



Future proofing plantation forests from pests

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Future proofing plantation forests from pests PROP-20244-SLMACC-FRI Contract No. CO4X0810

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EXECUTIVE SUMMARY

The problem

Despite the considerable threat that pests pose to plantation forests under climate change, little research has investigated how climate change will influence the potential distribution and abundance of the key pests of New Zealand's plantation resource. The objective of this research was to determine the potential distribution of four high impact invasive species under current and future climate within New Zealand. Three contrasting climate change models (CSIRO; NCAR; MIROC) were used with both medium (A1B) and high (A2) emission scenarios to project potential distribution of the pests under future climate.

The pest species, chosen in consultation with MAF, include two species that are currently in New Zealand and two that are potential threats to New Zealand. The species currently in New Zealand include the weed *Buddleja davidii* Franchet and the disease Dothistroma needle blight (caused by the pathogens *Dothistroma* spp.) while the potential threats include the disease pitch canker (caused by the pathogen *Fusarium circinatum* Nirenberg & O'Donnell), and the insect *Thaumetopoea pityocampa* (pine processionary moth). All four species were chosen because of their current and/or future economic impact on New Zealand plantation forestry.

Key Results

Pitch Canker (*Fusarium circinatum*)

The models show that currently only northern and coastal areas of the North Island have suitable climate for pitch canker. These regions include 43% of current plantations. Under climate change, the potentially suitable areas within current plantations increased by 108% to 134% depending on which model was used. For all of the climate change scenarios it is predicted that the majority of the North Island and northern and coastal areas of the South Island will have optimal climatic conditions for pitch canker. The change in potential pitch canker distribution under climate change would include most of the extensive forests located in the central North Island that are currently not predicted to be suitable for pitch canker.

Dothistroma needle blight

Under current climate the potential distribution of Dothistroma needle blight in New Zealand includes the entire North Island. The potential distribution in the South Island was also extensive and only relatively small areas in the south-west and inland Canterbury were projected to be unsuitable. The potential distribution of Dothistroma needle blight in New Zealand included all current plantations under both current and future climate.

Buddleja davidii

Projections of potential distribution show most of the North and South Island to be suitable for *B. davidii*. Regions that are unsuitable for *B. davidii* are located at high altitude adjacent to the main axial ranges in the South Island. There are large tracts of land suitable for *B. davidii* within the south-east of the South Island where *B. davidii* is currently scarce.

Although the potential distribution of *B. davidii* increased under all future climate scenarios these increases showed marked regional variability within New Zealand. As the entire North Island currently ranges from suitable to optimal for *B. davidii*, no further potential range expansion occurred under the future climate scenarios. However, in the South Island, model projections show considerable potential range expansion particularly in high country areas adjacent to the Southern Alps. Areas likely to be particularly prone to invasion are located in eastern and southern regions of the South Island as: (i) these regions show the greatest increases in climatic suitability for *B. davidii* under climate change; and (ii) *B. davidii* spread is exacerbated by disturbance associated with forested areas. A high proportion of future potential plantings are likely to be located in marginal lands in these regions.

Pine processionary moth (*Thaumetopoea pityocampa*)

Under current climate 60% of the total plantation area within New Zealand was projected to be suitable for *T. pityocampa*. Under climate change there were marked increases in climatic suitability for *T. pityocampa* and projections show between 82% and 93% of the plantation estate was suitable under future climate scenarios.

Under current climate the dispersal of *T. pityocampa* throughout New Zealand was predicted to result in average reductions of 16% in both merchantable and total stem volume over the course of a rotation. These impacts showed marked variation throughout New Zealand with estimated reductions in stand productivity under current climate ranging from 42.5% in Northland to 0% in many South Island regions. Under future climate these average national reductions in merchantable and total stem volume were more marked, ranging from 29% to 33% between scenarios, as climatic suitability for *T. pityocampa* increases.

Under the assumption that *T. pityocampa* is fully dispersed throughout New Zealand, projected losses in net present value of the plantation resource, over the course of one rotation (28 years), were \$1,306 M under current climate and ranged from \$2,239 M – \$2,493 M under climate change. At lower rates of dispersal, net present value losses ranged from between \$500 M to \$167 M, assuming respective linear spread rates of 2.53% of the plantation resource year⁻¹ (equivalent to 30 km year⁻¹) and 0.84% year⁻¹ (equivalent to 10 km year⁻¹). Potential losses in net present value for these two spread rates were markedly higher under all climate change scenarios.

At lower probabilities of establishment all economic losses were reduced in proportion with the diminished probability of establishment. For instance, under the probability of occurrence of 1% net present value losses under current climate ranged from \$5M to 1.67M, assuming respective linear spread rates of 2.53% year⁻¹ and 0.84% year⁻¹.

Assuming that *T. pityocampa* is controlled using aerial application of an insecticide (*Bacillus thuringiensis* (Bt)) losses in net present value were reduced but still relatively high.

Implications of Results for Client

Climate-change adaptation strategies that could be implemented to reduce the spread of *B. davidii* in the prone eastern and southern regions of the South Island are: (1) including it as a target for eradication in the Regional Pest Management Strategies (RPMS) of all eastern and southern territorial authorities in the South Island, and in particular, Marlborough to reduce the risk of spread from naturalised populations into North Canterbury; (2) preventing spread of the species across a “control line” that geographically separates infested regions on the west coast and northern regions of the South Island from the sporadically-occupied areas in eastern and southern areas; (3) invoking a nationally coordinated response through the National Interest Pest Response process.

Under current and future climate, invasion by either pitch canker or *T. pityocampa* could pose a major threat to New Zealand plantations. In view of the high risk that these organisms pose to New Zealand's *Pinus radiata* forests, continued vigilance and monitoring is recommended for prevention or early detection.

Although Dothistroma needle blight is present throughout New Zealand there are wide regional differences in severity. The potential distribution determined here indicates the likelihood that Dothistroma needle blight will be able to become established and does not describe disease severity. This highlights the need for the development of finer scale models that can be used to account for variation in severity throughout New Zealand under climate change.

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General Introduction

The current direct economic impacts of pests and diseases on plantation forests of New Zealand has been estimated to exceed NZ\$160 million per year (Turner et al., 2004). Additional costs associated with the fumigation of logs to remove insect pests from export timber are at least NZ\$12 million per year (Self and Turner, 2009). Not included in either of these figures are costs associated with lost opportunity because certain trees cannot be grown in New Zealand due to their vulnerability to pest attack (Watt et al., 2008).

As the climate changes, the substantial negative impacts of pests on plantation forestry are predicted to worsen within New Zealand (Watt et al., 2008). Climate change is likely to result in shifts in the geographic ranges of many species, as has already been observed (Parmesan and Yohe, 2003; Parmesan, 2006), and also influence their local abundance (Sutherst et al., 2007a). As New Zealand shifts to a warm temperate and subtropical climate, the country will become more susceptible to a broader range of pest species including some highly invasive and aggressive pest species from these climatic regions (Ganley et al., 2009; Watt et al., 2009b).

Despite the considerable threat that pests pose to plantations under climate change, little research has investigated how climate change will influence the potential distribution and abundance of the key pests of the New Zealand plantation resource (Watt et al., 2008). Quantifying the potential threat posed by pest species to plantation forests under climate change will require: (i) prediction of how climate change will influence potential pest distribution and abundance throughout New Zealand; and (ii) prediction of how these spatial changes in abundance will impact on plantation growth.

Process-based distribution models have been widely used to predict the effect of climate change on potential distribution of invasive plants (Kriticos et al., 2003b; Potter et al., 2009; Watt et al., 2009b), insects (Stephens et al., 2007) and pathogens (Desprez-Loustau et al., 2007; Watt et al., 2009a). As these models are underpinned by detailed global meteorological datasets they provide good representation of spatial and temporal variability in climate. The model can therefore be readily used to produce detailed spatial maps of distribution and abundance for a target pest species. Climate change surfaces are widely available for a range of IPCC emission scenarios (Nakićenović and Swart, 2000) and can be readily integrated into process-based distribution models to determine how spread and abundance of a target pest species alters under climate change.

The objective of this research was to determine the potential distribution of four high impact invasive species under current and future climate within New Zealand. These species, chosen in consultation with MAF, include two species that are currently in New Zealand and two that are potential threats to New Zealand. The invasive species currently in New Zealand include the weed *Buddleja davidii* Franchet and the disease Dothistroma needle blight (caused by the pathogen *Dothistroma* spp.) while the potential threats include the disease pitch canker (caused by the pathogen *Fusarium circinatum* Nirenberg & O'Donnell), and the insect *Thaumetopoea pityocampa* (pine processionary moth).

For *T. pityocampa* estimates of potential suitability were combined with a damage function, to determine potential volume losses in New Zealand pine plantations under current and future climate that could occur should *T. pityocampa* become invasive in New Zealand. These estimates of volume loss were then scaled up to determine reductions in net present value to the existing plantation estate under both current and future climate, over a range of spread rates and probabilities of occurrence.

1. Increased risk of pitch canker to New Zealand under climate change.

Summary

The objective of this study was to produce detailed maps describing the potential distribution of the high risk disease, pitch canker (caused by the pathogen *Fusarium circinatum* Nirenberg & O'Donnell) under current and future climate within New Zealand.

The CLIMEX models show that only northern and coastal areas of the North Island currently have optimal climate for pitch canker. Under all of the climate change scenarios it is predicted that the majority of the North Island and northern, coastal areas of the South Island will have optimal climatic conditions for pitch canker. The change in potential pitch canker distribution under climate change would include most of the extensive forests located in the central North Island, that are currently not predicted to be suitable for pitch canker.

Results highlight high risk regions in New Zealand, specifically the majority of the North Island and northern, coastal areas of the South Island. In view of the high risk that pitch canker poses to many of New Zealand's *Pinus radiata* forests, continued vigilance and monitoring for this disease is recommended for prevention or early detection of *F. circinatum*.

Introduction

Introduced pests and diseases threaten the biosecurity of New Zealand's forest estate on a daily basis. Pests that have become established in New Zealand have caused substantial economic losses. For example, *Dothistroma* needle blight is estimated to cause a loss of \$23 million per annum and *Cyclaneusma* needle cast causes losses of \$61 million per annum (Watt et al., 2008). The introduction of further pests could cause more issues for New Zealand's forest industry.

Fusarium circinatum Nirenberg & O'Donnell, the causal agent of the disease known as pitch canker, has been considered one of New Zealand's most undesirable and unwanted pathogens. Because of the high risk this disease poses to New Zealand's forest industry, strict quarantine regulations have been put in place by The Ministry of Agriculture and Forestry, Biosecurity New Zealand (MAFBNZ) to help prevent this pathogen from being introduced to New Zealand. These restrictions include a complete ban on any *Pinus* species or *Pseudotsuga menziesii* (Douglas-fir) live plant material into New Zealand and restrictions on seed imported from countries known to have pitch canker (Ministry of Agriculture and Forestry Biosecurity New Zealand, 2002).

Fusarium circinatum has been found to be pathogenic to, or reported on, over 60 species of pine and Douglas-fir, although the degree of susceptibility is variable (Storer et al., 1997; Hodge and Dvorak, 2000). *Pinus radiata*, which accounts for over 90% of all softwoods planted in New Zealand (N.Z.F.O.A., 2007), is considered the most susceptible species (Hodge and Dvorak, 2000). *Fusarium circinatum* is a wound pathogen, intact tissue is not vulnerable to invasion (Gordon et al., 2001). In general, pitch canker has been associated with wounds created by insects, weather or mechanical damage (Wingfield et al., 2008). Spores can be vectored to wounds by a variety of different agents, such as wind, rain, animals, insects or soil. The importance of specific vectors and wounding agents varies between locations that have pitch canker (Wingfield et al., 2008). In addition to horizontal transmission, *F. circinatum* can also be transmitted vertically by seed (Gordon et al., 2001).

Pitch canker disease in pines is characterised by exudation of large amounts of resin in response to an infection. All tissue of susceptible hosts can be infected by *F. circinatum*. Individual infections are unlikely to kill a tree but multiple infections can cause extensive dieback in the canopy and this may potentially lead to mortality (Storer et al., 2002). Tree mortality can be caused directly from girdling bole cankers. Pitch canker also affects seed and seedlings and thus, can be a serious nursery problem. Seed infections can result in the visible deterioration of the seed. However, infected seed frequently display no symptoms until the seed germinates and in some cases infected seed can germinate and produce symptomless seedlings from which the fungus can be isolated (Storer et al., 1998).

Fusarium circinatum is now present in many countries worldwide, including several countries with exotic or native pine industries such as the USA, Spain, Chile and South Africa (Wingfield et al., 2008). However, the severity and impact of pitch canker on pines grown in these countries differs. In the absence of host-associated insects it appears that the incidence and severity of pitch canker is influenced by climatic variables (Ganley et al., 2009). Specifically, the disease appears to be more problematic in humid subtropical and Mediterranean areas (Ganley et al., 2009). Outbreaks of pitch canker have also been correlated with severe damage caused from hurricanes (Kelley and Williams, 1982).

Recent modelling of the potential distribution of pitch canker worldwide, based on climate, shows a wide variation in the likelihood of disease establishment (Ganley et al., 2009). New Zealand is one of the countries expected to have optimal climate conditions for pitch

canker, which is of serious concern to the forest industry. Under current climate conditions it is expected that the majority of the North Island has climate conditions optimal for pitch canker establishment, whereas the majority of the South Island is predicted to be unsuitable. However, it is possible that more of New Zealand could become high risk for pitch canker, as future climate change scenarios predict an increase in temperatures and storms worldwide.

Given the importance of pitch canker and the threat it poses to New Zealand's current and future pine plantations, it would be useful to determine how climate change is likely to influence the potential distribution of this disease. In this study we used a previously developed CLIMEX model for pitch canker (Ganley et al., 2009) to determine the potential distribution of this disease under current climate and simulate a series of future climate scenarios to assess the sensitivity of the distribution of this disease to climate change in New Zealand. The potentially suitable area for pitch canker under both current climate and climate change was quantified by region. By combining these projections with information on the distribution of susceptible hosts, predictions of forest areas most at risk from pitch canker under current and future climate have been made.

Materials and Methods

The CLIMEX model

CLIMEX is a dynamic model that integrates modelled weekly responses of a population to climate to create a series of annual indices (Sutherst et al., 2007b). CLIMEX uses an annual growth index to describe the potential for population growth as a function of soil moisture and temperature during favourable conditions. It uses up to eight stress indices (cold, wet, hot, dry, cold-wet, cold-dry, hot-wet and hot-dry) to simulate the ability of the population to survive unfavourable conditions. CLIMEX also includes a mechanism for defining the minimum amount of thermal accumulation (number of degree days) during the growing season that is necessary for population persistence (PDD).

The growth and stress indices are calculated weekly, and then combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), that gives an overall measure of the potential of a given location to support a permanent population of the species (Sutherst et al., 2007b). The EI ranges from 0 for locations at which the species is not able to persist to a theoretical maximum of 100 for locations that are climatically perfect for the species (Sutherst et al., 2007b). It is usually only near the equator, where seasonal variation is minimal that values of 100 are ever attained (Stephens et al., 2007). In this study EI is classified into unsuitable (EI = 0), marginal (EI = 1-5), suitable (EI = 6-20) and optimal (EI > 20) categories for pitch canker establishment.

CLIMEX models are generally fitted to known distribution data using a manual iterative process. This involves adjusting growth and stress parameters and then comparing model results to the known distribution of the species. In setting these parameters, consideration is also given to the biological reasonability of the selected parameters. This process allows models to be developed that conform with all that is known about the pathogen across a range of knowledge domains.

Known distribution and model fitting

Reported records of pitch canker and/or *F. circinatum* were compiled from individual point locations and county, state and island level observations, for countries known to have pitch canker (Ganley et al., 2009). These records show the core range of the disease to be humid subtropical and Mediterranean areas. The disease and pathogen also extends

into warmer temperate climates and regions with tropical humid rainforest and savannah climates.

A previously constructed CLIMEX model (fully described in (Ganley et al., 2009)) was used to model current and future distribution of pitch canker. The fit of this model was validated using an extensive set of observed occurrences from locations not used in the original fitting dataset (Ganley et al., 2009). These validations showed that almost all observations of pitch canker occurred in suitable areas ($EI \geq 1$), for the species.

Climate change scenarios

Six climate change scenarios were used to project the potential distribution of pitch canker under climate change during the 2080s within New Zealand. These scenarios were developed from three Global Climate Models (GCMs) run using two standard International Panel on Climate Change (IPCC) scenarios, representing medium (A1B) and high (A2) emissions, drawn from the set of standardised emissions scenarios (IPCC et al., 2007). The GCM data employed in this project were drawn from the World Climate Research Programmes Coupled Model Intercomparison Project phase 3 multi-model dataset (Meehl et al., 2007). The three GCMs selected had relatively small horizontal grid spacing (100 – 175 km) and the requisite climatic variables at the monthly resolution required by CLIMEX. Selected GCMs included CSIRO Mark 3.0 (CSIRO, Australia), NCAR-CCSM (National Centre for Atmospheric Research, USA), and MIROC-H (Centre for Climate Research, Japan). Data from these GCMs were pattern-scaled to develop individual change scenarios relative to the base climatology (Whetton et al., 2005). The three models cover a range of climate sensitivity, defined as the amount of global warming for a doubling of the atmospheric CO₂ concentration compared with 1990 levels. The respective climate sensitivities are: CSIRO Mark 3.0 (2.11 °C), NCAR-CCSM (2.47 °C), and MIROC-H (4.13 °C).

Estimating land areas for Ecoclimatic Index classes

Areas of New Zealand with a suitable climate, (i.e., $EI \geq 1$) for pitch canker under current and future climate scenarios, were estimated by Regional Council administrative areas and state/territory boundaries respectively, using ArcGIS. A regional council boundary shapefile for New Zealand was used to extract EI data by region. The areas for each EI value (per region) were calculated and summarised to obtain the total area per EI value by region. The data was then classified using suitability values and the total area per suitability classification was calculated. The area distribution of EI by class (unsuitable, marginal, suitable, optimal) was also determined for current pine plantations, under current and the six future climate scenarios. Current New Zealand pine plantations were identified within the Land Cover Database layer (LCDB2), (1996). The two LCDB2 classes specific to pine were 'pine forest open canopy and pine forest closed canopy'.

Results

Potential distribution of pitch canker under current climate

Pine plantations are dispersed throughout New Zealand (Fig. 1.1a), with the large areas located in the central North Island, Northland, Gisborne and the northern South Island (N.Z.F.O.A., 2007). Under current climate the potential distribution of pitch canker included Northland and coastal areas within the North Island (Fig. 1.1b). Regional percentages of areas suitable for pitch canker exhibited a strong decline as latitude increased (Fig. 1.2c). The potential distribution of pitch canker within the South Island was very limited with only a small area in Marlborough and northern Canterbury projected to be suitable (Fig. 1.2).

The potential distribution included only 43% of New Zealand plantations (Table 1.1). However, most of these plantations, that were predominantly located in northern and coastal regions of the North Island, were projected to have a climate that was optimal for pitch canker (Table 1.1). Most of the extensive forests located in the central North Island were projected to have an unsuitable climate for pitch canker under current climate (Fig. 1.1b).

Table 1.1. Projected softwood plantation area, by EI class, under current climate for pitch canker and the percentage changes in areas under these classes for the six climate change scenarios.

	Current climate km ²	Percentage changes in plantation areas by EI class under future climate					
		CSIRO		NCAR-CCSM		MIROC-H	
		A1B	A2	A1B	A2	A1B	A2
Unsuitable (EI = 0)	8,060	-62	-65	-65	-71	-68	-68
Marginal (EI = 1-5)	0	0	0	0	0	0	0
Suitable (EI = 6-20)	61	570	798	801	1194	976	798
Optimal (EI > 20)	6,105	77	78	78	81	80	81

Potential distribution under climate change

Under climate change the potentially suitable areas in New Zealand increased under all scenarios (Fig. 1.3) from between 108% for the CSIRO A1B model to 134% for the NCAR A2 model. The projected future potential distribution exhibited slight variability between the three global climate models, but very little variation between the two emissions scenarios within each of these models (Fig. 1.3, Table 1.1). Percentage increases in potentially suitable area occurred in most regions and were most marked within the southern North Island provinces of Wellington, Manawatu-Wanganui and Taranaki (Fig. 1.2, 1.3). Within areas designated to be suitable there were substantial increases in EI for almost all regions (Fig. 1.2a). Climate change resulted in a 77 to 81% increase in plantation area designated to be optimal and a 65 to 71% reduction in the area that was unsuitable for pitch canker (Table 1.1).

