species from warmer (e.g. subtropical) regions which currently are unlikely to become established in New Zealand given its mainly temperate climate. Several studies have suggested that climate change will increase the risk of establishment of species from warm-temperate or subtropical regions ([Peacock and Worner, 2006](#); [Kriticos, 2012](#)).

Climate change may also affect the severity of damage from existing insect pests because warmer temperatures can be expected to accelerate insect development and therefore lead to an increase in population levels, especially in species that can complete more than one generation per year. An example of such a species is the Monterey pine aphid, *Essigella californica* ([Watson et al., 2008](#)). Although this aphid is presently not considered damaging in New Zealand, in parts of Australia with a warmer climate (i.e. warmer than New Zealand's current climate), *E. californica* can cause considerable defoliation of pines ([May and Carlyle, 2003](#)).

In other parts of the world, warming has been shown to increase population levels and damage by the mountain pine beetle and other bark beetles ([Hicke et al., 2006](#); [Marini et al., 2012](#); [Bentz and Jönsson, 2015](#); [Bentz et al., 2016](#)). Warming can thus lead to an expansion of areas affected by tree-feeding insects ([Battisti et al., 2005](#); [Marini et al., 2012](#)). The unprecedented spread of the mountain pine beetle into the boreal

forest east of the Rocky Mountains, as a result of climate change, is of particular concern because it could cause substantial mortality of jack pine, *Pinus banksiana* Lamb., and other eastern pines (Cullingham *et al.*, 2011). Furthermore, warmer temperatures, especially if associated with greater frequency of drought conditions, can increase the susceptibility of trees to attack and damage from bark beetles or wood borers such as *S. noctilio* (Carnegie and Bashford, 2012). Both warming and increasing drought incidence can lead to an expansion of areas affected by tree-feeding insects (Battisti *et al.*, 2005; Marini *et al.*, 2012). Although no identified insect pest in plantation forests in New Zealand has yet been observed to have increased in its severity through climate change, this is likely to occur in the future.

### Competition with weeds

The future prevalence of weed problems is likely to be related to (i) the future distribution, growth and competitive strength of the currently problematic weeds, and (ii) the potential of weeds that are either already present in New Zealand, but not yet widely distributed, or that could enter the country to become problem weeds, especially under changed climatic conditions.

The weed species that compete most strongly with *P. radiata* within New Zealand are tall woody weeds. Within this group, gorse (*Ulex europaeus*), Scotch broom (*Cytisus scoparius*), bracken (*Pteridium esculentum*), blackberry (*Rubus fruticosus*) and wilding conifers (e.g. *Pinus contorta* and *Pseudotsuga menziesii*) are the most competitive and invasive (Watt *et al.*, 2008). In addition, buddleja (*Buddleja davidii*), *Acacia* spp. and pampas (*Cortaderia* spp.) are problematic weeds in some specific regions. Tall shrubby species reduce plantation growth more than short species such as grasses and herbaceous species, as they compete more vigorously for both water and light and are not as effectively shaded out as trees grow taller (Richardson *et al.*, 1999; Watt, 2003).

Little research has investigated the future distribution of the most problematic weed species in New Zealand under climate change. Potter *et al.* (2009) found that changes in climate will have little effect on the potential distribution of broom, with all regions remaining suitable for the species. In contrast, it is expected that under future climate change, buddleja may expand its range within the southeast of New Zealand (Watt *et al.*, 2010; Kriticos *et al.*, 2011).

Expansion of 'sleepers' is likely to pose a future threat to plantation forests. Sleeper weeds are weeds that are present in New Zealand, but whose distribution or vigour is limited under current climatic conditions. For instance, the exotic tree *Melaleuca quinquenervia*, which is currently established in Auckland and Northland, could become quite invasive if the species' thermal requirement for reproduction within northern areas of New Zealand is surpassed in the future (Watt *et al.*, 2009). Range expansion of this species could have significant consequences as *M. quinquenervia* has been found to be extremely difficult to control in exotic locations, such as Florida (Austin, 1978; Woodall, 1983).

Kudzu (*Pueraria montana*) is a perennial, semi-woody, climbing leguminous vine, which is extremely invasive and damaging in the south-eastern US. It has recently been found in northern

New Zealand. Although we do not currently have an estimate of the potential distribution of this species, the distribution where it is invasive in the US is quite similar to that of *M. quinquenervia*. During the 1990s, kudzu has migrated northwards in the continental US from its original distribution, a shift which is in line with previous model predictions (Sasek and Strain, 1990). This change demonstrates the responsiveness of the weed to climatic conditions and highlights that the potential for range expansion under climate change should not be underestimated.