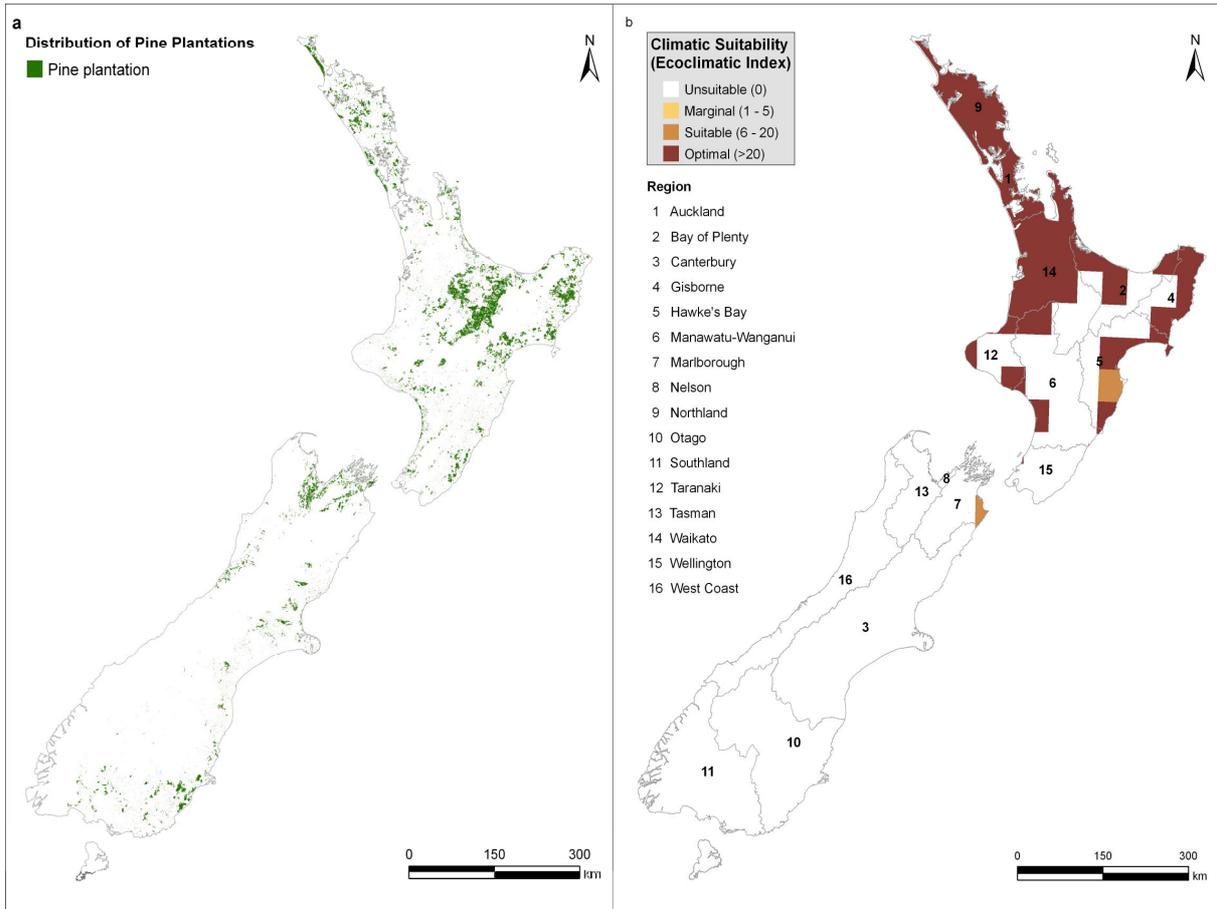


Figure 1.1. New Zealand map showing (a) location of existing *Pinus* spp. plantations and (b) ecoclimatic suitability, by region, for pitch canker, under current climate.

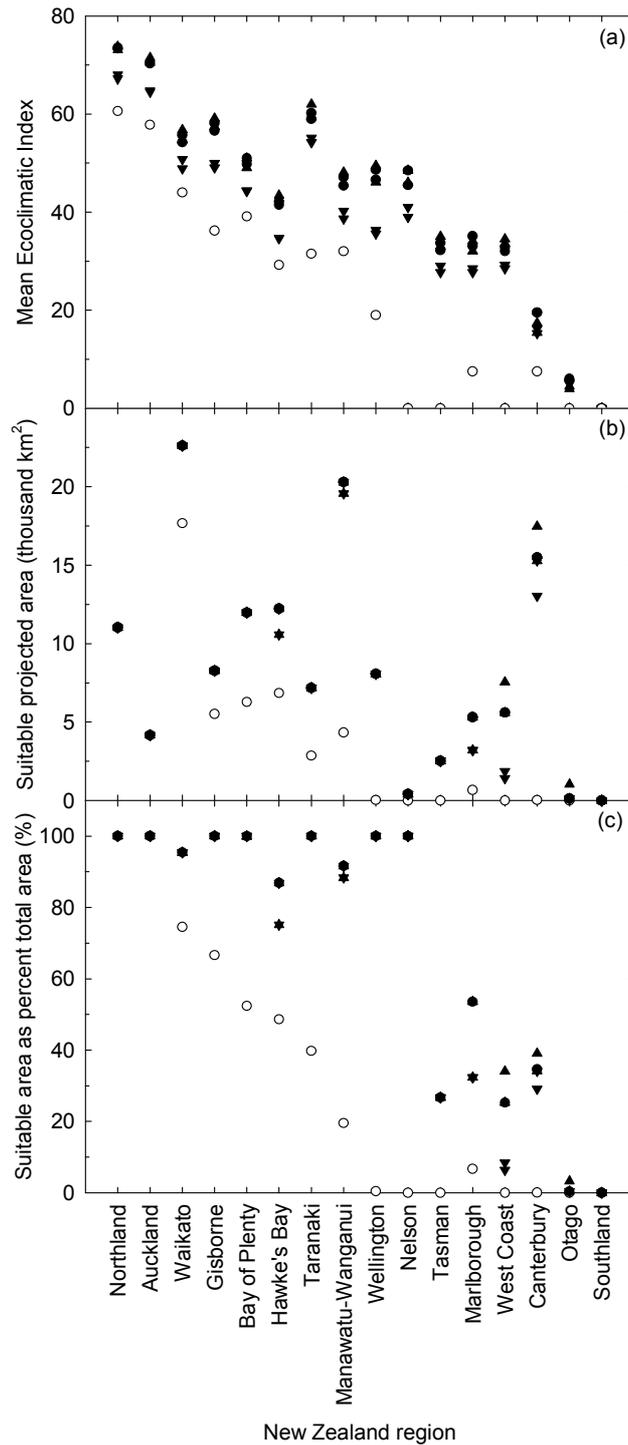


Figure 1.2. (a) Mean Ecoclimatic Index and suitable area for pitch canker, expressed as an (b) absolute amount and (c) percentage of total region area, under current (open circles) and future climate (under A1B and A2 scenarios) projected using the CSIRO (downward facing triangles), MIROC (closed circles) and NCAR (upward facing triangles) models. Regions within New Zealand are sorted left to right in order of increasing latitude.

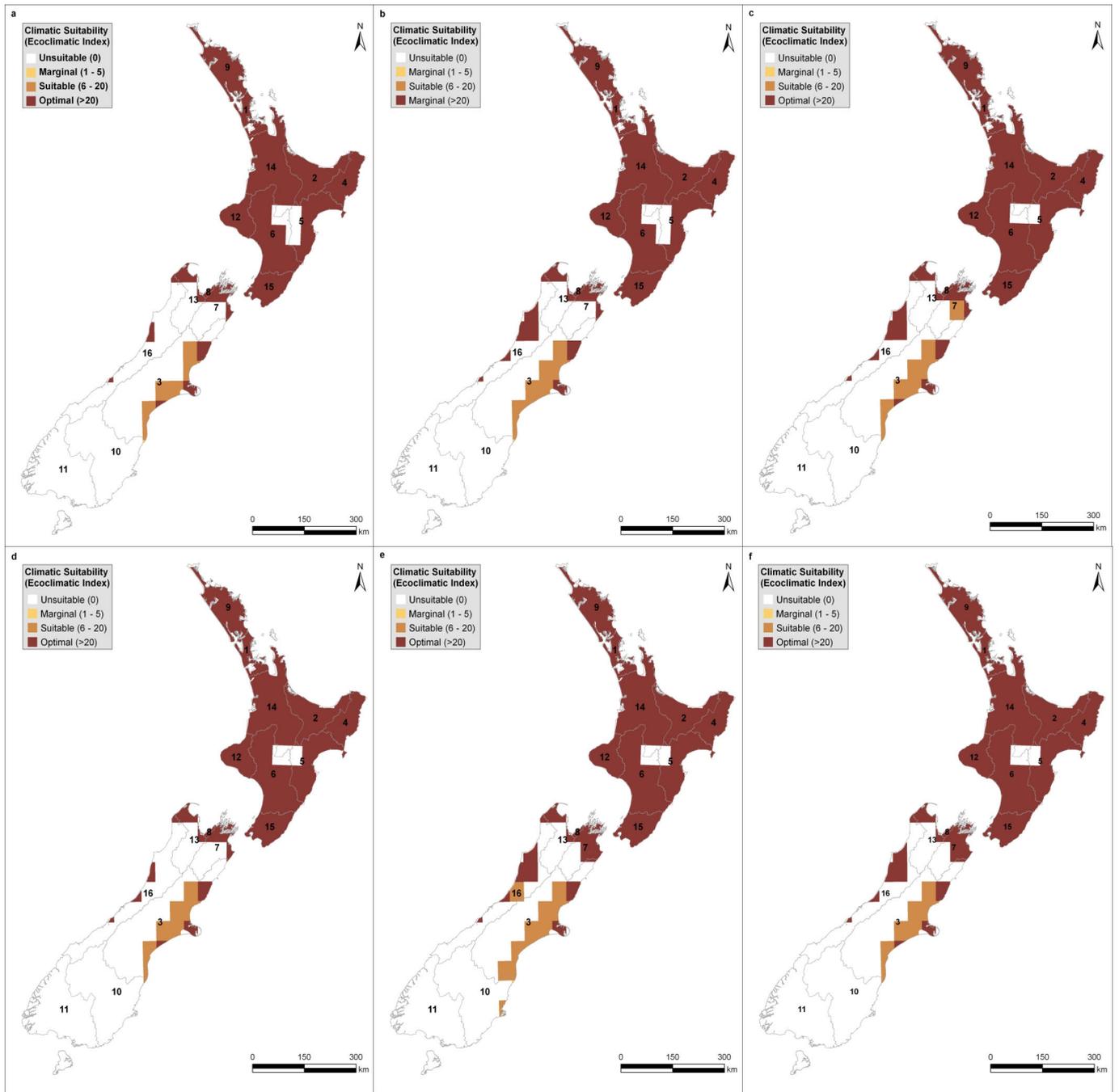


Figure 1.3. New Zealand map showing Ecoclimatic Index (EI) for pitch canker under climate change scenarios (in 2080s) derived from: (a) CSIRO Mark 3.0; (b) NCAR-CCSM; (c) MIROC-H run with the AIB emissions scenario; (d) CSIRO Mark 3.0; (e) NCAR-CCSM; (f) MIROC-H run with the A2 emissions scenario.

Discussion

The increased suitability for pitch canker establishment under climate change is of serious concern to the New Zealand forest industry. All of the future climate change scenarios predict that most of the North Island will have optimal conditions for pitch canker to develop and this will extend into the northern, coastal areas of the South Island. The change in potential pitch canker distribution under climate change would include most of the extensive forests located in the central North Island, which are currently not shown to be suitable for pitch canker.

Models of the potential global distribution of pitch canker under current climate suggest that areas predicted to be marginal or suitable for pitch canker would be unlikely to have outbreaks of the disease in the absence of specific, host-associated insects (Ganley et al., 2009). Conversely, areas predicted to be optimal for pitch canker establishment would be likely to have disease outbreaks regardless of whether specific insect vectors/wounding agents were present (Ganley et al., 2009). When applied to New Zealand this would mean that almost the entire North Island and northern coastal regions of the South Island would be likely to have optimal climate conditions for pitch canker, should *F. circinatum* be introduced to New Zealand. However, the coastal Canterbury region would be unlikely to have disease problems as long as suitable insect vectoring/wounding agents were not present. Areas predicted to be unsuitable would not be expected to have pitch canker, even if suitable insects were present in the region. This would mean that the majority of pine and Douglas-fir forests in the South Island would not be at risk if *F. circinatum* were introduced.

The distribution models predict the likelihood that pitch canker could become established in a region and do not include estimations of the severity of disease. Variations in disease severity across the areas predicted to have optimal climate conditions for pitch canker would be anticipated. Specifically, coastal regions, areas with high humidity or subtropical climates would be expected to have more severe outbreaks. This is based on variations in severity of pitch canker outbreaks in California and the south-eastern USA. In California, pitch canker has progressed significantly faster in the areas adjacent to the coast that are frequently covered in fog than in coastal, inland populations of *P. radiata* (Wikler et al., 2003). Outbreaks of pitch canker would also be expected to increase after severe storms, as occurs in south-eastern USA (Kelley and Williams, 1982).

Currently there are no insects present in New Zealand that are known to be associated with pitch canker disease outbreaks in the USA, such as *Ips* spp., *Ernobius punctulatus* and *Pissodes nemorensis*. Although 150 species of insects have been recorded on *P. radiata* in New Zealand, it is unlikely that many, or even any, of the insect species present in New Zealand would feed or create wounds suitable for infection by *F. circinatum*. It is possible that some of the insects in New Zealand may be able to vector the pathogen. Thus, in areas predicted to have marginal to suitable conditions for pitch canker, the likelihood of disease establishment would be low.

Other potential wounding agents/vectors in New Zealand to be considered are possums, birds and livestock. Possums are known to cause substantial damage to young plantations of *P. radiata*, including damage to the terminal shoots and lateral branches through browsing, although generally they have little effect on trees over 14 years old (Green, 2004). It is possible that possums could create wounds suitable for pitch canker infections to occur. Likewise, livestock run through plantations could create wounds on the roots or branches that potentially could become infected. Some bird species that can damage trees by either bending branches or causing considerable damage with their beaks or claws could also have an effect on the establishment of pitch canker infections. It

is also possible that possum fur and/or bird feathers could vector the pathogen. In putative high severity areas (i.e. coastal regions, areas with high humidity or subtropical climates), damage caused by possums, livestock and some bird species could increase the incidence of infections. Further work is required to understand the potential impact this could have on pitch canker in New Zealand.

Globally, the spread of *F. circinatum* and pitch canker is on the increase. In the last decade pitch canker has been found in at least four countries in Europe (European and Mediterranean Plant Protection Organization, 2004; Landeras et al., 2005; Carlucci et al., 2007; Bragança et al., 2009) as well as in Korea (Lee et al., 2000). Projections of potential distribution for pitch canker within Europe suggest further scope for expansion within this continent (Ganley et al., 2009). The increased distribution of *F. circinatum* worldwide is of concern to New Zealand and other pitch canker-free countries as it increases the risk that the pathogen could inadvertently be introduced to New Zealand. Continued vigilance and monitoring for this disease is essential for prevention or early detection of *F. circinatum* in the forestry sector.

2. Impact of climate change on Dothistroma needle blight in New Zealand.

Summary

The objective of this study was to produce detailed maps describing the potential distribution of the high risk disease, dothistroma needle blight (caused by *Dothistroma pini* and *D. septosporum*) under current and future climate within New Zealand.

The potential distribution of Dothistroma needle blight in New Zealand included all plantations under both current and future climate. The potential distribution determined here indicates the likelihood that Dothistroma needle blight will be able to become established and does not describe disease severity. This highlights the need for the development of finer scale models that can be used to account for variation in severity throughout New Zealand under climate change.

Introduction

Dothistroma needle blight is a foliar disease of *Pinus* spp. that is characterised by red bands on needles. It causes defoliation of the tree and in extreme cases, mortality. The pathogen is present throughout New Zealand wherever suitable hosts are grown and is estimated to cause losses of \$24 million per annum (Bulman, 2007). *Pinus radiata*, which accounts for over 90% of all softwoods planted in New Zealand (N.Z.F.O.A., 2007), is considered highly susceptible to the disease (Watt et al., 2009a). Currently Dothistroma needle blight is controlled by spraying copper oxides and *Dothistroma* resistant *P. radiata* is often planted in areas where the disease is severe.

There are two species of *Dothistroma* that are known to cause Dothistroma needle blight, *D. pini* and *D. septosporum*. These species were recently separated based on genetic diversity (Barnes et al., 2004). Only *D. septosporum* has been found in New Zealand, the sexual stage *Mycosphaerella pini* (Rostrup ex Monk) is not present. Spores are dispersed during rain or heavy mist and spore germination is dependent on the moisture and temperature the spores are exposed to (Gadgil, 1967; Gibson, 1972). In the field, optimum temperature and prolonged needle leaf wetness are important factors for increasing disease incidence and severity.

Although Dothistroma needle blight is present throughout New Zealand there are wide regional differences in severity. Research shows an air temperature of 16 to 20° C and continuously wet conditions to be optimum for infection and growth of the fungus causing Dothistroma needle blight. Consequently, the most severely affected regions are those with high rainfall and moderate temperatures. In the North Island, infection levels tend to be low in Northland, Hawke's Bay and the Wairarapa, whereas the central North Island, Waikato and Taranaki are the most severely affected regions. In the South Island, infection is most severe around Westland with low infection levels found throughout the remainder of the South Island.

The strong correlation between climate and disease makes Dothistroma needle blight an ideal disease for modelling using climate-based programs such as CLIMEX. Recent modelling of the global distribution of this disease has shown that it can tolerate a very wide geographical and climatic range (Watt et al., 2009a). The distribution of Dothistroma needle blight worldwide has also been predicted under a variety of climate change scenarios. Although the models showed an overall global reduction in potentially suitable area under climate change, range expansions were predicted for several areas including Scandinavia, Eastern Europe, British Columbia and New Zealand (Watt et al., submitted).

There are indications that the changes predicted by these climate-based models are in the process of occurring. Outbreaks of Dothistroma have been observed in various parts of the world since the 1950s. However, more recently there have been several reports of Dothistroma outbreaks or range expansions that are thought to be linked to changes in climate. For instance, range expansion of Dothistroma needle blight has recently been reported in Finland and Estonia (Hanso and Drenkhan, 2008; Müller et al., 2009). In British Columbia, Canada and Britain, severe outbreaks of Dothistroma needle blight have been correlated with wetter and warmer summer/spring conditions (Woods et al., 2005; Brown and Webber, 2008). This range expansion of Dothistroma needle blight is of serious concern to New Zealand's forest industry as it could point to increased disease pressure in this country and further losses to the forest sector.

Given the importance of Dothistroma needle blight to New Zealand's forest industry, determining how climate change is likely to influence the distribution of this disease would be of considerable use to forest managers. In this study we use previously developed CLIMEX models for Dothistroma needle blight to determine the potential distribution of this

disease and simulate a series of future climate scenarios to assess the sensitivity of the distribution of this disease to climate change in New Zealand. The potentially suitable area for *Dothistroma* needle blight under both current climate and climate change was quantified by region. By combining these projections with information on the distribution of available hosts, predictions of forest areas most at risk from *Dothistroma* needle blight under current and future climate have been made.

Materials and Methods

The CLIMEX model

CLIMEX is a dynamic model that integrates modelled weekly responses of a population to climate to create a series of annual indices (Sutherst et al., 2007b). CLIMEX uses an annual growth index to describe the potential for population growth as a function of soil moisture and temperature during favourable conditions. It uses up to eight stress indices (cold, wet, hot, dry, cold-wet, cold-dry, hot-wet and hot-dry) to simulate the ability of the population to survive unfavourable conditions. CLIMEX also includes a mechanism for defining the minimum amount of thermal accumulation (number of degree days) during the growing season that is necessary for population persistence (PDD).

The growth and stress indices are calculated weekly, and then combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), that gives an overall measure of the potential of a given location to support a permanent population of the species (Sutherst et al., 2007b). The EI ranges from 0 for locations at which the species is not able to persist to a theoretical maximum of 100 for locations that are climatically perfect for the species (Sutherst et al., 2007b). Due to seasonality in climate, it is usually only near the equator where climatic conditions are stable enough that values of 100 are ever attained (Stephens et al., 2007). In this study EI is classified into unsuitable (EI = 0), marginal (EI = 1-5), suitable (EI = 6-20) and optimal (EI > 20) categories for *Dothistroma* needle blight.

CLIMEX models are generally fitted to known distribution data using a manual iterative process. This involves adjusting growth and stress parameters and then comparing model results to the known range of the species and any additional information that is available (e.g. its observed growth phenology at a known location for which appropriate climatic data is available). In setting these parameters, consideration is also given to the biological reasonability of the selected parameters. This process allows models to be developed that conform with all that is known about the species across a range of knowledge domains.

Known distribution and model fitting

The known distribution of *Dothistroma* spp. (*D. pini* and *D. septosporum*) were compiled from an extensive literature search of herbarium and disease databases as described in detail previously (Watt et al., 2009a). *Dothistroma* spp. have a cosmopolitan distribution, occurring in Eurasia, Africa, Oceania and the Americas. These occurrences span a diverse range of environments that include tropical, subtropical, temperate, Mediterranean, continental, and subarctic climates. Records were not separated for *D. pini* and *D. septosporum* as these species can only be separated using molecular markers (Barnes et al., 2004). As they were only recently designated as two separate species the identity of the majority of records remains unknown.

A previously constructed CLIMEX model (fully described in (Watt et al., 2009a)), was used to model current and future distribution for *Dothistroma* needle blight. The fit of this model was validated using an extensive set of observed occurrences from locations not used in

the original fitting dataset (Watt et al., 2009a). These validations showed that almost all observations of Dothistroma needle blight occurred in suitable areas ($EI \geq 1$).

Climate change scenarios

Six climate change scenarios were used to project the potential distribution of Dothistroma needle blight under climate change during the 2080s within New Zealand. These scenarios were developed from three Global Climate Models (GCMs) run using two standard International Panel on Climate Change (IPCC) scenarios, representing medium (A1B) and high (A2) emissions, drawn from the set of standardised emissions scenarios (IPCC et al., 2007). The GCM data employed in this project were drawn from the World Climate Research Programmes Coupled Model Intercomparison Project phase 3 multi-model dataset (Meehl et al., 2007). The three GCMs selected had relatively small horizontal grid spacing (100 – 175 km) and the requisite climatic variables at the monthly resolution required by CLIMEX. Selected GCMs included CSIRO Mark 3.0 (CSIRO, Australia), NCAR-CCSM (National Centre for Atmospheric Research, USA), and MIROC-H (Centre for Climate Research, Japan). Data from these GCMs were pattern-scaled to develop individual change scenarios relative to the base climatology (Whetton et al., 2005). The three models cover a range of climate sensitivity, defined as the amount of global warming for a doubling of the atmospheric CO₂ concentration compared with 1990 levels. The respective climate sensitivities are: CSIRO Mark 3.0 (2.11 °C), NCAR-CCSM (2.47 °C), and MIROC-H (4.13 °C).

Estimating land areas for Ecoclimatic Index classes

Areas of New Zealand with a suitable climate, (i.e., $EI \geq 1$), for Dothistroma needle blight, under current and future climate scenarios, were estimated by Regional Council administrative areas using ArcGIS. A regional council boundary shapefile for New Zealand was used to extract EI data by region. The areas for each EI value (per region) were calculated and summarised to obtain the total area per EI value by region. The data was then classified using suitability values and the total area per suitability classification was calculated. The area distribution of EI by class (unsuitable, marginal, suitable, optimal) was also determined for current pine plantations under current and the six future climate scenarios. Current New Zealand pine plantations were identified within the Land Cover Database layer (LCDB2), (Terralink NZ Ltd, 1996) using ArcGIS. The two LCDB2 classes specific to pine were 'pine forest open canopy and pine forest closed canopy'.

Results

Potential distribution of Dothistroma needle blight under current climate

Pine plantations are dispersed throughout the country (Fig. 2.1a), with the largest areas located in the central North Island, Northland, Gisborne and the northern South Island (N.Z.F.O.A., 2007). Under current climate the potential distribution of Dothistroma needle blight in New Zealand includes the entire North Island (Fig. 2.1b). The potential distribution in the South Island was also extensive, only relatively small areas in the south-west and inland Canterbury were projected to be unsuitable (Fig. 2.1b). The potential distribution included close to all current plantations in New Zealand (Table 2.1).

Table 2.1. Projected softwood plantation area, by EI class, under a current climate suitable for *Dothistroma* needle blight. Also shown are actual changes in suitable area under these classes for the six climate change scenarios.

	Current climate km ²	Changes in plantation areas by EI class under future climate					
		CSIRO		NCAR-CCSM		MIROC-H	
		A1B	A2	A1B	A2	A1B	A2
Unsuitable (EI = 0)	4	-4	-4	-4	-4	-4	-4
Marginal (EI= 1-5)	0	0	0	0	0	0	0
Suitable (EI = 6-20)	145	-3	-9	-9	-62	-135	-3
Optimal (EI >20)	14076	+7	+14	+14	+66	+139	+7

Potential distribution under climate change

Under climate change, the potentially suitable area in New Zealand for *Dothistroma* needle blight was projected to increase (Fig. 2.2). For the NCAR and MIROC models all of the country is projected to be suitable, while for the CSIRO model the entire country, apart from a small area in Southland is projected to be suitable (Figs. 2.2, 2.3). For the existing plantation forests, close to all plantations were projected to be suitable for *Dothistroma* needle blight (Table 2.1). Under climate change EI generally increases, as reflected by the reductions in areas classed as suitable and concurrent increases in areas projected to be optimal (Table 2.1).

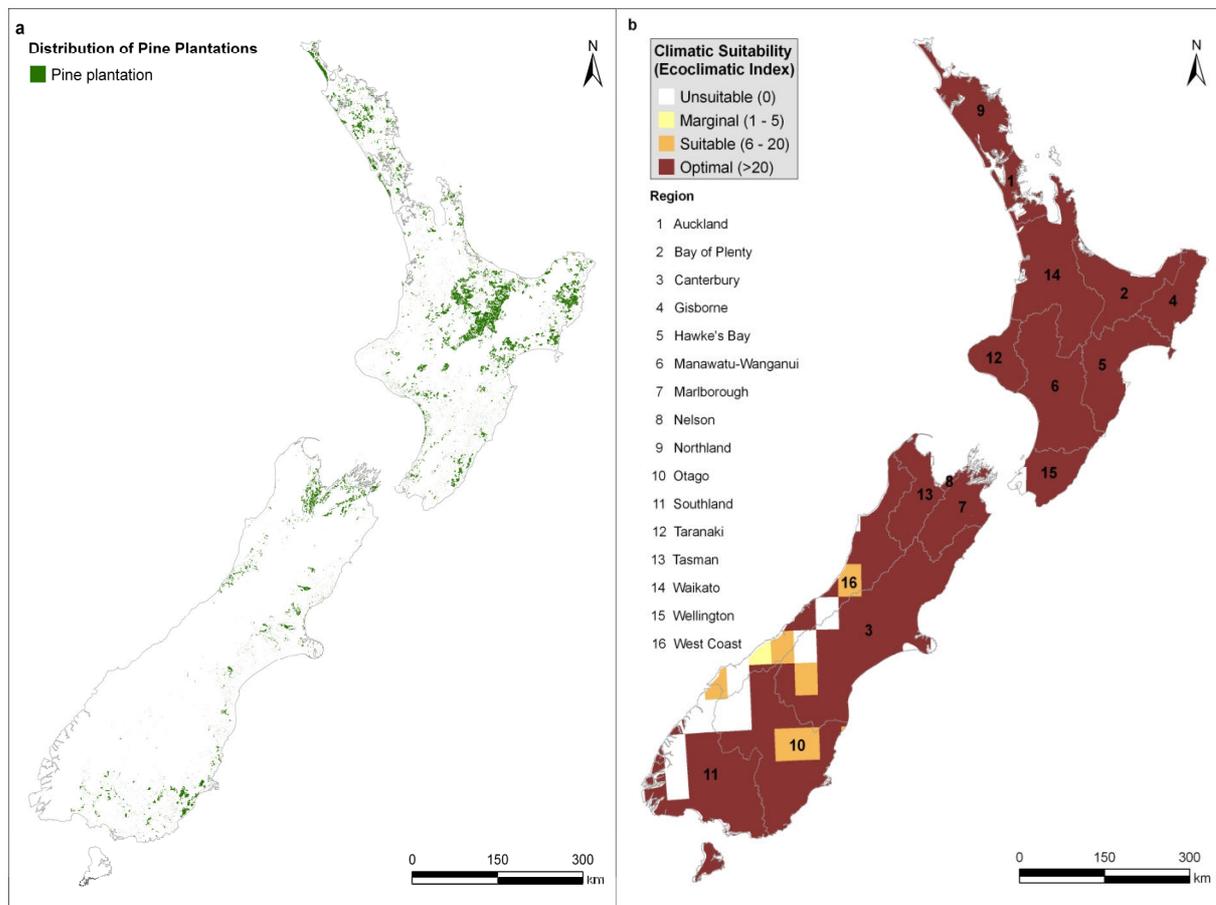


Figure 2.1. New Zealand map showing (a) location of existing *Pinus* spp. plantations and (b) ecoclimatic suitability, by region, for *Dothistroma* needle blight under current climate.

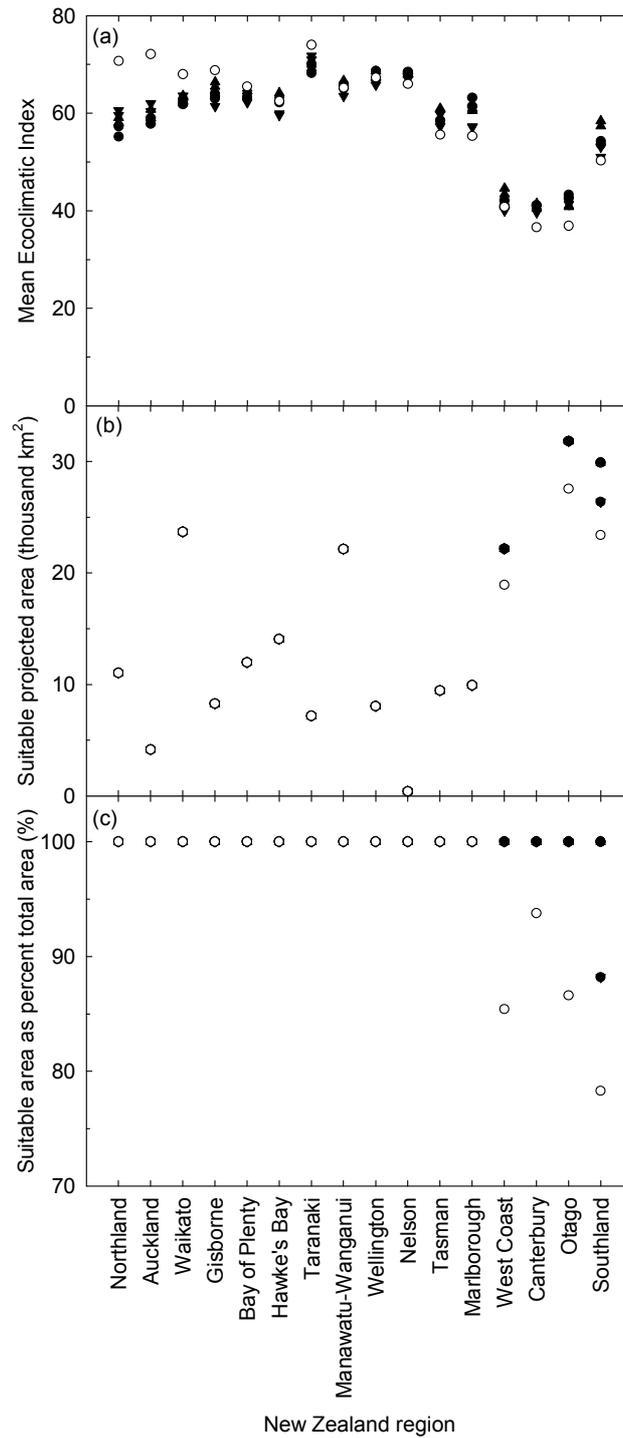


Figure 2.2. (a) Mean Ecoclimatic Index and suitable area for *Dothistroma* needle blight, expressed as an (b) absolute amount and (c) percentage of total region area, within New Zealand under current (open circles) and future climate (under A1B and A2 scenarios) projected using the CSIRO (downward facing triangles), MIROC (closed circles) and NCAR (upward facing triangles) models. Regions within New Zealand are sorted left to right in order of increasing latitude.

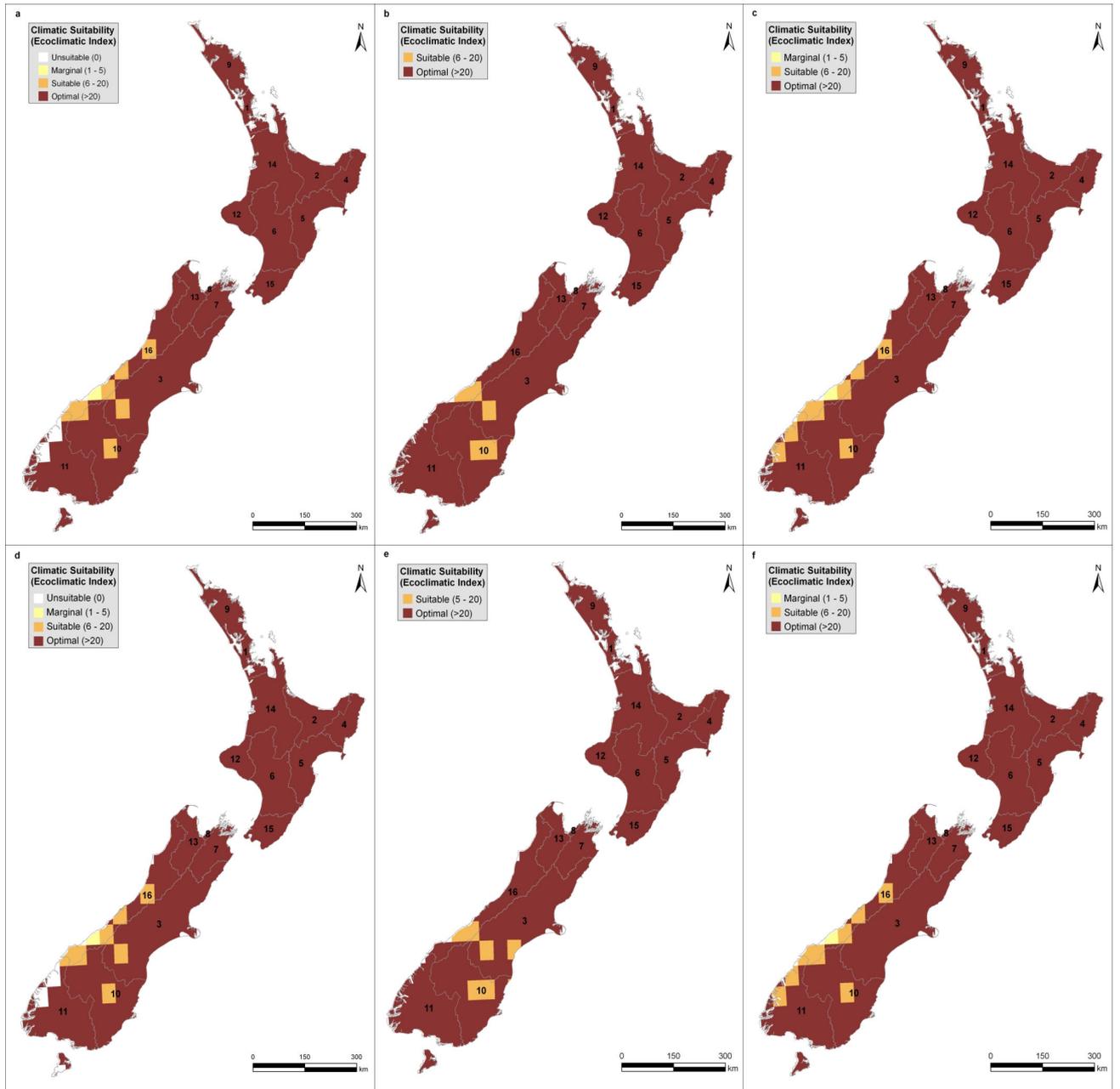


Figure 2.3. New Zealand map showing ecoclimatic suitability (EI) for *Dothistroma* needle blight under climate scenarios derived from: (a) CSIRO Mark 3.0; (b) NCAR-CCSM; (c) MIROC-H run with the AIB emissions scenario; (d) CSIRO Mark 3.0; (e) NCAR-CCSM; (f) MIROC-H run with the A2 emissions scenario.

Discussion

The distribution models for *Dothistroma* needle blight under climate change predict an increase in the disease range in New Zealand. Although current climate models show the majority of New Zealand currently has climate conditions suitable for *Dothistroma* needle blight, this area is expected to expand in southern regions. Most importantly, there are no areas predicted to become unsuitable for the disease and the predicted disease range under climate change remains the same over the primary pine growing areas.

The distribution models presented in this paper show the likelihood that *Dothistroma* needle blight will be able to become established in a region. The models do not include estimations of the severity of disease. This is evident with what is known about *Dothistroma* needle blight in New Zealand. For instance, although *Dothistroma septosporum* is present all over New Zealand and the disease occurs throughout the primary pine growing areas, there are regional differences in severity (Bulman et al., 2008). In the North Island, infection levels tend to be low in Northland, Hawke's Bay and the Wairarapa, whereas the central North Island, Waikato and Taranaki are the most severely affected regions (Bulman et al., 2008). In the South Island, infection is most severe around Westland with low infection levels throughout the remainder of the South Island (Bulman et al., 2008).

The CLIMEX models predict the majority of New Zealand will continue to have optimal climatic conditions for *Dothistroma* needle blight. This highlights the need for severity models to be completed for this disease that can show the current regional variation in disease levels, as well as predict the severity of *Dothistroma* needle blight throughout New Zealand under climate change. It is expected that severity models would be able to show regional variations where the disease could become worse or areas where there would be alleviations in disease pressure. In general, regions with high rainfall and moderate temperatures are likely to be high risk areas for *Dothistroma* needle blight. Such models would be helpful in planning future planting and forest management regimes.

Dothistroma needle blight is currently controlled in New Zealand through the spraying of copper oxides (Bulman et al., 2008). Trees are also pruned to help suppress disease levels and *Dothistroma* resistant pine material can be planted in high risk areas. Alternative methods for control of this disease are also being investigated. In view of the continued disease pressure expected under climate change improvements to the current control methods are recommended to help reduce the impact of this disease in the forestry sector. Severity models would be helpful in predicting high risk areas so future planting regimes could include *Dothistroma* resistant material or alternative species where required.

Currently, there is only one strain of *D. septosporum* present in New Zealand and molecular studies have shown a lack of variation within isolates in New Zealand (Hirst et al., 1999; Bradshaw, 2007). The introduction of other strains of *D. septosporum*, especially the other mating type could cause further problems to the forest industry if more virulent strains were to become established. Likewise, the impact that *D. pini*, the other *Dothistroma* species known to cause *Dothistroma* needle blight, could have on the forest industry is unknown. Continuation of the strict quarantine measures for importing live conifer plant material are essential for the prevention or early detection of other strains of *D. septosporum* or *D. pini* to New Zealand.

3. Using species niche models to inform strategic management of weeds in a changing climate. Demonstration of the method using *Buddleja davidii* within New Zealand as an example.

Summary

The expansion of the global area planted in fast-growing forest species seems likely as a means of offsetting carbon dioxide emissions and developing a sustainable bio-energy resource. In New Zealand, 0.8 to 4.9 million hectares of land have been identified as suitable for afforestation. Selecting appropriate sites for these plantations will require consideration of the effect of climate change on plantation growth and risks from abiotic and biotic factors.

Buddleja davidii has been identified as a weed that has impact on plantation forest production in New Zealand. While it is currently restricted mainly to the North Island, a large proportion of the area identified for forest expansion is in eastern and southern regions of the South Island where the weed is presently relatively scarce. Using a process-oriented climatic niche model (CLIMEX), predicted expansion of *B. davidii* is expected to be greatest in these eastern and southern regions of the South Island. Furthermore, since *B. davidii* predominantly colonises disturbed areas, the likely increases in plantation forest area can be expected to promote the spread of *B. davidii*. Adaptation strategies under climate change to manage *B. davidii* are discussed.

This study highlights the general utility of process-oriented niche models in identifying possible threats to planned primary production activities from invasive weed species. The synoptic overview afforded by distribution maps allows managers to identify regions that are likely to become less suitable in the future for the weed, and conversely areas that will be more suitable, and are not currently occupied. This type of knowledge is invaluable in planning and allocation of often scarce resources to most effectively control high impact weeds. Without the synoptic view of the invasion and the assets at risk, there is a strong potential for regional pest management to be parochial, and consequently less effective at all scales.

Introduction

Plantation forestry is a major industry in the southern hemisphere and contributes significantly to the economy of many countries (Lewis and Ferguson, 1993; N.Z.F.O.A., 2007). Although difficult to quantify, sustainably managed plantation forests also make major positive contributions to environmental and social issues, including erosion control, water quality, biodiversity conservation and opportunities for recreation (Ford-Robertson, 1996; Richardson et al., 1999; Palma, 2005; Brockerhoff et al., 2008; Giltrap et al., 2009).