There is a risk that currently established exotic woody tree species native to Australia may become more dominant competitors in New Zealand under a warmer climate. *Acacia* spp. have very high growth rates and can rapidly occupy disturbed sites, vigorously competing with planted *P. radiata* seedlings (Turvey *et al.*, 1983). As tree species, they can compete further into the rotation than even tall weed species (Hunt *et al.*, 2006), which are predominantly shrubs. Some species have the ability to resprout after their stems have been severed which makes them hard to control. Seed germination is also often stimulated by fire. The likely increases in fire frequency and severity will make sites more predisposed to invasion by these species. Some *Acacia* species are already a localized problem in northern and eastern parts of the country (Watt *et al.*, 2008).

Climate change is also likely to affect growth rates of weeds through changes in CO<sub>2</sub>, root-zone water storage, temperature and changing length of the growing season. If relative growth of both plantation trees and weeds increases at the same rate then competition levels may not significantly change. However, in agricultural settings there is evidence that weeds exhibit a stronger positive response to CO<sub>2</sub> than crop plants which is likely to lead to reductions in crop yields (Ziska *et al.*, 2011; Ziska, 2011). The basis for this increased competitive behaviour of weeds is unclear but may be related to the vigorous and generally indeterminate growth habit of weeds and greater genetic and phenotypic plasticity associated with wild species (Ziska and McConnell, 2015). The growth response of different weeds to climate change has been shown to vary widely (Sheppard and Stanley, 2014). As a consequence, increases in CO<sub>2</sub> have been shown to preferentially select for more responsive invasive species within plant communities (Ziska and McConnell, 2015).

### Discussion

Climate change impact assessments of forest systems are often dominated by a focus on biophysical factors, which generally show positive effects of climate change on forest productivity (Reyer, 2015). This is largely due to the growth response to elevated CO<sub>2</sub> (Hickler *et al.*, 2015; Reyer, 2015), and even temperature increases by a few degrees, or precipitation changes by a few per cent, especially when coupled with increasing CO<sub>2</sub> concentrations, may not be of great detriment to the physiological growth potential of many forest stands (e.g. Kirschbaum *et al.*, 2012).

Other factors impinging on the fate of forest stands, on the other hand, can be much more negative. This has been experienced most clearly by the expansion of the mountain pine beetle in North America (Hicke *et al.*, 2006; Marini *et al.*, 2012) that has the potential to lead to the death of susceptible stands that

had previously been protected by mortality of the insect pests during severe winters (Cullingham *et al.*, 2011). Because of the tight linkage between temperature and distribution of the pest species, its range expansion under future warming can be anticipated with very high probability. This pattern is expected to pre-dominate for many pest species (e.g. Logan *et al.*, 2003).

Similarly, wildfire risk is strongly linked to climatic factors such as temperature, humidity and wind speed which, together with stand attributes like fuel load and fuel moisture contents, largely control fire risks in forest systems. These factors are generally expected to change towards increasing fire risk in the future (e.g. Flannigan *et al.*, 2009; Pechony and Shindell, 2010). Forest stands are also at risk from wind damage, although climate change risks for wind are more nuanced and depend on changes in climatic factors as much as changes in stand properties (Moore and Watt, 2015).

For a balanced assessment of the combined climate change effects of all agents of change, it is therefore necessary to consider all of the key aspects of change in an integrated assessment. This requires collaboration between different science disciplines and the bringing-together of different approaches and numeric evaluations. The present work took a first step in such an assessment by cataloguing the various changes that our forests might be subject to in the future. A further stage of development in an integrated assessment would see the different processes combined in unified ecosystem models that can also quantitatively integrate these processes. Although linkages were included between predictions of productivity and wind damage, most effects that were assessed in this study were not linked in a dynamic way which is a limitation of our approach. For instance, by direct inclusion of pest and disease damage in a comprehensive model, the plant physiological status could be directly linked to plant susceptibility to certain diseases. Conversely, any pest or disease damage could directly affect plant growth, with consequences for future photosynthetic carbon gain or, vulnerability to wind or fire damage. However, this would require significantly greater system complexity and mathematical integration of very different model components. Such integration will ultimately be needed for a true assessment of climate change impacts and avoidance of any bias in climate impact assessments brought about by omission of any important aspects of system processes and interactions.