New opportunities for improving financial returns to tree growers are likely to provide major incentives for plantation forest expansion. In particular, afforestation with fast-growing species is an effective means of offsetting carbon dioxide emissions to meet national commitments under the Kyoto protocol (Dixon et al., 1994). Recent research has also shown that plantation forests can be economically viable, independent and sustainable sources of bio-fuels (Hall et al., 2009). These factors are likely to result in increased rates of afforestation. For example, in New Zealand between 0.8 and 4.9 million hectares of marginal land has been identified as suitable for afforestation with a variety of exotic or native tree species planted for a wide range of end products (Hall et al., 2009).

The establishment and management of new plantings under climate change will be challenging. Selecting suitable sites and optimal species requires spatial information on how climate change could influence tree growth and the risks from abiotic and biotic factors through time. Climate change effects are likely to be direct, through changes in air temperature, atmospheric CO₂ concentration, and water balance (Watt et al., 2008). But there are also likely to be indirect effects on plantation growth, mediated through changes in the distribution and abundance of weeds, pathogens and insects, and through the severity of abiotic factors such as wind, snow and fire (Somerville, 1995; Wharton and Kriticos, 2004; Kriticos et al., 2007; Sutherst et al., 2007a; Watt et al., 2008; Potter et al., 2009; Watt et al., 2009b).

In plantation forestry, competition from weeds is the most important risk affecting establishment success and consequent tree growth and survival (Richardson, 1993; Mason and Milne, 1999; Watt et al., 2003; Wagner et al., 2006). Without management of this competing vegetation, tree survival on most sites would be very low, and the yield of the surviving trees would be dramatically decreased (Wagner et al., 2006). The degree of weed competition strongly depends on the type of weeds. Tall woody plants retard tree growth more than grasses and herbaceous species (Richardson et al., 1996; Watt et al., 2007) and are generally more difficult to control, often requiring repeated management treatments.

Maps describing the potential distribution of key high-impact weed species under climate change projections could be useful to land managers assessing the risks of expanding into new areas, or converting to plantation forestry from a different land use. As climate strongly influences plant distribution and abundance, such maps may provide a useful indication of the effects of climate change on species range boundaries. We propose that determining the intersection of potentially suitable areas for high impact weeds with regions designated for future plantations provides a useful basis for evaluating potential vegetation management risks.

Buddleja davidii Franchet, is a perennial, semi-deciduous shrub that readily establishes on disturbed sites predominantly in regions with temperate, Mediterranean, subtropical, and tropical climates (Tallent-Halsell and Watt, 2009). Native to central and southwestern China, *B. davidii* has been introduced as an ornamental to the Americas, New Zealand, Australia, Europe and some parts of Africa because of its fragrant and colourful flowers.

As well as being widely regarded as an attractive garden plant *B. davidii* is also a highly invasive species that competes strongly with other species in native ecosystems and plantation environments. In Europe, *B. davidii* poses such a significant conservation management threat that it has been identified as the highest priority target for biological control (Sheppard et al., 2006). Similarly, in the extensive plantations common in the central North Island of New Zealand, *B. davidii* retards tree growth more than any of the other major co-occurring weed species (Richardson et al., 1996). It has been rated by forest managers as the most problematical weed species within this region (Watt et al., 2008).

CLIMEX™ (Hearne Scientific, Melbourne, Australia, (Sutherst et al., 2007b), is a computer package popular as a tool contributing to risk assessments for arthropod pests, and diseases. CLIMEX has been used successfully to project the potential distribution of invasive plants including tropical woody weeds (Kriticos et al., 2003a; Kriticos et al., 2003b; Dunlop, 2006), sub-tropical trees (Watt et al., 2009b), and temperate shrubs (Potter et al., 2009). Since CLIMEX includes global meteorological databases and process-based algorithms for simulating species climatic responses, it can project species potential distributions into novel climates with more confidence than empirically-based regression models (Kriticos and Randall, 2001).

In this report we consider how the development of distribution maps using CLIMEX can be used to inform policy makers, planners and investors of the risk associated with establishment of new plantations under changing climate. As a case study we focussed on how changes in the potential distribution of *B. davidii* under climate change, described by Kriticos *et al* (submitted) are likely to overlap with current and planned forest plantations in New Zealand. This information was then used to identify strategies to mitigate the potential impact of *B. davidii* on the future plantations. We then discuss the utility of this approach as a generic approach for identifying impacts of high impact biotic risks on plantation forests under climate change.

Materials and Methods

The CLIMEX model

CLIMEX is a dynamic model that integrates modelled weekly responses of a population to climate to create a series of annual indices (Sutherst et al., 2007b). CLIMEX uses an annual growth index to describe the potential for population growth as a function of soil moisture and temperature during favourable conditions. It uses up to eight stress indices (cold, wet, hot, dry, cold-wet, cold-dry, hot-wet and hot-dry) to simulate the ability of the population to survive unfavourable conditions. CLIMEX also includes a mechanism for defining the minimum amount of thermal accumulation (number of degree days) during the growing season that is necessary for population persistence (PDD).

The growth and stress indices are calculated weekly, and then combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), that gives an overall measure of the potential of a given location to support a permanent population of the species (Sutherst et al., 2007b). The Ecoclimatic Index (EI), ranges from 0 for locations at which the species is not able to persist to a theoretical maximum of 100 for locations that are climatically perfect for the species (Sutherst et al., 2007b). Due to seasonality in climate, it is usually only near the equator where climatic conditions are stable enough that values of 100 are ever attained (Stephens et al., 2007). In this study EI is classified into unsuitable (EI = 0), marginal (EI = 1-5), suitable (EI = 6-25) and optimal (EI > 25) categories for *B. davidii*.

CLIMEX models are generally fitted to known distribution data using a manual iterative process. This involves adjusting growth and stress parameters and then comparing model results to the known range of the species and any additional information that is known about it (e.g. its observed growth phenology at a known location for which appropriate climatic data is available) (Sutherst et al., 2007b). In setting these parameters, consideration is also given to the biological reasonability of the selected parameters. This process allows models to be developed that conform with all that is known about the species across a range of knowledge domains.

Known distribution of *Buddleja davidii* and model fitting

The global distribution of naturalised *B. davidii*, which has been previously described by Kriticos *et al.* (submitted), was determined from a survey of locality data held by various institutions and an extensive literature review. These records show the core distribution of *B. davidii* to be warm humid regions that include temperate, subtropical, tropical and Mediterranean climates. The species range does extend into cool humid continental climates but the distribution in these areas is somewhat limited.

Climate suitability simulations were made using a previously constructed CLIMEX model for *B. davidii*, that has been fully described previously (Kriticos et al., submitted). Under current climate the projected potential worldwide distribution has been previously described (see (Kriticos et al., submitted)). The potential New Zealand distribution is reproduced from Kriticos et al (submitted) as Figure 3.1c.

Climate change scenarios

Six climate change scenarios were used to project the potential distribution of *B. davidii* during the 2080s under climate change. These scenarios were developed from three Global Climate Models (GCMs) run using two standard International Panel on Climate Change (IPCC) scenarios, representing medium (A1B) and high (A2) emissions, drawn from the set of standardised emissions scenarios (IPCC, 2007). The GCM data employed in this project were drawn from the World Climate Research Programmes Coupled Model Intercomparison Project phase 3 multi-model dataset (Meehl et al., 2007). The three GCMs selected had relatively small horizontal grid spacing (100 – 175 km) and the requisite climatic variables at the monthly resolution required by CLIMEX. Selected GCMs included CSIRO Mark 3.0 (CSIRO, Australia), NCAR-CCSM (National Centre for Atmospheric Research, USA), and MIROC-H (Centre for Climate Research, Japan). Data from these GCMs were pattern-scaled to develop individual change scenarios relative to the base climatology (Whetton et al., 2005). The three models cover a range of climate sensitivity, defined as the amount of global warming for a doubling of the atmospheric CO₂ concentration compared with 1990 levels. The respective climate sensitivities are: CSIRO Mark 3.0 (2.11 °C), NCAR-CCSM (2.47 °C), and MIROC-H (4.13 °C).

Estimating land areas for Ecoclimatic Index classes

Areas of New Zealand with a suitable climate (i.e., EI ≥ 1) for *B. davidii* under both current and future climate were estimated using Regional Council administrative areas with ArcGIS. A regional council boundary shapefile was used to extract EI data by region. The area for each EI value (per region) was calculated and summarised to obtain the total area per EI value by region. The data was then classified using suitability values and the total area per suitability classification was calculated. The areal distribution of EI was also determined for current and potential plantations, under current and future climate as projected using the CSIRO A1B and NCAR A2 scenarios.

Estimating areas for potential afforestation

Land area in New Zealand suitable for future plantations was identified using the selection process and criteria previously described (Hall et al., 2009). Briefly, the selection of candidate area for afforestation was undertaken using GIS analysis and a range of

datasets that included elevation, slope and land use layers. Highly productive lands (based on land use classification and land use), developed areas (e.g. cities), existing plantations, indigenous forest area and other areas such as wetlands, and the Public Conservation Land administered by the Department of Conservation were excluded.

From these datasets a range of selection criteria were used to delineate four scenarios for potential new afforestation. We present the extremes of the four potential afforestation scenarios described in detail (Hall et al., 2009). The most conservative base scenario, that identifies 0.83 million ha of land for future afforestation assumes suitable areas to have a slope of less than 45° and elevations lower than, respectively, 800 and 700 m a.s.l., in the North and South Island. This scenario includes a range of low performing and underutilised land classes. In the least conservative scenario, 4.93 million ha of land is identified as suitable for future afforestation. Compared to the base scenario, the assumption around elevation is relaxed to 1 000 m a.s.l., and this scenario also assumes high producing grassland to be suitable for afforestation (Hall et al., 2009). It should be emphasised that the least conservative scenario represents an extreme that is unlikely to be realised in practice, whereas the afforestation of the 0.83 million ha in the conservative scenario is realistic.

Results

Areas suitable for afforestation

Under the conservative climate-change scenario the area suitable for future afforestation is 0.83 million ha (Fig 3.1a). In total 90% of this potential new forested land is in the South Island, with most of it in the south-eastern regions of Canterbury (342 000 ha), and Otago (318 000 ha). For the least conservative climate-change scenario 4.93 million ha was found to be suitable for afforestation (Fig 3.1b). This area was evenly split between the North (2 505 000 ha) and South Islands (2 422 000 ha). Under this scenario, the regions with the two largest areas that could potentially be afforested were Canterbury (1 020 000 ha), and Otago (886 000 ha). With the exception of eastern and southern regions of the South Island, *B. davidii* is relatively widespread in all areas identified for future afforestation (Figs. 3.1a,b).

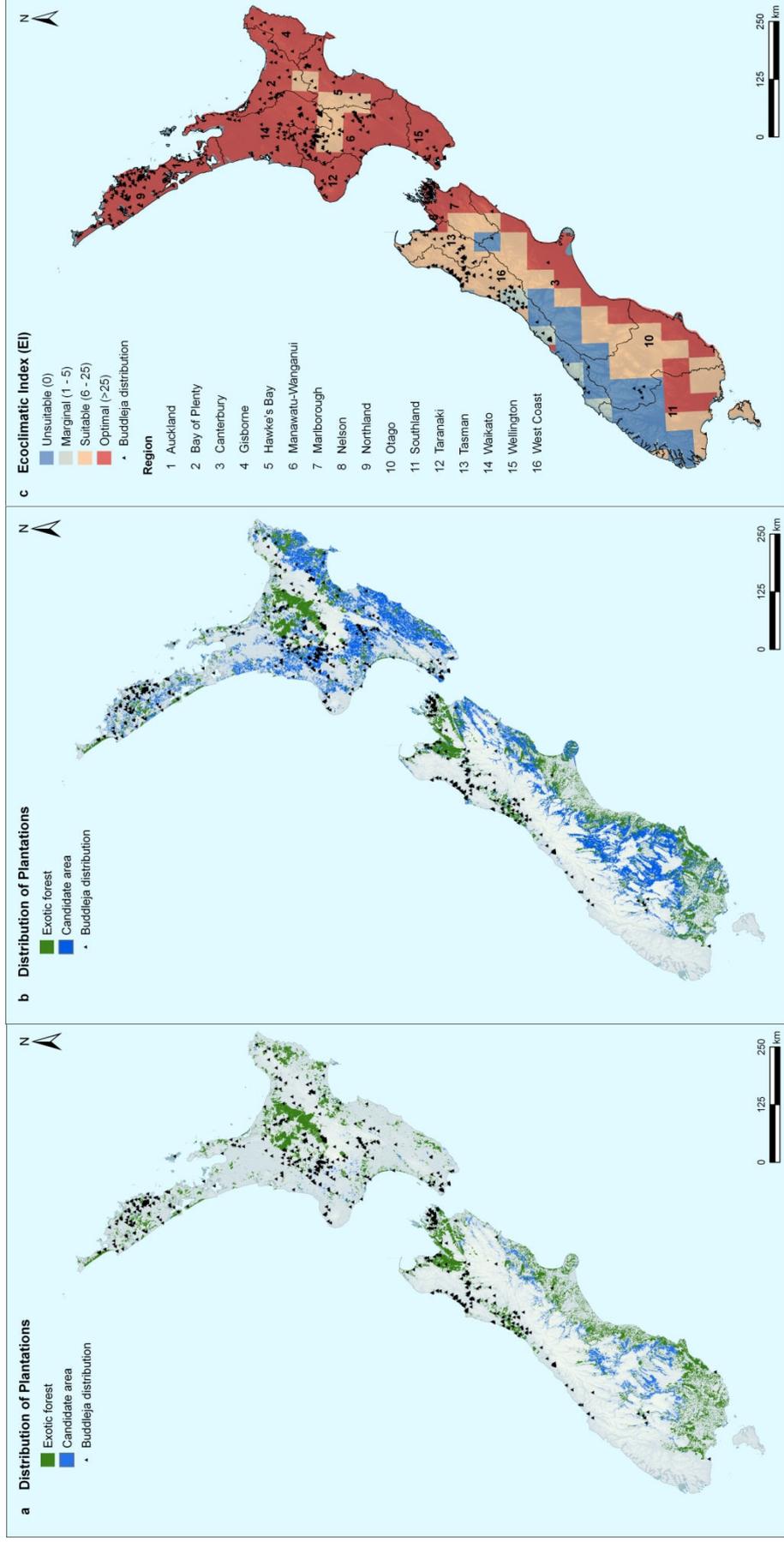


Figure 3.1. New Zealand map showing afforestation scenarios with existing (green) and proposed (blue) plantations assuming an (a) low level (0.83 M ha) of future afforestation and (b) high level (4.93 M ha) of future afforestation. Also shown is (c) the ecoclimatic index for *Buddleja davidii* by region, under current climate. Maps shown in (a) and (b) were reproduced from Hall et al., (2009). On all figures the actual current distribution of *Buddleja davidii* is shown (black circles). Regional boundaries are shown as black lines.

Model fit and potential distribution of *Buddleja davidii* under current climate

Model projections of the potential distribution for *B. davidii* corresponded well with the observed distribution in New Zealand (Fig. 3.1c). There were a small number of observations of *B. davidii* in Otago, Southland and the West Coast in areas that were projected to be unsuitable (Fig. 3.1c). However, the misfit was due to a scaling issue (see (Kriticos and Leriche, in press) for a detailed description of this issue), whereby microclimatic variation was inadequately captured at the 0.5 degree grid resolution used. Closer inspection shows that all observations were located at warmer, low elevations, well below the mean elevation of the grid cells in which they occurred.

Projections of potential distribution under current climate show most of the North and South Island to be suitable for *B. davidii* (Fig. 3.1c). Regions that are unsuitable for *B. davidii* are located at high altitude adjacent to the main axial ranges in the South Island (Fig. 3.1c). There are large tracts of land (tens of thousands of square kilometres) suitable for *B. davidii* within the south-east of the South Island where *B. davidii* is currently scarce (Fig. 3.1c).

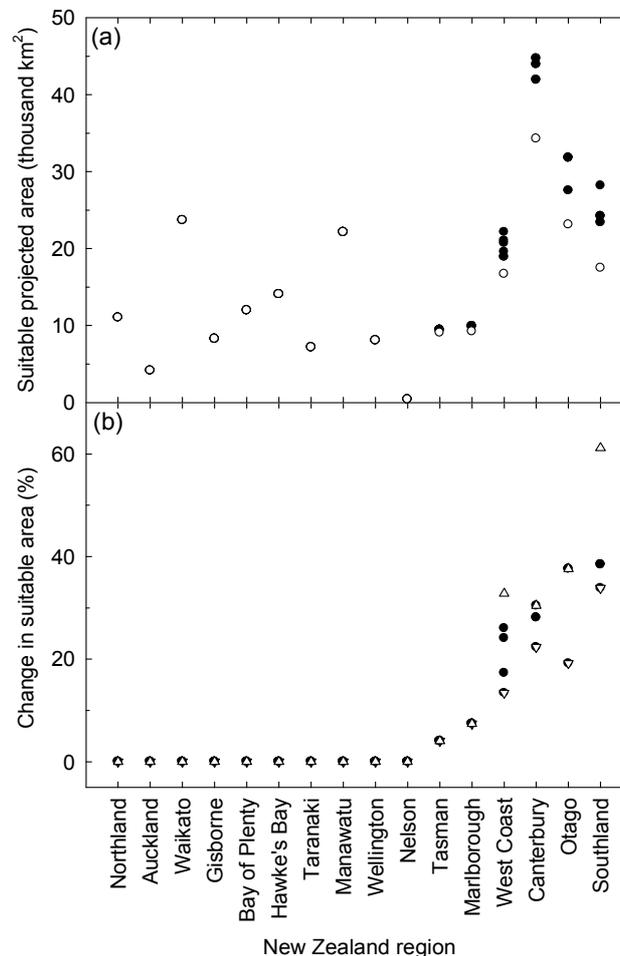


Figure 3.2. (a) Area projected to be suitable for *B. davidii*, by region, under current climate (open circles) and projected future climate (filled circles); (b) Percentage change in suitable area under climate change, expressed relative to current climate, using the CSIRO AIB model (downward facing triangles), NCAR A2 model (upward facing triangles), and the remaining four climate change scenarios (filled circles). Regions (as shown in Figure 3.1c) are sorted left to right in order of increasing latitude.

Within the climatically suitable areas, EI values under current climate ranged widely between regions, and were negatively correlated with region latitude (Fig. 3.3a). Regional averages for EI ranged five-fold from 8 on the West Coast of the South Island to 43 in Auckland and Northland (Fig. 3.3a).

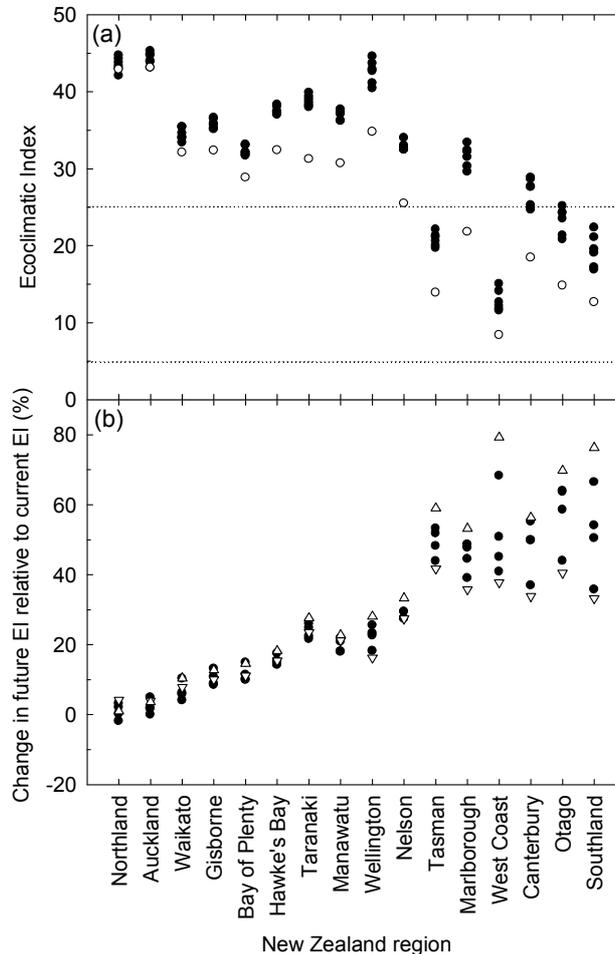


Figure 3.3. (a) Variation in EI, by region, under current (open circles) and future climate (filled circles); (b) Percentage change in EI, expressed relative to current climate, using the CSIRO AIB model (downward facing triangles), NCAR A2 model (upward facing triangles), and the remaining four climate change scenarios (filled circles). Regions (as shown in Fig. 3.1c) are sorted left to right in order of increasing latitude.

Potential distribution under climate change

Although the potential distribution of *B. davidii* increased under all future climate scenarios (Figs. 3.2, 3.4) these increases exhibited marked regional variability within New Zealand. As the entire North Island currently ranges from suitable to optimal for *B. davidii* (Fig. 3.1c), no further potential range expansion occurred under the future climate scenarios (Fig. 3.2). However, in the South Island, model projections show considerable potential range expansion (Figs. 3.2) particularly in high country areas adjacent to the Southern Alps (Fig. 3.4).

Proportional range increases in the South Island increased positively with region latitude, ranging from 4% in Tasman for all six scenarios to between 34 and 61%, respectively, for the CSIRO A1B and NCAR A2 in Southland (Fig. 3.2b). For all regions within the South Island expansion was lowest under the CSIRO AIB scenario (Fig. 3.2b; downward facing triangle) and highest under the NCAR A2 scenario (Fig. 3.2b; upward facing triangle).

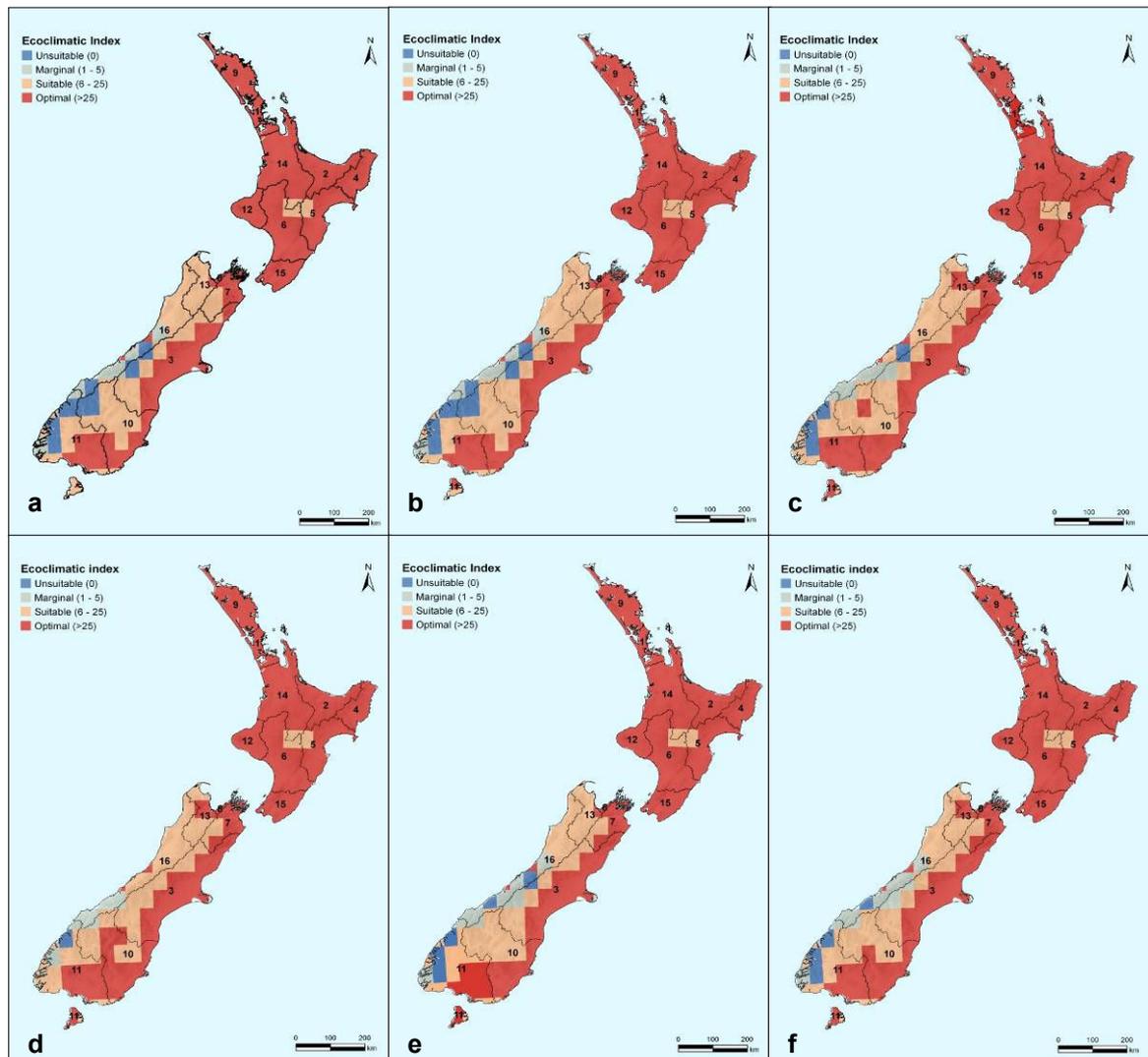


Figure 3.4. New Zealand map showing ecoclimatic suitability for *B. davidii* under climate scenarios derived from: (a) CSIRO Mark 3.0; (c) NCAR-CCSM; (e) MIROC-H run with the AIB emissions scenario; (b) CSIRO Mark 3.0; (d) NCAR-CCSM; (f) MIROC-H run with the A2 emissions scenario.

As well as affecting the potential distribution of *B. davidii*, the future climate scenarios had a marked influence on the EI of suitable areas throughout New Zealand. Although there were small areas throughout New Zealand, where EI declined slightly under climate change, in general there was a moderate to marked increase in EI throughout most regions (Fig. 3.5). At a regional level these increases, relative to current climate, exhibited a positive relationship with latitude, ranging from -2 to 4% in Northland to 40 to 70% in Otago (Fig. 3.3b).

Averaged across regions, changes in EI under climate change, relative to current climate, were on average lowest for the CSIRO model (average of 23% increase), intermediate for the MIROC model (average of 27.5% increase), and greatest for the NCAR model (average of 33.5% increase). In contrast, changes in EI exhibited less than 3% variation between the two emission scenarios used (AIB and A2) for all three models.

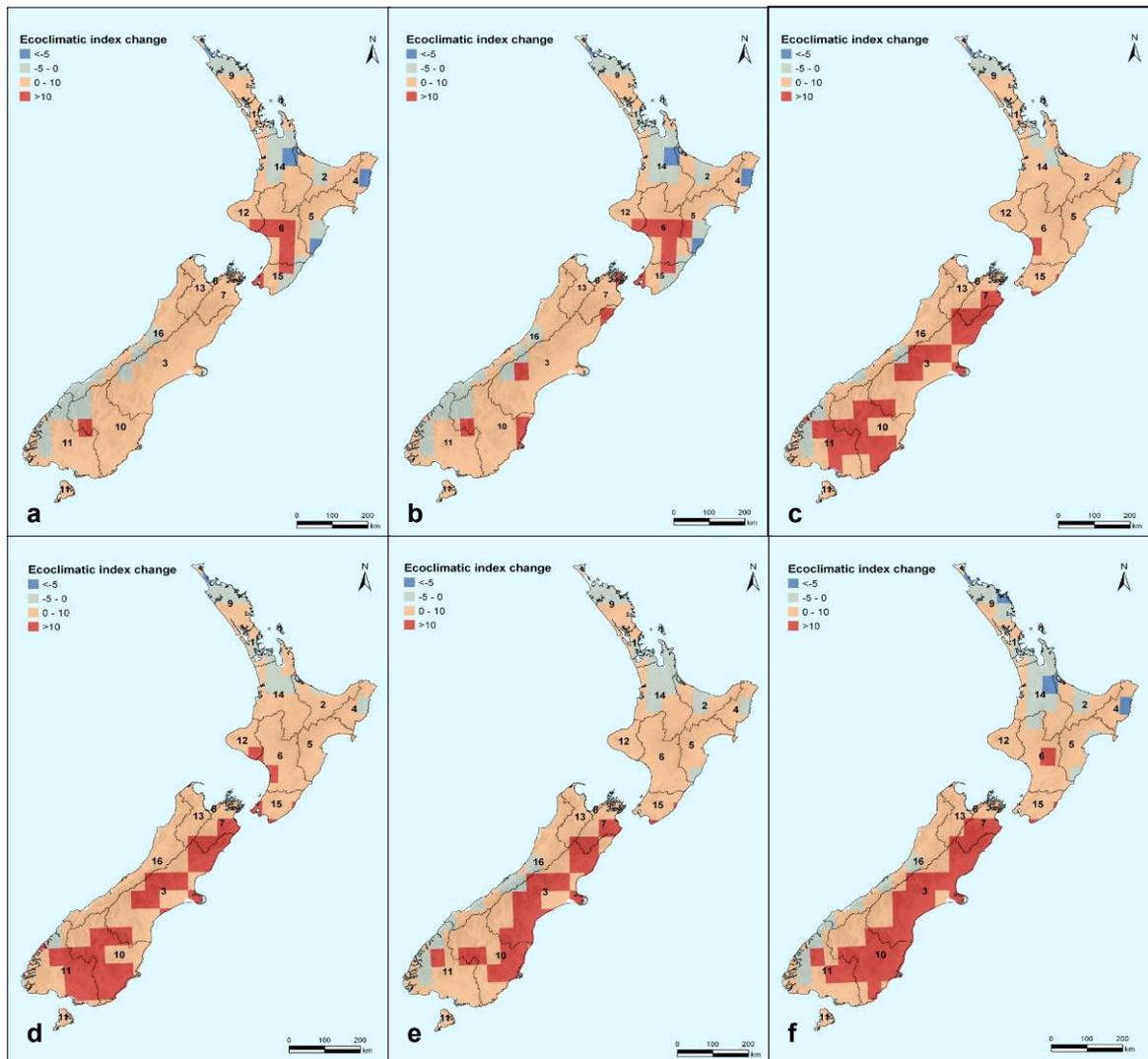


Figure 3.5. New Zealand map showing change in ecoclimatic suitability (EI) of New Zealand, relative to EI under current climate, for *B. davidii* under climate scenarios derived from: (a) CSIRO Mark 3.0; (c) NCAR-CCSM; (e) MIROC-H run with the AIB emissions scenario; (b) CSIRO Mark 3.0; (d) NCAR-CCSM; (f) MIROC-H run with the A2 emissions scenario.

Ecoclimatic index under current and proposed plantations

Climate change is likely to shift the area distribution of EI substantially to the right for both current and proposed future plantations, increasing the suitability of these plantations for invasion from *B. davidii* (Fig. 3.6). For current plantations, areas projected to be unsuitable, marginal, suitable and optimal for *B. davidii*, constituted, respectively, 0.6, 0.9, 30 and 68.5% of the total plantation area. Compared to current climate, climate change substantially reduces the area projected to be suitable (reductions of 19% of plantation area for CSIRO AIB and 22% for NCAR A2), which is offset by increases in areas projected to be optimal for *B. davidii* (increases of 19% of plantation area for CSIRO AIB and 24% for NCAR A2).

For the proposed plantations, similar changes were noted for both the planting scenarios (Figs. 3.6b, c). In contrast to current climate under which 8% of area was unsuitable, very little area (0 to 1%) was unsuitable under the two extreme climate change scenarios examined (Fig. 3.6b, c). Compared to current climate the area defined to be suitable was considerably lower under both climate change scenarios. In contrast, considerably more of the area was classified as optimal under future climate as modelled by both CSIRO AIB and NCAR A2 scenarios, compared to current climate.

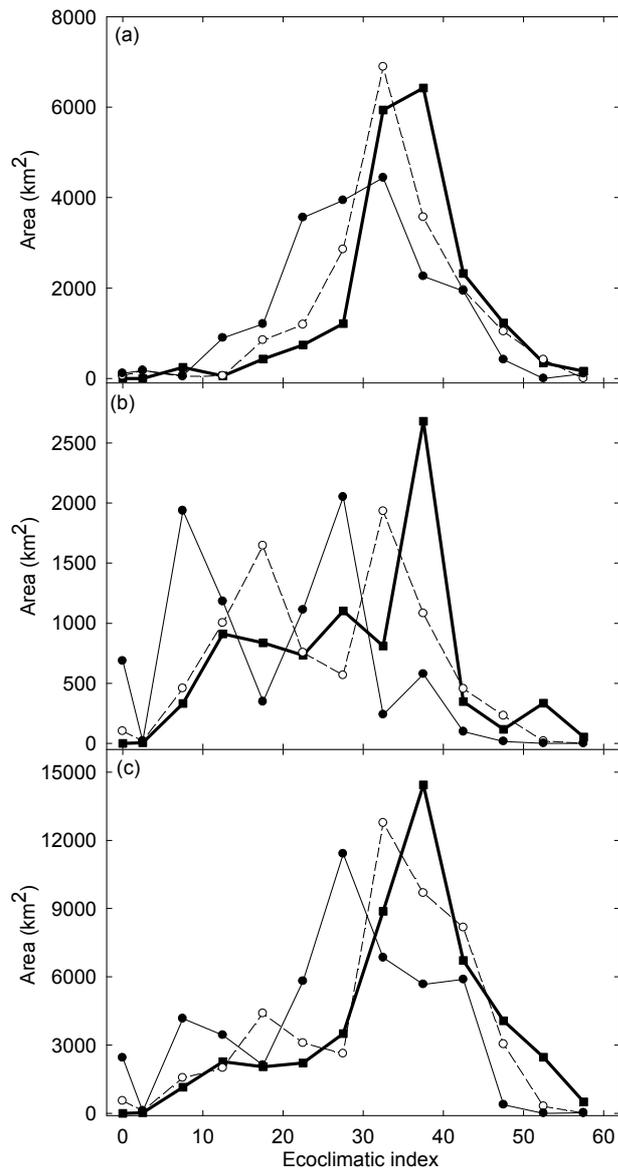


Figure 3.6. Frequency distribution of plantation area by Ecoclimatic Index for *Buddleja davidii*, for: (a) current plantations; (b) proposed plantings assuming 0.83 M ha; (c) proposed plantings assuming 4.9 M ha afforestation. Each figure shows the frequency distribution of plantation area by EI, under current climate (filled circles, solid line), future climate projected using CSIRO A1B (open circles, dashed line) and NCAR A2 (filled squares, thick line) models.

Examination of the present distribution of *B. davidii* clearly shows that there are sparse populations of the species in eastern and southern regions. Given the threat posed to future plantation expansion in this area a control line is likely to be of significant use in reducing spread rates. Figure 3.7 shows one potential position of a control line which follows Tasman and the West Coast regional boundaries, and bisects Marlborough along a major arterial road. This control line delineates populations of *B. davidii* in the north and west, that are too numerous to totally control, from populations in the south and east, that are relatively sparse in number and could feasibly be eradicated locally or regionally.

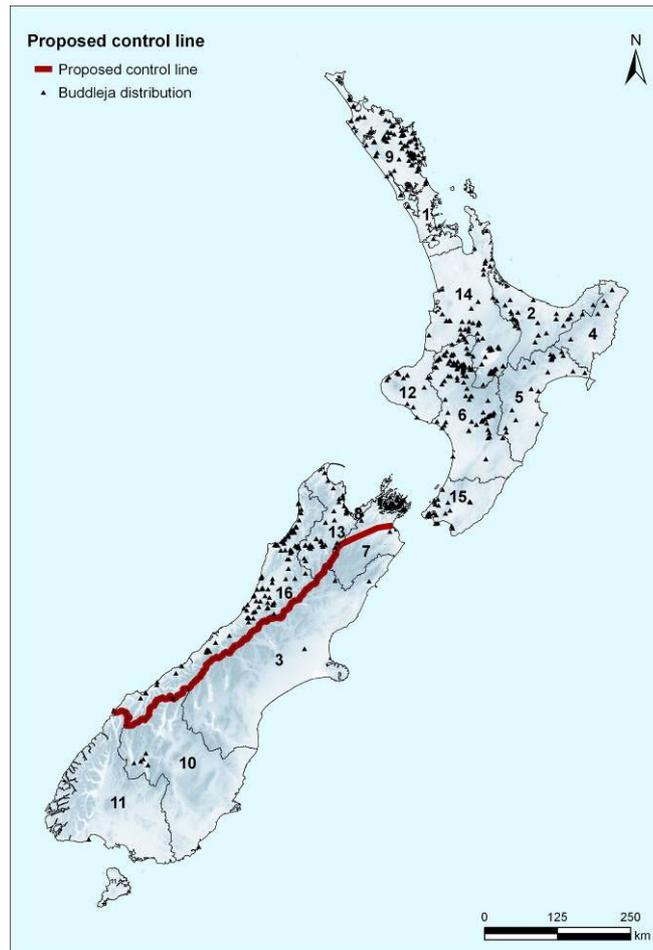


Figure 3.7. Map of New Zealand, showing the proposed control line and the current distribution of *Buddleja davidii*. The control line follows the regional boundaries of West Coast and Tasman and bisects Marlborough along a major road (State Highway 63). The current distribution of *Buddleja davidii* is shown as black circles.

Discussion

It is apparent from this analysis that under current climate *B. davidii* is capable of occupying a far greater range than it currently inhabits within New Zealand. Of most concern are currently unoccupied regions in the east and south of the South Island. Under future climate scenarios the climate suitability for *B. davidii* increases in this region, which increases the scope for marked range expansion.

The risk of *B. davidii* expanding its range into eastern and southern regions of the South Island of New Zealand is likely to be increased by planned changes in land use. Under both future forest scenarios considered, these regions show the greatest potential for further afforestation, with estimates ranging from approximately 0.71 million ha to 2.14 million ha. Currently the predominant land use in this region is pastoral agriculture, with forest plantations comprising only 3% of the total land area. The proportion planted to forests is less than half of the national average (6.9%), and around 1/7th of that in the key forestry regions of the Central North Island, where *B. davidii* currently has the most impact (N.Z.F.O.A., 2007).

As *B. davidii* predominantly colonises disturbed areas (Miller, 1984), substantial increases in plantation forest area within this region are likely to exacerbate the rate of spread of *B. davidii*. Eastern and southern regions within the South Island are presently characterised

by agricultural land with vigorous grass species that have been shown to out-compete *B. davidii* (Tran Hop. unpub data). In the absence of effective control measures, establishment of forest plantation mosaics are likely to exacerbate the rate of spread and abundance of *B. davidii* within this region, as has previously occurred in other regions where plantations constitute a high proportion of the land area (e.g. Bay of Plenty, 20.6%).

The invasion of the south-eastern regions is likely to be problematic for forest owners and New Zealand policymakers alike. Within New Zealand *B. davidii* has a high impact on plantation species, as it exhibits fast growth (Watt et al., 2007), broad environmental tolerance (Kriticos et al., submitted) and a short juvenile period (Thomas et al., 2009), after which it produces an extremely large number (up to 3 million seeds per plant) of wind dispersed seed (Miller, 1984; Thomas et al., 2009). As a result, invasion by *B. davidii* is likely to more detrimentally affect plantations than competition from the current local suite of weeds that presently colonise plantations on the South Island of New Zealand.

These insights gained from considering the climate modelling and weed distribution data provide the basis for planning to strategically manage the impacts of *B. davidii* in New Zealand. In the following text we describe the elements of a strategic approach to managing this weed threat under the future climate scenarios. The guiding principles in formulating this strategy are to apply cost-effective, technically feasible management as appropriate, and to balance the costs against expected impacts.

Coordinated Regional Management. The regional government bodies in New Zealand (territorial authorities) are the logical planning units for a nationally coordinated strategic management plan for a weed such as *B. davidii*. These authorities have the legislation and procedures to apply a range of control efforts against weeds. The boundaries depicted in Fig 3.7 also reflect, to a significant degree, the biogeographical environmental patterns. It is logical therefore that we would seek to define the strategic management of the weed using these planning units, defining appropriate management goals and approaches on a regional basis.

Inclusion of the weed in pest management plans of the relevant territorial authorities in the eastern and southern South Island may provide a cost-effective means of pre-empting further invasion and consequent impacts. The centrepiece of the strategy should be a strategic exclusion zone in the south-east of the South Island. Within the exclusion zone, defined by the *B. davidii* strategic control line, monitoring and control activities should be undertaken to methodically identify and, where possible, eradicate populations. Within this zone, if there are any populations that are identified as too large to be feasibly eradicated then they should be targeted for containment, with the aim of ensuring that these populations do not constitute an invasion threat to the rest of the exclusion zone. This may require a long-term management technique such as planting to a forest or shrubland which is then managed to minimise disturbance.

Removing horticultural threats. An important primary consideration in the control strategy is the threat posed by amenity plantings in urban centres. It is well known that non-indigenous species expand their range fastest in a new environment *via* multiple loci (Mack et al., 2000). Therefore, the continued presence of *B. davidii* cultivars in urban areas will provide a means of continued introduction into the eastern and southern regions of the South Island. In New Zealand there is legislation to prevent the sale and propagation of amenity species that have undesirable invasive traits. Application of this legislation to *B. davidii* would be required to effectively reduce the collateral threats posed by these horticultural invasion foci.