## Sensitivities and areas for future research

This review identified the growth response to increasing CO<sub>2</sub> as a key sensitivity of the overall response of forest systems to future climate change, but there is still considerable uncertainty of the magnitude of this response. Some workers have focused on photosynthetic processes and expect large increases in CO<sub>2</sub> responsiveness, especially under water-limited conditions (e.g. Lloyd and Farquhar, 1996; Franks *et al.*, 2013). Others have argued that stimulation of photosynthesis is inconsequential under many natural conditions and can be overridden by other growth-limiting factors (e.g. Körner *et al.*, 2007; Fatichi *et al.*, 2014). Others have presented a more diverse picture, suggesting that CO<sub>2</sub> stimulated carbohydrate supply may stimulate growth under some conditions, especially under low light or water stress, but may have little effect on productivity in other

circumstances, such as under severely nutrient-limited conditions (e.g. Ceulemans and Mousseau, 1994; Kirschbaum, 2011). Empirical evidence in support of these various positions is mixed (e.g. Norby *et al.*, 1999; Nowak *et al.*, 2004; Donohue *et al.*, 2013; Kirschbaum and Lambie, 2015), but a recent reanalysis of the results of past short-term CO<sub>2</sub> growth experiments suggested that future growth enhancement may lie about half way between the values calculated with constant and increasing CO<sub>2</sub>, respectively (Kirschbaum and Lambie, 2015). Clearly, more research is still needed to refine the likely growth response to increasing CO<sub>2</sub> of plantations in New Zealand and elsewhere. That single factor constitutes the largest single uncertainty in current modelling of plant responses to future conditions and makes it still difficult to confidently forecast changes to productivity and risk of wind damage.

Current projections show that the risks to plantations from the two most damaging diseases in New Zealand are unlikely to change markedly. Nonetheless, further research should be undertaken to examine the potential impact of the damaging disease red needle cast (*P. pluvialis*) under current and future climates. Currently, there is also no significant damage to plantations from insect pests. However, it would be useful to determine how climate change affects the climatic suitability of plantation forest regions for a range of high-risk species such as bark beetles and defoliators. The impact of weeds on plantations in the future is likely to depend on the degree to which current 'sleeper' weeds and naturalised aggressive woody tree species (e.g. *Acacia* spp.) can expand their range and increase in vigour. The future potential distributions of these key weed species should be determined using process-based weed distribution models. Further research is also required to determine how important weed species will respond to climate change and how effectively they will compete with plantations in the future. Given the potentially damaging role wind and fire are projected to have on future plantations, it would also be useful to refine our spatial understanding of the impacts of these factors.

## Conclusion

Overall, our analyses showed productivity gains for *P. radiata* from the direct effects of climate change that ranged from relatively minor to substantial depending on the response to increasing CO<sub>2</sub>. These simulations suggest that the direct effects of climate change are likely to favourably affect forest productivity even if the potential CO<sub>2</sub> response is only partly realized. Although fire risk is projected to increase in the future, most damage is likely to ensue from the greater vulnerability of plantations to wind damage, that results from increased height growth.

Changes in trade and increased global travel are likely to influence the origin of future incursions of invasive pests, with invasions from regions in eastern Asia likely to constitute a growing risk. Currently, the most significant biotic disturbances of New Zealand plantations come from two needle cast diseases, for which climate projections show very little change in damage over the course of this century. Although New Zealand does not currently have any damaging forest insect species, population levels and resulting damage are likely to increase in the future as warmer temperatures accelerate insect

development and increase the susceptibility of host plants to attack. Competition within plantations from aggressive woody tree species, and in particular those originating from Australia is likely to increase as a result of climate change.

The effects of climate change present global plantation forests with many challenges but also new opportunities. This study quantifies the increases in productivity expected due to climate change. Changes in wind conditions will have implications for silvicultural practices, particularly for stands grown to maximize carbon, while there will be significantly increased wild-fire risk to plantation forests. The future impact from biotic factors are complex and often species dependent, but this study highlights the major threat species and notes the highest-risk source locations. The results from this ambitious synthesis of climate change threats should provide decision makers the foresight to mitigate against avoidable threats, adapt to committed future changes and capitalize on future opportunities.

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## Conflict of interest statement

None declared.

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