Prevention of spread into exclusion zone. The second element of an effective strategic exclusion zone, would involve the prevention of inter-regional spread of the species. This would require the prevention of movement from the West Coast and Tasman into

Canterbury, Otago and eastern Southland (Fig. 3.7). The Southern Alps provide a natural barrier that *B. davidii* is unlikely to traverse unassisted. The most likely natural pathway for spread into Canterbury is therefore from Marlborough, *via* interconnecting hill country or the coast. Inclusion of *B. davidii* in the Marlborough regional pest management strategy would help to reduce the risk of movement of the species into northern Canterbury. In addition to avoiding the movement of gravel and soil from infested sites by road between the regions, a public education campaign may be a requisite element of the strategy, reducing the likelihood of intentional spread.

Biological Control. The large area of New Zealand that is already heavily invaded by *B. davidii* underlines the role of the existing biological control programme (Kriticos et al., 2009) as a means of suppressing the population and reducing impacts throughout the North Island. The biological control programme may also reduce the propagule pressure, and hence the difficulty of effecting the strategic containment or eradication of the population in the more sparsely invaded areas identified above. One particularly attractive facet of biological control under climate change is the potential for the control agent and the target pest to respond simultaneously to the changing climate. Whilst the response of the system will clearly not be tightly synchronised, we should expect for example that both species will shift their ranges in the same direction, thereby maintaining some degree of sympatry.

The elements of a strategic pest management plan outlined above require collective recognition of the benefits of harmonised collective effort and the threat posed by uncoordinated pest management. We suggest that the analyses presented here provide a means of presenting the case for coordinated action. In order to achieve collective agreement around a strategic pest management initiative there may need to be discussions regarding transfer payments in order to achieve an equitable socially-optimal outcome. These discussions will inevitably involve national government, the territorial authorities and industry.

Quantification of the total costs of invasive weeds to the primary industries and carbon markets is likely to ultimately drive the development of control strategies. Determination of total costs requires both the costs arising from current infestations, and the future costs resulting from further invasions. Process-oriented niche models as we have used here offer one means of identifying land areas that could support these weeds in the future, and could possibly be used to quantify the impacts throughout these heterogeneous areas. When considered in conjunction with the current and future potential distribution, information on impacts could be used to develop an objective estimate of the total potential impact to the plantations in the introduced range.

In summary, the modelling approach outlined here can be used to guide planners of current and emerging risks from weeds, and can inform the development of appropriate management systems. Without the synoptic view of the invasion and identification of the assets at risk there is a strong potential for regional pest management to be parochial and reactive, and consequently less effective at all scales. Given the increasing frequency of biological invasions, rapid development of coordinated management strategies using such models will become increasingly necessary for mitigating impacts on primary production systems.

4. Determination of the potential cost of pine processionary moth to New Zealand under current and future climate.

Summary

Within southern Europe and around the Mediterranean Sea, recurrent and widespread outbreaks of pine processionary moth, *Thaumetopoea pityocampa* (Lepidoptera: Thaumetopoeidae), causes major defoliation of pines. Given the reliance of the New Zealand forestry industry on *Pinus radiata* it is important to determine how this pest could impact the industry should it arrive in New Zealand. The objective of this study was to produce detailed maps describing the potential distribution of *T. pityocampa* and predict reductions in volume and value of the plantation resource that could result from invasion.

Under current climate, 60% of the total plantation area within New Zealand was projected to be suitable for *T. pityocampa*. Under climate change there were marked increases in climatic suitability for *T. pityocampa* and projections show between 82% (for the CSIRO A1B) and 93% (for the NCAR A2) of the plantation estate was suitable under future climate scenarios. Range increases, most of which occurred in the South Island, were least for the CSIRO model, intermediate for the MIROC model and greatest for the NCAR model.

Over an entire rotation, the modelled impact of *T. pityocampa* on both total and merchantable stem volume is likely to be substantial. Under current climate the dispersal of *T. pityocampa* throughout New Zealand was predicted to result in average reductions of 16% in merchantable and total stem volume. These impacts showed considerable variation throughout New Zealand with estimated reductions in stand productivity under current climate ranging from 42.5% in Northland to 0% in many South Island regions. Under future climate, these average national reductions in merchantable and total stem volume increased as climatic suitability for *T. pityocampa* increases, ranging from 29% under the CSIRO AIB scenario to 33% under the NCAR A2 scenario.

Under the assumption that *T. pityocampa* is fully dispersed throughout New Zealand, projected losses in net present value (NPV) of the plantation resource, over the course of one rotation (28 years), were \$1,306 M under current climate and ranged from \$2,239 M – \$2,493 M under climate change.

At lower rates of dispersal, NPV losses under current climate ranged from between \$500 M to \$167 M, assuming respective linear spread rates of 2.53% of the plantation resource year⁻¹ (equivalent to 30 km year⁻¹) and 0.84% year⁻¹ (equivalent to 10 km year⁻¹). Potential reductions in NPV for these two spread rates were higher under all climate change scenarios. At lower probabilities of establishment all economic losses were reduced in proportion with the diminished probability of establishment. For instance, under a probability of occurrence of 1%, losses in NPV under current climate, ranged from \$5M to 1.67M, assuming respective linear spread rates of 2.53% year⁻¹ and 0.84% year⁻¹.

Losses in NPV made under the assumption that *T. pityocampa* is controlled using aerial application of an insecticide (*Bacillus thuringiensis* (Bt)) were reduced but still relatively high. When expressed as a proportion of the reductions in NPV assuming no control, values under current climate were 47%, 80% and 83%, respectively, assuming *T. pityocampa*, is fully dispersed (throughout suitable areas) and dispersed at a rate of 2.53% year⁻¹ and 0.84% year⁻¹. Under future climate these proportions averaged 38%, 46% and 46%, of the no-control option, respectively, assuming full dispersal, or dispersal at a rate of 2.53% year⁻¹ or 0.84% year⁻¹.

Introduction

Pine forests in southern Europe sustain significant damage from several native European pests of pines. In particular, recurrent and widespread outbreaks of the pine processionary moth, *Thaumetopoea pityocampa* (Lepidoptera: Thaumetopoeidae), cause major defoliation of pines across southern Europe and around the Mediterranean Sea (Démolin, 1969; Masutti and Battisti, 1990). *Pinus radiata* planted in Southern Europe is typically even more affected by *T. pityocampa* than the native pines (Buxton, 1983; Cobos-Suarez and Ruiz-Urrestarazu, 1990; Brockerhoff et al., 2007). The most substantial plantings of *P. radiata* in Europe are in Spain (approx. 300,000 ha, mainly in the Basque Region of northern Spain) and a smaller area in the south of France, Portugal, and other countries around the Mediterranean Sea. There is substantial insecticide use in Spain to prevent defoliation and yield losses due to *T. pityocampa* (Cobos-Suarez and Ruiz-Urrestarazu, 1990). Given the high susceptibility of *P. radiata* to *T. pityocampa* and the possibility of an accidental introduction of this pest into New Zealand by way of trade or tourism, it is an obvious target for an impact assessment.

The severity of *T. pityocampa* outbreaks in Europe, which has increased in recent years, is thought to be a result of a warming climate because of reduced winter mortality, combined with latitudinal and altitudinal spread into areas that were previously too cold (Battisti et al., 2005; Robinet et al., 2007). This moth is rather unusual in that its main feeding period is during winter, and therefore, winter temperatures have a major influence on *T. pityocampa* distribution and potential damage. The larvae feed gregariously and shelter in a silken nest, which also reduces their exposure to adverse climatic conditions. The climatic requirements of *T. pityocampa* are relatively well understood. *T. pityocampa* requires a mean minimum temperature in January greater than -4°C or a cumulative annual sunshine of at least 1800 hours (Huchon and Démolin, 1970). At mean minimum temperatures below 0°C , approximately 100 additional sunshine hours are required for every degree below 0°C to compensate for this. In addition, microclimatic conditions also influence the distribution of *T. pityocampa* by affecting larval feeding during winter. According to Battisti et al. (2005) *T. pityocampa* larvae can only feed when the temperature inside the nest during the day reaches at least 9°C (which activates feeding activity) and at least 0°C the following night for feeding to occur. Robinet et al. (2007) used this information to model the expected distribution of *T. pityocampa* across France and to determine the likely effects of a changing climate on its distribution.

CLIMEX modelling uses the climatic characteristics of locations where a species of interest is known to occur, to produce an annual index of climatic suitability. A CLIMEX model has recently been developed for *T. pityocampa* (Leriche, Kriticos et al., unpublished) which we use here to assess the climatic suitability of New Zealand under current and future climate.

These estimates of potential suitability were combined with a damage function, to determine potential volume losses in New Zealand pine plantations under current and future climate that could occur should *T. pityocampa* become invasive in New Zealand. These estimates of volume loss were used to determine reductions in net present value to the existing plantation estate under both current and future climate, over a range of spread rates and probabilities of occurrence. Because damages can be averted by using insecticides such as *Bacillus thuringiensis* (Bt) we also considered how application of this insecticide affected projected losses in net present value.

Materials and Methods

CLIMEX is a dynamic model that integrates modelled weekly responses of a population to climate to create a series of annual indices (Sutherst et al., 2007b). CLIMEX uses an annual growth index to describe the potential for population growth as a function of soil moisture and temperature during favourable conditions. It uses up to eight stress indices (cold, wet, hot, dry, cold-wet, cold-dry, hot-wet and hot-dry) to simulate the ability of the population to survive unfavourable conditions. CLIMEX also includes a mechanism for defining the minimum amount of thermal accumulation (number of degree days) during the growing season that is necessary for population persistence (PDD).

The growth and stress indices are calculated weekly and then combined into an overall annual index of climatic suitability, the Ecoclimatic Index (EI), that gives an overall measure of the potential of a given location to support a permanent population of the species (Sutherst et al., 2007b). The EI ranges from 0 for locations at which the species is not able to persist to a theoretical maximum of 100 for locations that are climatically perfect for the species (Sutherst et al., 2007b). Due to seasonality in climate, it is usually only near the equator where climatic conditions are stable enough that values of 100 are ever attained (Stephens et al., 2007).

CLIMEX models are generally fitted to known distribution data using a manual iterative process. This involves adjusting growth and stress parameters and then comparing model results to the known distribution of the species and including any additional information about the insect, such as minimum and maximum growth temperatures. In setting these parameters, consideration is also given to the biological reasonability of the selected parameters. This process allows models to be developed that conform with the known biology of the species.

Known distribution and model fitting

Due to its pest status in Europe, there has been a significant amount of research effort applied to understanding the current and potential distribution of *T. pityocampa* in its native range, as well as the factors limiting it, including an *ad hoc* correlative model (Huchon and Démolin, 1970; Robinet et al., 2007) and laboratory studies into survival and feeding behaviour at low temperatures (Buffo et al., 2007; Hoch et al., 2009). Whilst the latter studies may inform niche modelling for international pest risk assessment, the ability of a correlative model to provide robust projections into a novel climate is questionable (Duncan et al., 2009).

In fitting the CLIMEX parameters for the *T. pityocampa* model, three sources of data were considered: distribution data that indicated locations where the climate was suitable for persistence, the published results of a set of laboratory experiments and previous modelling of its *Pinus* spp. hosts. Also modelled was the nest building behaviour of *T. pityocampa*, which allows the larvae to overwinter without entering diapause or quiescence (Hoch et al., 2009). The larvae build silk nests on sun-exposed branches in which they rest during the day. If night-time temperatures are suitable, they forage at night. This behaviour and biogenic heating of the nests means that the larvae experience a microclimate that is significantly different from the Stevenson screen air-temperatures used to develop long-term climatic records (Breuer and Devkota, 1990). One effect of this factor is that observed relationships between laboratory conditions and long-term climatic averages are more problematical than when modelling most other species.

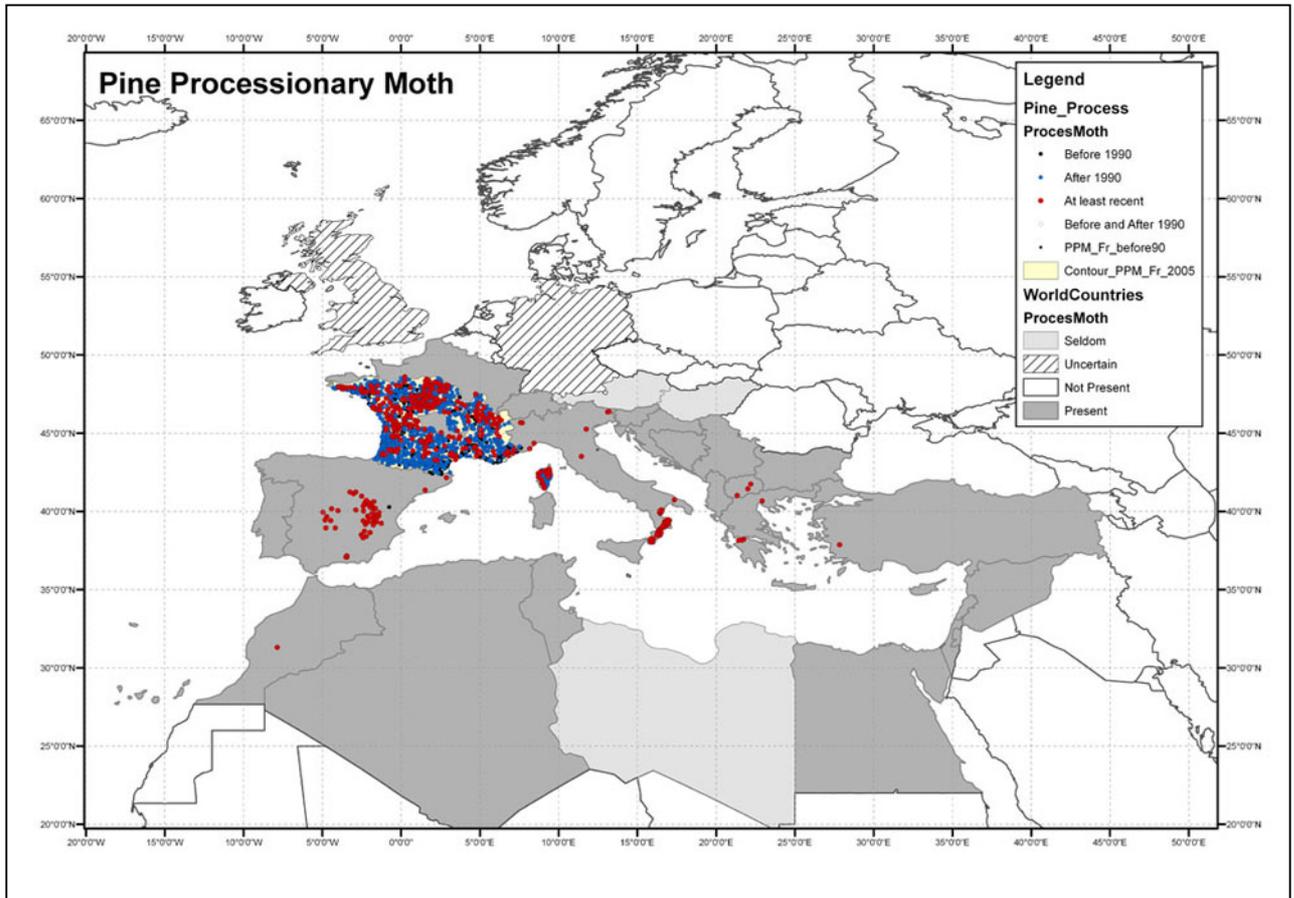


Figure 4.1. Known distribution of *Thaumetopoea pityocampa* in Europe, Asia and North Africa.

Distribution data for *T. pityocampa* (Fig. 4.1) were assembled from a literature review and various databases including the entry for processionaria del pino in the *Atlas Linguistico Y Etnografico de Castilla-La Mancha* (CTGREF-INRA, 1980; EPPO/CABI, 1996; Schmidt et al., 1997; Salvato et al., 2002; Palmeri et al., 2005). Noting the recent range expansion by *T. pityocampa*, presumably in response to climate warming (Battisti et al., 2005; Robinet et al., 2007), we took care to define a geographic dataset that corresponded as closely as possible to the 1961-1990 climate dataset used for fitting our niche model (Fig. 4.1). The CLIMEX stress parameters were fitted to this pre-1990 European Asian and north African data.

The parameters used to model the distribution of *T. pityocampa* are described in Table 4.1.

Table 4.1. CLIMEX parameter values used for *Thaumetopoea pityocampa*. Parameter mnemonics are taken from Sutherst *et al.* (2007b).

Index	Parameter	Value ^a
Temperature	DV0 = lower threshold	5.6 °C
	DV1 = lower optimum temperature	18.0 °C
	DV2 = upper optimum temperature	25.0 °C
	DV3 = upper threshold	30.0 °C
	PDD = degree-day threshold ^b	600 °C Days
Moisture	SM0 = lower soil moisture threshold	0.25
	SM1 = lower optimum soil moisture	0.40
	SM2 = upper optimum soil moisture	0.80
	SM3 = upper soil moisture threshold	2.00
Cold stress	TTCS = temperature threshold	-4.0 °C
	THCS = stress accumulation rate	-0.05 Week ⁻¹
Heat stress	TTHS = temperature threshold	32.0 °C
	THHS = stress accumulation rate	0.005 Week ⁻¹
Dry stress	SMDS = threshold soil moisture	0.2
	HDS = stress accumulation rate	-0.007 Week ⁻¹

^aValues without units are dimensionless indices of a 100 mm single bucket soil moisture profile.

^bMinimum annual total number of degree-days above DV0 needed for population persistence.

Growth parameters. The temperature growth parameters for *T. pityocampa* were mostly derived from published observations and development rate experiments. The lower temperature limit for development DV0 was set to 5.6 °C in order to allow sufficient development of the moth at apparently suitable northern European locations. The lower and upper temperature optima (DV1 and DV2) were set to 18 and 25 °C respectively, representing a bracketing of the upper value for the maximum temperature under which processions occur. The upper temperature limit for development (DV3) was set to 30 °C, as at elevated temperatures around 30 to 32 °C no larval activity is noted (Breuer and Devkota, 1990) and in some case mortality is observed (Astiaso Gallart, 1992).

The lower soil moisture for growth (SM0) was set to a value of 0.25 that allowed appropriate persistence at the dry range limits in north Africa. The upper soil moisture level for growth (SM3) was taken from a previous model indicating the upper level suitable for *Pinus* spp. (Watt *et al.*, 2009a). The soil moisture optima were fitted to give a growth index that broadly agreed with the impact observations.

Stress parameters. The distribution data most strongly influences the fitting of the stress parameters as these most directly influence the ability of a species to persist in an area. The primary limiting factor for *T. pityocampa* in Europe is cold stress. Two forms of cold stress appear to affect *T. pityocampa* in different parts of its range. Whilst the supercooling point of individuals of *T. pityocampa* has been shown to be -7 °C (Hoch *et al.*, 2009), the ecological limit for colony survival are temperatures of approximately -5 °C (Buffo *et al.*, 2007). Since larvae need to forage during the cool season, but may only do so when their nests become warm, a degree day cold stress was fitted to the northern range boundary. This mechanism required 20 degree days above 12 °C to stave off cold stress. This set of degree day parameters is likely to be consistent with the observation by (Hoch *et al.*, 2009) that feeding did not occur until daily temperatures reached 9 °C day/0 °C night. The difference may be because Hoch *et al.* (2009) used a square wave day/night time temperature experiment, compared with a circadian daily temperature cycle in the field, and in CLIMEX, or to the differences between instantaneous nest temperatures and

long-term average screen temperatures as they relate to survival and feeding behaviours of *T. pityocampa*.

The combination of lethal cold temperature and degree day cold stresses limited the ability of *T. pityocampa* to occupy sites in the Pyrenees and north of the Central massif in southern France. It also prevented occupation of southern Britain. Seasonal dry stress appears to affect *T. pityocampa* in central Spain and the south of Italy and Greece. Dry stress becomes limiting in northern Africa where the dry stress parameters were fitted to the single known point location at Marrakech in Algeria (Schmidt et al., 1997). Heat stress appears to affect *T. pityocampa* in southern Spain and at Marrakech. The heat stress parameters were fitted to limit its distribution in these regions. The paucity of data in these hot dry regions means that model results in the hot and dry extremes should be considered indicative, rather than reliable.

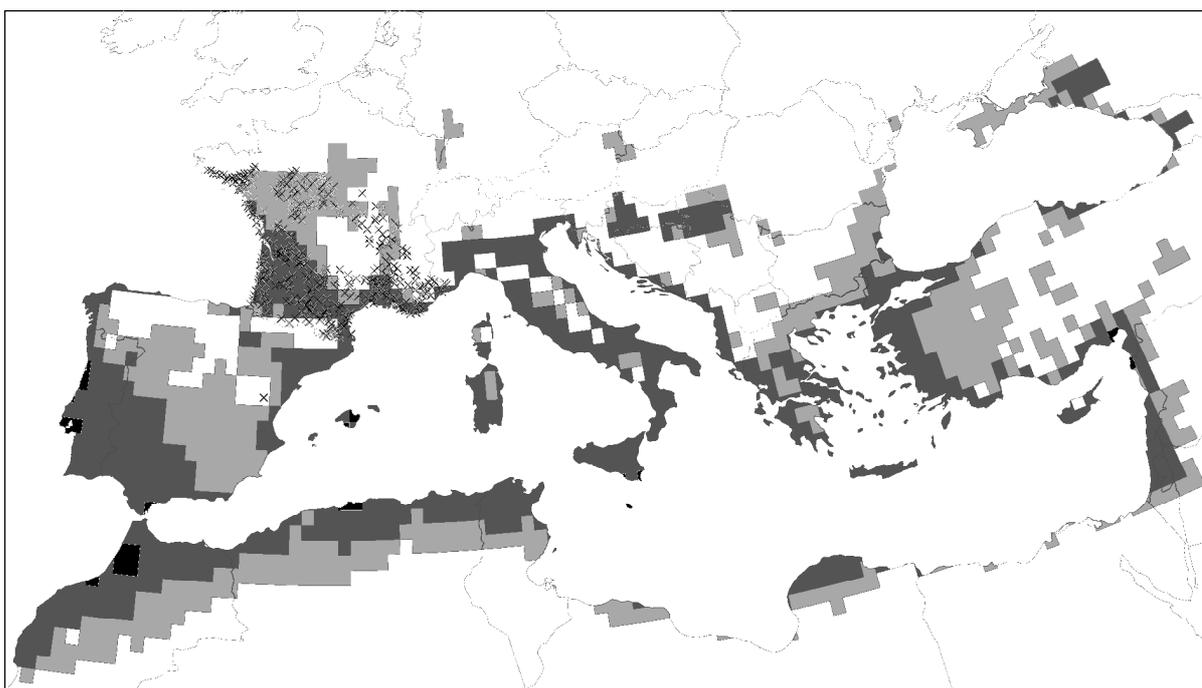


Figure 4.2. Europe showing known occurrences up to 1990 (black crosses) and modelled climatic suitability for the *Thaumetopoea pityocampa* under current (1961-1990) climate averages as indicated by the CLIMEX Ecoclimatic index (EI): □ unsuitable (EI =0); ■ marginal (EI = 1-5); ■ suitable (EI = 6-20); ■ Optimal (EI>20).

Using the parameter values described in Table 4.1, the projected potential distribution within Europe, Asia and north Africa fitted known observations reasonably well (Fig. 4.2.). The shape of the northern range limit is well-defined and was captured by the model. Points that did not accord with the model results were mainly located in areas of dissected terrain and we would expect that these points would fall within the climatically suitable zone if the model was applied to a sufficiently fine resolution climatology surface. This scaling issue has been explored elsewhere (Kriticos and Leriche, in press). Whilst the hot and dry range limits of *T. pityocampa* are less well defined with occurrence records, the model nonetheless matches the known distribution throughout the Mediterranean. This model uncertainty does not affect the ability of the model to project the climate suitability of New Zealand.

Development of a damage function

Values describing the annual percentage of growth decrease (radial, diametric and circumference) over the five years following attacks by *T. pityocampa* compared to non-attacked trees were used in this study to define growth losses attributable to *T.*

pityocampa. Fourteen sites across Europe were used to build the relationship between EI values and the level of damage on a range of pine species (Lemoine, 1977; Laurenthervouet, 1986; Markalas, 1998; Carus, 2004; Kanat et al., 2005). These pine species did not include *P. radiata*, which is a preferred host and highly susceptible to attack.

Values of EI at these locations were extracted and regressed against the damage. As no damage value beyond 82.6% was reported in the literature, the damage function was capped at 85%. For the fourteen sites, EI accounted for 59% of the variance in the damage (Fig. 4.3). The following three stage function was used to model annual percentage growth losses (D) as a function of EI,

$$\begin{aligned} D &= 0 && \text{where EI} < 3 \\ D &= 41.372 \ln(\text{EI}) - 43.161 && \text{where } 3 \leq \text{EI} \leq 22 \\ D &= 85 && \text{where EI} > 22 \end{aligned} \tag{4.1}$$

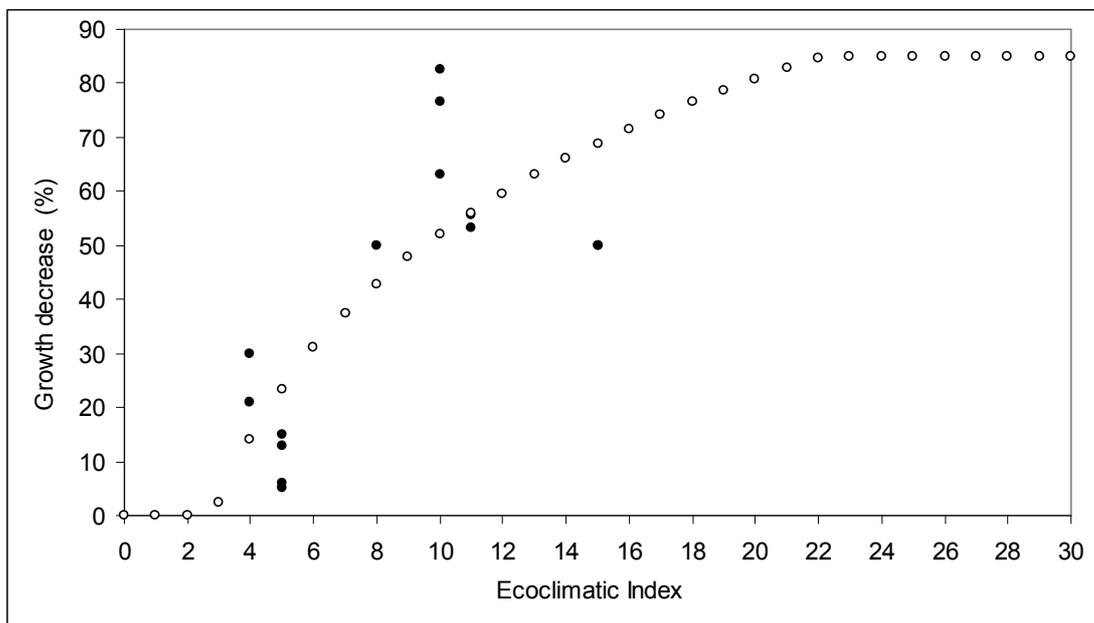


Figure 4.3. Relationship between Ecoclimatic index and measured (solid circles) and modelled (open circles) percentage growth decrease in pine species, for trees attacked by *Thaumetopoea pityocampa* (compared to trees not attacked).

As *P. radiata* is more susceptible to *T. pityocampa* than other pine species, we assumed that the damage function described above would provide a conservative estimate of damage.

Determination of *P. radiata* productivity

An empirical model describing the widely used index of productivity, 300 Index, for *P. radiata* was developed. The 300 Index, defines the stem volume mean annual increment (MAI) at age 30 years with a reference regime of 300 stems ha⁻¹ (Kimberley et al., 2005). The 300 Index was used to describe productivity as this allowed the impact of *T. pityocampa* on volume to be directly determined as this represents an annual increment that can be adjusted to account for damage on an annual basis. Another advantage of using 300 Index is that volume translates readily into value, allowing potential economic losses resulting from *T. pityocampa* damage to be determined.

A total of 99 permanent sample plots that covered a representative range of all permanent sample plots found throughout New Zealand (Fig. 4.4) were extracted for the modelling. The final data covers a wide environmental range across New Zealand and observations

were only limited in the lower North Island and the West Coast of the South Island regions (Fig. 4.4). The 300 Index were calculated for the 99 locations using the procedure described by Kimberley et al. (2005).

Briefly, the 300 Index, was determined using a plot measurement consisting of the basal area, Mean Top Height, stocking at a known age, initial stocking, timing and extent of thinnings and timing and height of prunings. The 300 Index estimation procedure utilised the 300 Index model and an empirical growth model that is sensitive to all the above inputs, and that was calibrated to a site by the 300 Index. Effectively, it is a local site productivity parameter. An iterative procedure was used to determine the 300 Index parameter value consistent with the plot measurement.

As previous research has shown temperature and rainfall to be the two key determinants of *P. radiata* productivity (Watt et al., 2005), a multiple regression model was constructed using these variables. To maintain internal consistency with the model describing the effects of climate on *T. pityocampa*, plot measurements were linked to the underlying CLIMEX dataset describing variation in temperature and rainfall throughout New Zealand at a 0.5 degree resolution. Plot data describing 300 Index were averaged at this resolution to match the scale of these climatic measurements. In the final model, both temperature and rainfall were highly significant and included in the model as quadratic terms (Table 4.2). The final model accounted for 42% of the variance in 300 Index.

Using the CLIMEX rainfall and temperature surfaces as input, productivity surfaces of 300 Index were developed under current climate, using the empirical model described above. The climate change scenarios, described in the next section, were used to estimate 300 Index under future climate. This projection of future productivity assumes no effects of increases in CO₂ on tree growth. Although simplistic it does provide a means of conservatively estimating potential impacts from *T. pityocampa* on plantation productivity and value under climate change.

Table 4.2. Statistics for the final model describing the 300 Index. Shown are the *F* and *P*-value for each term included in the model.

Term	<i>F</i> -value	<i>P</i> -value
Precipitation (<i>P</i>)	21.6	<0.0001
<i>P</i> ²	16.6	0.0002
Mean annual temp (<i>T</i> _a)	6.44	0.0151
<i>T</i> _a ²	6.65	0.0137

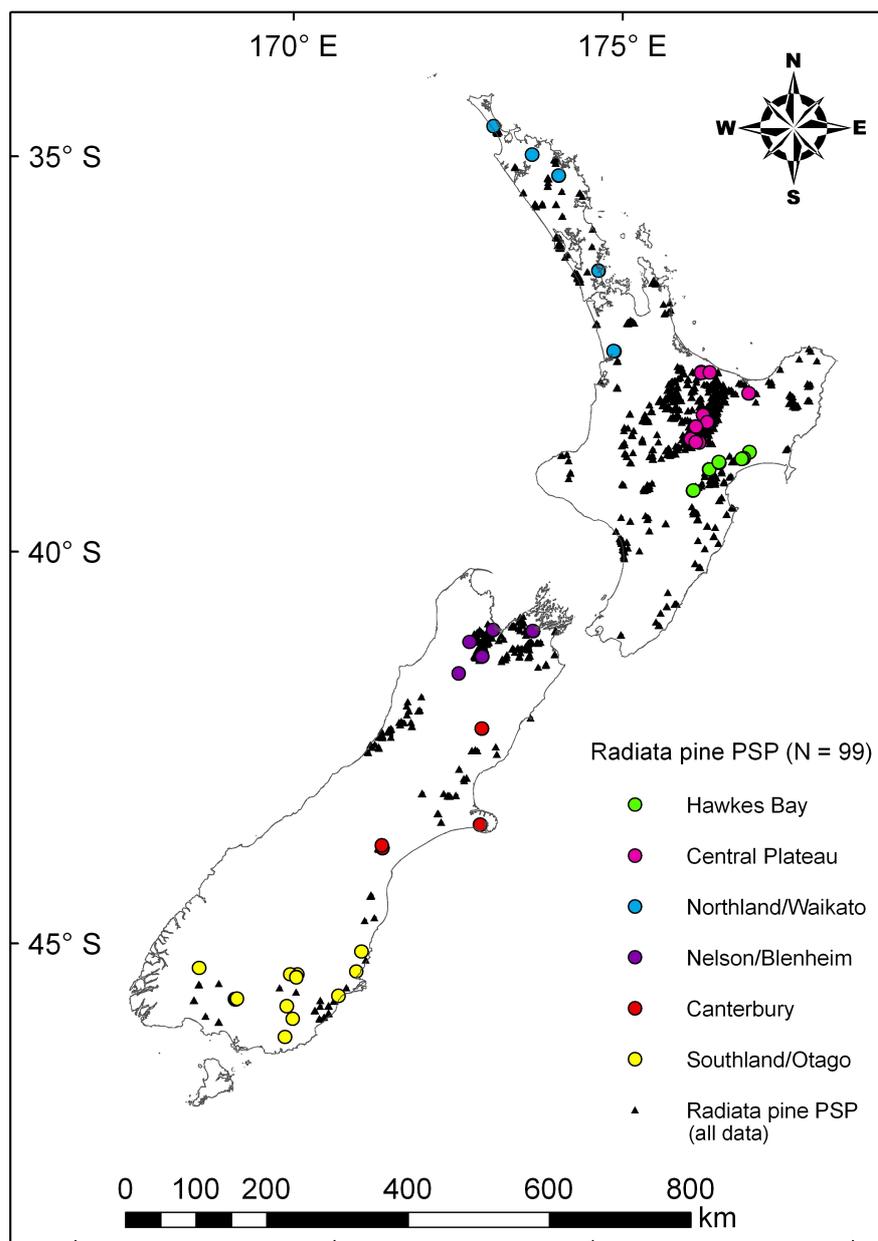


Figure 4.4. Map of New Zealand showing the location, by region, of the 99 permanent sample plots used in this study. Also shown are the location of the ~1,764 permanent sample plots found throughout New Zealand.

Climate change scenarios

Six climate change scenarios were used to project the potential distribution of *T. pityocampa* and determine *P. radiata* productivity under climate change within New Zealand. These scenarios were developed from three Global Climate Models (GCMs) run using two standard International Panel on Climate Change (IPCC) scenarios representing medium (A1B) and high (A2) emissions, drawn from the set of standardised emissions scenarios (IPCC et al., 2007). The GCM data employed in this project were drawn from the World Climate Research Programmes Coupled Model Intercomparison Project phase 3 multi-model dataset (Meehl et al., 2007). The three GCMs selected had relatively small horizontal grid spacing (100 – 175 km) and the requisite climatic variables at the monthly resolution required by CLIMEX. Selected GCMs included CSIRO Mark 3.0 (CSIRO, Australia), NCAR-CCSM (National Centre for Atmospheric Research, USA), and MIROC-H (Centre for Climate Research, Japan). Data from these GCMs were pattern-scaled to

develop individual change scenarios relative to the base climatology (Whetton et al., 2005). The three models cover a range of climate sensitivity, defined as the amount of global warming for a doubling of the atmospheric CO₂ concentration compared with 1990 levels. The respective climate sensitivities are: CSIRO Mark 3.0 (2.11 °C), NCAR-CCSM (2.47 °C), and MIROC-H (4.13 °C).

Determining impacts of *T. pityocampa* on *P. radiata* productivity under current and future climate

Damage attributable to *T. pityocampa* was determined spatially by linking the percent damage, as described by Equation 4.1, to the projections of the 300 Index. As the 300 Index describes the mean annual increment, the modified volume for trees affected by *T. pityocampa* over the rotation, *R*, on a per hectare basis was determined as;

$$V_m = (300 \text{ Index} \times R) - [((D/100) \times 300 \text{ Index}) \times R/2] \quad (4.2)$$

This equation assumes that *T. pityocampa* attacks the plantation for half of the rotation length, an assumption that is consistent with previous observations. An average rotation length of 28 years was used in all analyses (N.Z.F.O.A., 2007).

The mean total volume, based on the 300 Index, is a total stem volume. As there is typically 15% breakage in harvesting and approximately 10% of stands are unstocked estimates of volume for stands both with and without *T. pityocampa* were reduced by 25% per hectare to determine the merchantable volume. All economic analyses of damage relate to the merchantable volume.

Determination of economic damage to New Zealand plantations from *T. pityocampa*

Surfaces were created that described *P. radiata* volume throughout New Zealand, under current climate and climate change. Using the damage function described in Equation 4.1, these surfaces were modified to estimate the damage that is likely to occur under current and future climate if *T. pityocampa* became invasive within New Zealand.

To estimate potential damage to pine plantations these surfaces were delimited to current pine plantation areas. The average volume in current plantations was determined both with and without *T. pityocampa*, on a national and regional scale under both current and future climates.

The impact of *T. pityocampa* on the value of the New Zealand plantation estate was determined using discounted cashflow analysis. Analyses were undertaken to determine annual losses, over a 28 year period from 2010 to 2037, using the most up to date age class distribution available (National Exotic Forest Description, 2007). In this analysis, it was assumed that the age class was harvested once it reached 28 years, which is the current average rotation length in New Zealand (N.Z.F.O.A., 2007). The total merchantable volume, shown in Table 4.4, was applied to each age class area to determine total volume for the age class. From these estimates, mean percentage reductions in volume attributable to *T. pityocampa* were determined. These percentage reductions in volume for each age class were scaled to account for the time during which the age class was exposed to the moth.

Under the first scenario of no control, losses in value for each age class, scheduled for clearfelling beyond 2010, were discounted back to the present time, and summed, with the losses for 2010, to obtain a total net present value loss for the New Zealand plantation estate that is scheduled for clearfelling over the next 28 years. The discount rate used was 8%. Analyses were undertaken to determine the effect of *T. pityocampa* on plantation value under both current and future climate (assuming the age class distribution does not

change in the future). Sensitivity analysis was undertaken to determine how the probability of establishment and dispersal rate influenced losses in value (more details on these are given below).

These analyses were repeated for a control scenario using Bt. For the analysis Bt was applied every second year throughout the 28 year rotation period and following Gatto (2009), it was assumed that Bt completely negates any detrimental impact of *T. pityocampa* on crop volume. As previously described, losses attributable to cost of application of Bt were determined by discounting these values back through time.

Assumptions made around probability of establishment, rate of spread and costs of Bt are as follows;

Probability of establishment. It is difficult to determine the probability of establishment of *T. pityocampa* with any certainty (Brockhoff et al. 2007). There is only limited information from border interception records that can be used to estimate arrival rates of exotic Lepidoptera at New Zealand's borders. We can assume that that *T. pityocampa* arrives less frequently than gypsy moth, which is often intercepted in shipments of imports from north-east Asia. Potential pathways include, for example, accidental transport of *T. pityocampa* egg masses on pine needles on the external surface or inside of sea containers. Egg masses could also be imported with baggage of tourists returning from infested areas (Note: many campgrounds in southern Europe have pine trees that may be infested). We estimate the probability of establishment ranges between 0.2% and 1% per year, and consequently included both values in the analysis.

Rate of spread. We assume *T. pityocampa* would become established at a single point of introduction, that would most likely be in Auckland. The radial rate of spread of a number of invasive Lepidoptera has been shown to range from 3 to 170 km per year (Liebhold and Tobin 2008). Spread values for *T. pityocampa* observed near the boundary of its distribution are up to 5 km per year (1995-2004) (Battisti et al. 2006). Given that the climate would be suitable across much of New Zealand and pose minimal restriction on spread (from Auckland), we estimate that the rate of spread ranges between 10 and 30 km year⁻¹. As the distance from Auckland to Invercargill is 1,185 km, at dispersal rates of 10 and 30 km year⁻¹ *T. pityocampa* would take, respectively, 118.5 and 39.5 years to disperse throughout the country. Based on this, percentage dispersal rates throughout the plantation resource used in the modelling that correspond to the rates of 10 and 30 km year⁻¹, were determined to be, respectively, 0.84% of the plantation resource year⁻¹ (100%/118.5 years) and 2.53% year⁻¹ (100%/39.5 years).

For simplicity, a linear rate of percentage spread was used as it was assumed that the slow rate of increase resulting from the lag phase would be offset by the close proximity of the majority of New Zealand plantations to Auckland. We also investigated the impact of *T. pityocampa* being fully dispersed throughout the plantation resource on value losses under both current and future climate.

Cost of Bt treatment to avert damages:

A recent study in Portugal used a value of 60 euros ha⁻¹ per treatment for use of Bt to control *T. pityocampa* (see Gatto et al. 2009) (ca. NZ\$120 ha⁻¹ at the current (12 Dec. 2009) exchange rate). This corresponds well with the costs of NZ\$125 ha⁻¹ for Bt treatment (including survey costs) used by New Zealand Ministry of Agriculture and Forestry (MAF 2002) for economic impact assessment of the painted apple moth incursion in Auckland. We used a value of NZ\$125 ha⁻¹ and treatments were assumed to be applied every second year. We conservatively assumed Bt treatment would be effective, with no residual damage.

Results

Potential distribution of *T. pityocampa* within current plantations

Under current climate, 60% of the total plantation area within New Zealand was projected to be suitable for *T. pityocampa* (Fig. 4.5). By region, the percentage of plantation area suitable for *T. pityocampa* declined with latitude from 100% in Northland and Auckland to 0% in most South Island regions (Figs. 4.5, 4.7).

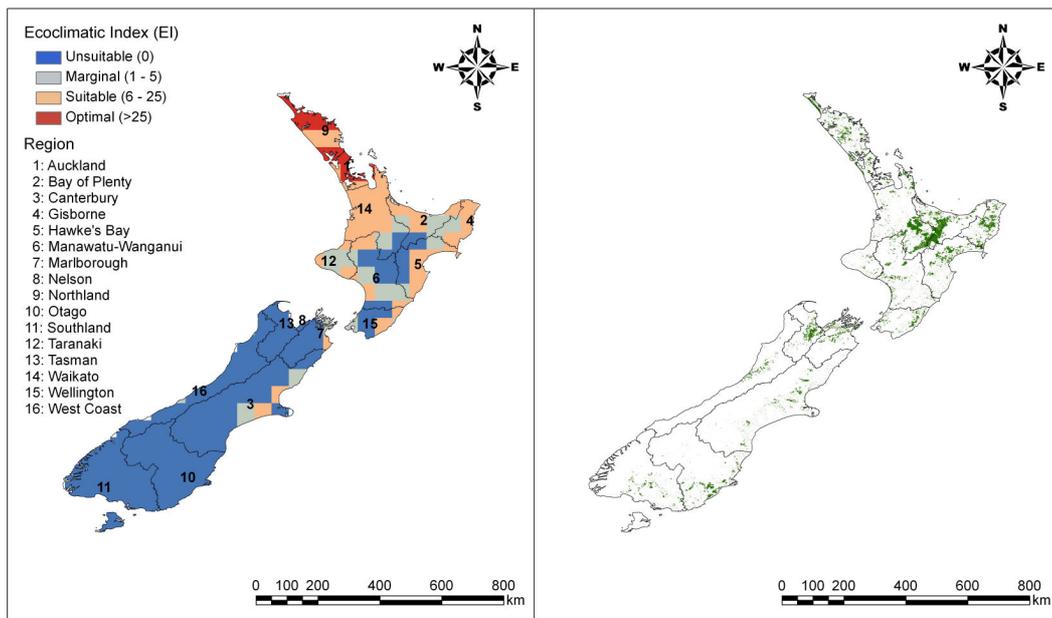


Figure 4.5. New Zealand map showing: (a) ecoclimatic suitability, by region, under current climate for *T. pityocampa* and (b) existing (green) pine plantations.

Under climate change there were marked increases in climatic suitability for *T. pityocampa* and projections show between 82% (for the CSIRO A1B) and 93% (for the NCAR A2) of the plantation estate was suitable under future climate scenarios (Fig. 4.6). Range increases, most of which occurred in the South Island were least marked for the CSIRO model, intermediate for the MIROC model and most marked for the NCAR model (Figs. 4.6, 4.7).

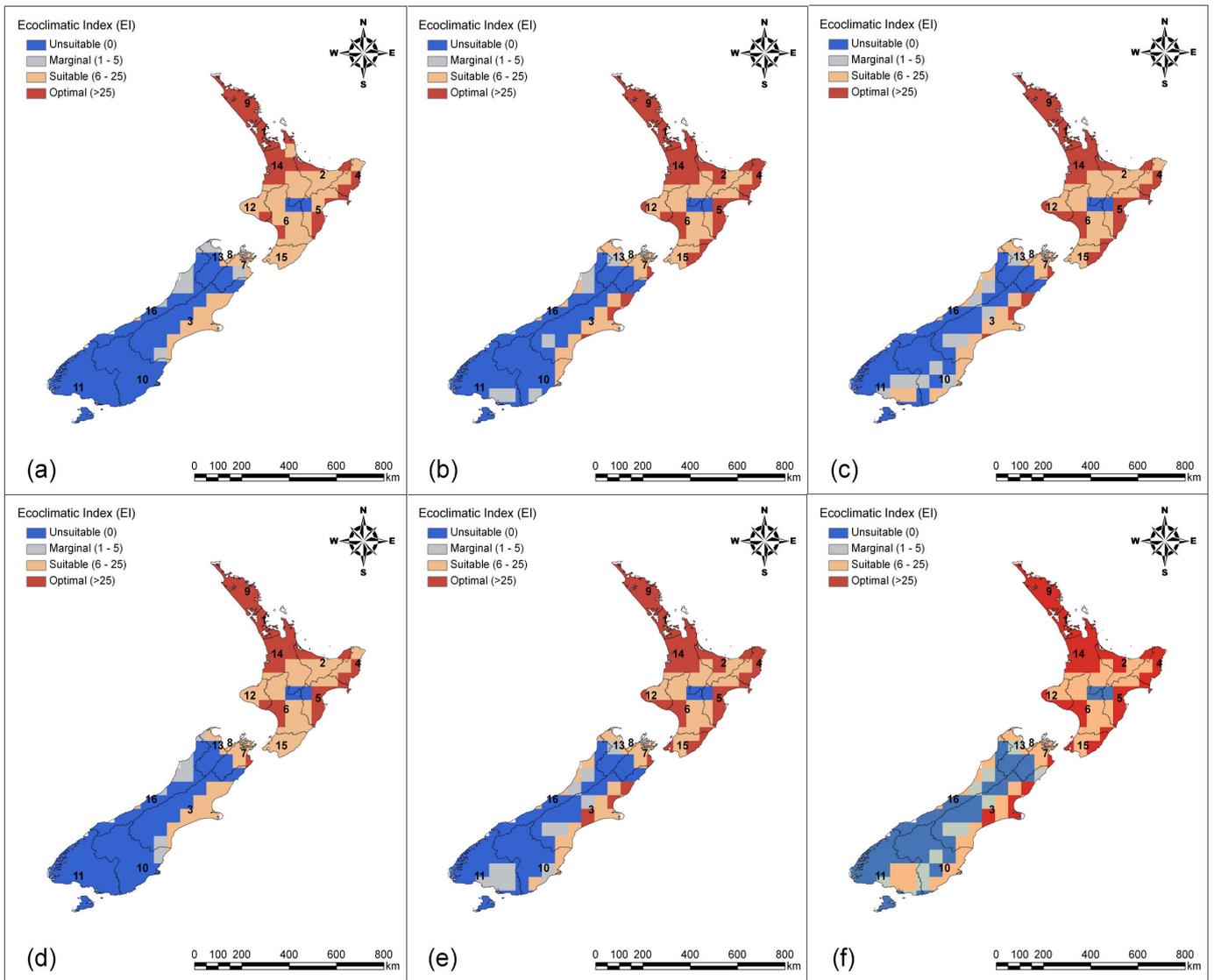


Figure 4.6. New Zealand map showing Ecoclimatic Index for *T. pityocampa* under climate scenarios derived from (a) CSIRO Mark 3.0, (b) MIROC-H and (c) NCAR-CCSM run with the AIB emissions scenario (d) CSIRO Mark 3.0, (e) MIROC-H and (f) NCAR-CCSM run with the A2 emissions scenario.

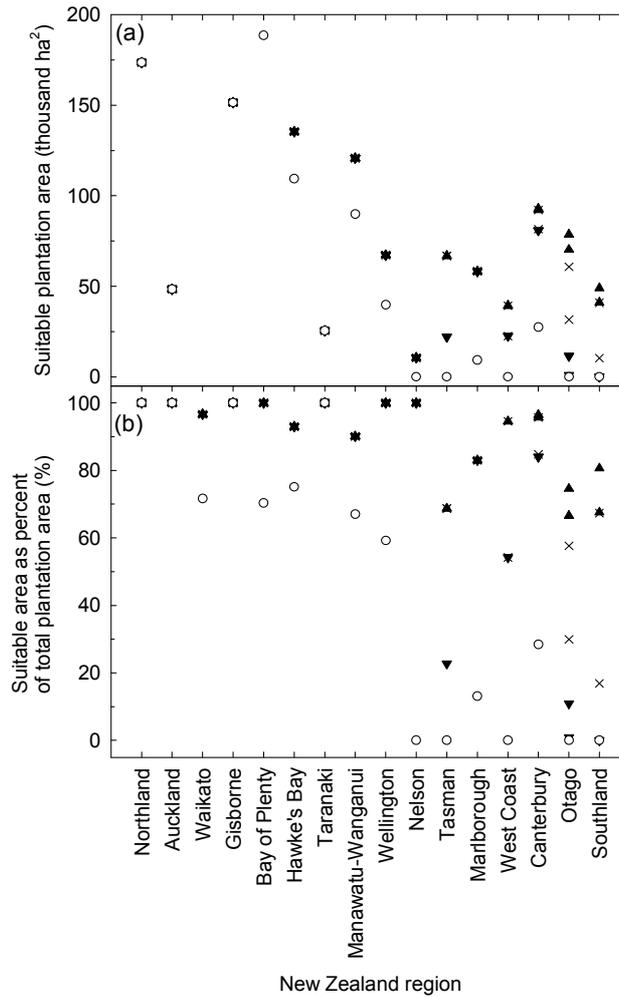


Figure 4.7. (a) Suitable projected plantation area for *T. pityocampa* by region and (b) suitable area expressed as a percentage of total plantation area for *T. pityocampa*. Symbols shown in both figures represent current climate (open circles) and future climate as projected by the CSIRO AIB and A2 models (downward facing triangles), MIROC A1B and A2 models (crosses), and the NCAR A1B and A2 models (upward facing triangles). Regions are sorted left to right in order of increasing latitude.

Variation in volume and stumpage value with and without *T. pityocampa*

Over an entire rotation the modelled impact of *T. pityocampa* on both total (Table 4.3) and merchantable (Table 4.4) stem volume was predicted to be substantial. Under current climate, the dispersal of *T. pityocampa* throughout New Zealand was predicted to result in average reductions of 16% in both merchantable and total stem volume (Tables 4.3, 4.4). These impacts showed marked variation throughout New Zealand with estimated reductions in stand productivity under current climate ranging from 42.5% in Northland to 0% in many South Island regions, where climate is not suitable (Fig. 4.8c).

Under future climate reductions in volume increased, ranging from an average of 29% under the CSIRO AIB scenario to 33% under the NCAR-CCSM A2 scenario (Tables 4.3, 4.4). In all regions impacts of *T. pityocampa* increase under climate change with the greatest increases occurring in the lower North Island and South Island (Fig. 4.8c).

Table 4.3. Influence of *T. pityocampa* on mean modelled total stem volume over an entire rotation for the current national pine plantation estate under current and future climate. Shown for each climate scenario is the mean total stem volume without (*V*) and with *T. pityocampa* (*V_m*). Also shown is the percentage reduction in total stem volume, attributable to damage from *T. pityocampa*, determined as $[(1 - (V_m/V))] \times 100$.

	Current climate	Future climate					
		CSIRO		NCAR-CCSM		MIROC-H	
		A1B	A2	A1B	A2	A1B	A2
No <i>T. pityocampa</i> (m ³ ha ⁻¹)	754	708	699	706	695	696	682
With <i>T. pityocampa</i> (m ³ ha ⁻¹)	636	505	490	488	469	482	467
Percent reduction (%)	16	29	30	31	33	31	32

Table 4.4. Influence of *T. pityocampa* on mean modelled merchantable volume over an entire rotation for the current national pine plantation estate under current and future climate. Shown for each climate scenario is the mean total stem volume without and with *T. pityocampa*. Also shown is the percentage reduction in total stem volume attributable to damage from *T. pityocampa*.

	Current climate	Future climate					
		CSIRO		NCAR-CCSM		MIROC-H	
		A1B	A2	A1B	A2	A1B	A2
No <i>T. pityocampa</i> (m ³ ha ⁻¹)	566	531	524	530	521	522	512
With <i>T. pityocampa</i> (m ³ ha ⁻¹)	477	378	368	366	352	362	350
Percent reduction (%)	16	29	30	31	33	31	32

Table 4.5. Estimated reduction in total estate net present value (million \$NZ) that would result from an invasion of *T. pityocampa* assuming no control of the pest. Values are shown both for current and future climate scenarios and describe the sensitivity to the probability of establishment and dispersal rate throughout New Zealand.

Probability of estab. %	Dispersal Rate % year ⁻¹	Current climate	Future climate					
			CSIRO		NCAR-CCSM		MIROC-H	
			A1B	A2	A1B	A2	A1B	A2
100	All forests	1,306	2,239	2,295	2,408	2,493	2,350	2,377
100	2.53	500	856	878	921	954	899	909
100	0.84	167	285	293	307	318	300	303
1	2.53	5.00	8.56	8.78	9.21	9.54	8.99	9.09
1	0.84	1.67	2.85	2.93	3.07	3.18	3.00	3.03
0.2	2.53	1.00	1.71	1.76	1.84	1.91	1.80	1.82
0.2	0.84	0.33	0.57	0.59	0.61	0.64	0.60	0.61

Under the assumption that *T. pityocampa* is fully dispersed throughout New Zealand, projected losses in net present value of the plantation resource were \$1,306 M under current climate and ranged from \$2,239 M to \$2,493 M under climate change (Table 4.5). At lower rates of dispersal, net present value (NPV) losses ranged from between \$500 M to \$167 M, assuming respective spread rates of 2.53% year⁻¹ (30 km year⁻¹) and 0.84% year⁻¹ (10 km year⁻¹). Potential reductions in NPV for these two spread rates were markedly higher under all climate change scenarios (Table 4.5). At lower probabilities of

establishment, all losses in NPV were reduced in proportion with the diminished probability of establishment (Table 4.5).

Losses in NPV (made under the assumption that *T. pityocampa* is controlled using aerial application of Bt) were reduced but still relatively high. Reductions in NPV ranged widely across a combination of dispersal rates and establishment probabilities (Table 4.6). When expressed as a proportion of the reductions in NPV, assuming no control, values under current climate were 47%, 80% and 83%, respectively, of the corresponding no control values, assuming *T. pityocampa*, is fully dispersed (throughout suitable areas) and dispersed at a rate of 2.53% year⁻¹ and 0.84% year⁻¹. Under future climate, these proportions averaged 38%, 46% and 46%, of the no-control option, respectively, assuming full dispersal and dispersal at a rate of 2.53% year⁻¹ and 0.84% year⁻¹.

Table 4.6. Estimated reduction in total estate net present value (million \$NZ) that would result from an invasion of *T. pityocampa* if control measures were put in place. Values are shown both for current and future climate scenarios and describe the sensitivity to the probability of establishment and dispersal rate throughout New Zealand.

Probability of estab. %	Dispersal rate % year ⁻¹	Current Climate	Future climate					
			CSIRO		NCAR-CCSM		MIROC-H	
			A1B	A2	A1B	A2	A1B	A2
100	All forests	617	844	854	949	949	892	940
100	2.53	401	414	414	414	414	414	414
100	0.84	138	138	138	138	138	138	138
1	2.53	4.01	4.14	4.14	4.14	4.14	4.14	4.14
1	0.84	1.38	1.38	1.38	1.38	1.38	1.38	1.38
0.2	2.53	0.80	0.83	0.83	0.83	0.83	0.83	0.83
0.2	0.84	0.28	0.28	0.28	0.28	0.28	0.28	0.28

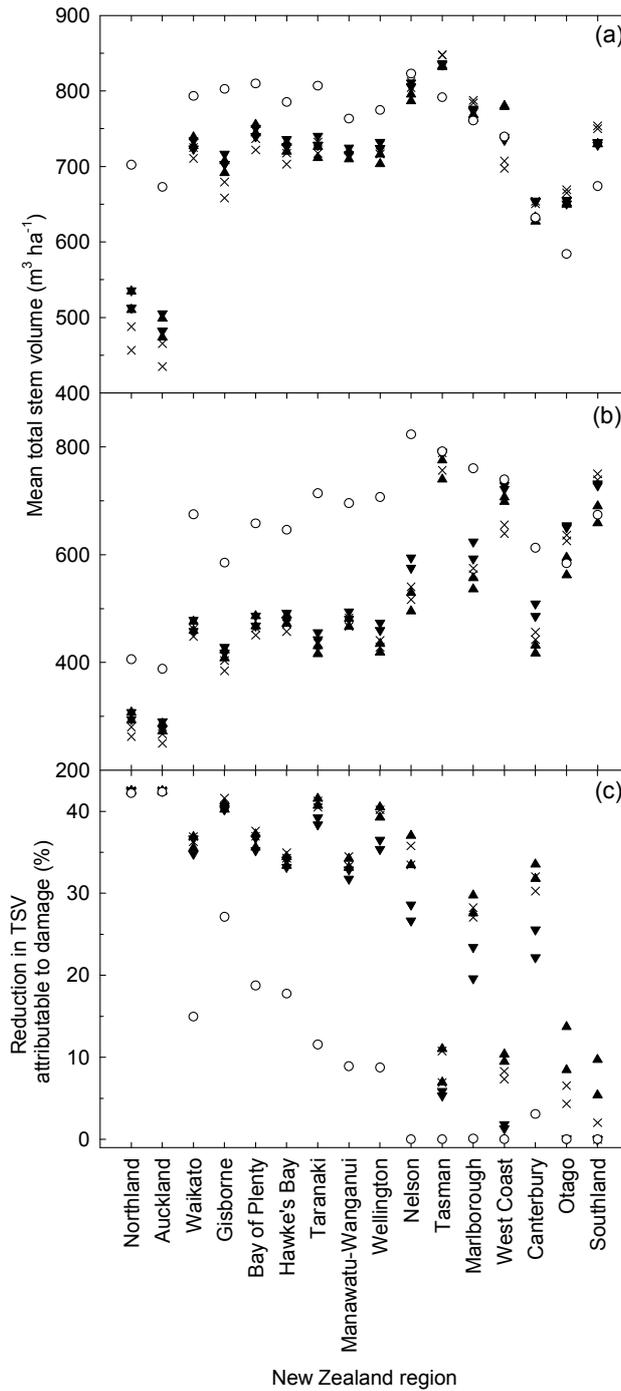


Figure 4.8. Regional variation in mean modelled total stem volume (a) without (V) and (b) with *T. pityocampa* (V_m). Also shown is (c) the percentage reduction in total stem volume, attributable to damage from *T. pityocampa*, determined as $[(1 - (V_m/V))] \times 100$. Symbols shown in both figures represent current climate (open circles) and future climate as projected by the CSIRO AIB and A2 models (downward facing triangles), MIROC A1B and A2 models (crosses), and the NCAR A1B and A2 models (upward facing triangles). Regions are sorted left to right in order of increasing latitude. All presented graphs assume that *T. pityocampa* impacts on the stand over the entire 28 year rotation length.

Discussion

CLIMEX projections predict that about 60% of New Zealand's plantation forest area is climatically suitable for *T. pityocampa* under the current climate. Should this pine defoliator become established in New Zealand, outbreaks are likely to occur at a high frequency because *P. radiata* is a preferred host and highly susceptible to attack. This situation is likely to be exacerbated as *T. pityocampa* would experience freedom from natural enemies which contrasts to the situation in its native region where many effective natural enemies occur. Consequently, the damages resulting from an establishment of *T. pityocampa* are expected to be significant and the volume reductions reported here are likely to be quite realistic.

According to our projections, the net present value (NPV) of New Zealand's entire current plantation resource under current climate would be reduced by 1.3 billion dollars over a period of 28 years (one rotation), under the scenario that *T. pityocampa* is present throughout New Zealand.

To our knowledge, this pest is not yet present in New Zealand. We also considered a range of establishment probabilities and dispersal rates. Assuming a 1% probability of establishment and a spread rate of 30 km year⁻¹, the NPV of New Zealand's plantations would be reduced by almost 5 million dollars. Even under the least-impact scenario of an establishment probability of 0.2% and a low spread rate of 10 km year⁻¹, the NPV would still be reduced by 0.33 million dollars, highlighting the potential seriousness of this insect.

These estimates only account for direct losses of stumpage value due to defoliation, however, other damages would be incurred, if this insect became established. For example, there would be considerably less carbon sequestration and loss of recreational value as well as human health costs because the urticating hairs of *T. pityocampa* cause serious dermatitis. An attempt to value these costs has been made previously (Gatto et al., 2009).

With the expected impact of *T. pityocampa* on New Zealand's plantation forests, it is obvious that pest management options should be considered. With an assumed control cost of \$125 ha⁻¹, using Bt (MAF, 2002), growth losses due to *T. pityocampa* could be minimised, but the control costs are still relatively high, particularly under climate change and once the insect is dispersed throughout the plantation estate.

The effects of *T. pityocampa* are expected to worsen under a range of climate change scenarios within New Zealand. This result is consistent with range shifts in Europe, where climate change is thought to exacerbate both the extent of the affected area and the extent of damage (due to reduced winter mortality) (Battisti et al., 2005; Battisti et al., 2006; Robinet et al., 2007).

Ultimately, this study should serve as a case study for one example of a potentially invasive insect pest of pines.

Accidental shipments of *T. pityocampa* egg masses with sea containers originating from infested regions are probably the highest risk introduction pathway. There are frequent outbreaks of *T. pityocampa* in southern Europe which suggests that there is a high propagule pressure from its native region. These outbreaks often affect pines in urban and semi-urban areas in close proximity to industrial sites with shipping container activity. It is conceivable that needles carrying egg masses could accidentally be transported on the surface or inside a container. Several other lepidopterous defoliators previously considered low risk have recently become established in New Zealand including the

white-spotted tussock moth, painted apple moth and gum leaf skeletonizer. Even if *T. pityocampa* did not become established in New Zealand in the near future, the rate of defoliator introductions in New Zealand and overseas indicates that there is a high risk of such an invasion.

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