Effects of climate change on current and potential biosecurity pests and diseases in New Zealand

Prepared for Ministry for Primary Industries by

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1.   Executive summary

This report summarises potential impacts of climate change on pests, weeds and diseases of relevance to New Zealand's biosecurity systems. It represents the best current information from experts in the Crown Research Institutes and Lincoln University.

NIWA have used general circulation models from a range of sources to project future New Zealand climates from 1990 to 2090 under a range of greenhouse gas emissions scenarios. The results have been downscaled to 0.05 degrees arc, an approximately 5×4 km grid of 11,491 points covering New Zealand.

Review of historical trends in value of New Zealand imports suggest that north-east Asia is likely to dominate pest import pathways in the future, with increasing risks associated with India, South America and other emerging economies. Changes in climate, shipping routes, the commodities traded and international pest distributions will shape future border biosecurity risks to New Zealand. Further research in this area might clarify how future trade trends will impact biosecurity risk.

Climate change will create new biosecurity challenges by allowing establishment of new exotic pests, weeds and diseases which are currently prevented by New Zealand's climate. The potential establishment of subtropical pests and current seasonal immigrants are of greatest concern, along with taxa that are already recognized as high risk. Climate is just one of several factors that affect invasion potential, and others such as import pathways, border management and host suitability may also change in the future.

Climate change will create opportunities for new crop types to be grown commercially in some sectors, and necessitate the use of new species in others (e.g. C_4 grasses in Northland pastures, drought-resistant forage plants in eastern areas). Primary production industries could benefit from working with MPI to ensure that biosecurity systems adequately protect these future crops.

The pest status of many species currently present in New Zealand may change significantly as a result of climate change. In particular, currently innocuous 'sleeper' weeds, pests and diseases may become problematic due to changing ecological interactions with host plants and natural enemies, or shifts in their own phenology. While not a major focus of this review, this area would benefit from further research.

Species distribution models based on climatic requirements (e.g. CLIMEX) may be useful for projecting future ranges of pests, weeds and diseases. A preliminary examination of 24 arthropod species (twelve already present in New Zealand, twelve currently absent) suggested potential range increases for most and that lower temperature limits may be useful as a general indicator of the likelihood of establishment in New Zealand.

An online database of CLIMEX models has been created. The website allows CLIMEX models to be run for current and future climates under a range of general circulation models and carbon dioxide emission scenarios. Results are presented in a meaningful way that facilitates their use for biosecurity risk analysis. The website is currently in beta testing phase but is nonetheless available to authorised users.

Other approaches are available for assessing biosecurity risks under climate change, such as climate matching between New Zealand and the world under current and future climates. This has been done previously, but not with the high resolution climate data now available, not on a meaningful sector-by-sector basis, and not with the results made readily available for exploration by risk analysts. MPI has indicated that this would be useful to them, but we were unable to resource it from the current project.

2.   Introduction

2.1.   IMPORTANCE OF CLIMATE CHANGE FOR NEW ZEALAND BIOSECURITY

New Zealand has an economy based on very efficient primary production systems. Our agriculture, horticulture and forestry make up of 65% of New Zealand's exports and are all totally dependent on exotic crop species. New Zealand's isolation and effective biosecurity systems means that we currently have only a small fraction of the world's known pests and diseases. This, together with a benign maritime climate, allows many plants grow better here than in their country of origin. However, just as those exotic species thrive in New Zealand's favourable climate and dearth of natural enemies, so can invasive exotic pests and diseases.

New Zealand's long geographic isolation also means that the indigenous ecosystems have a high degree of endemism. In such environments, the devastating impact of introduced mammals has been well documented, and though these ecosystems may have some resistance to exotic invertebrate invaders, generalist species remain a threat (Brockerhoff et al. 2010).

Climate change is widely regarded as one of the greatest challenges facing ecological systems in the coming century. Much research on mitigation and adaptation is being carried out internationally, but New Zealand's geographical and ecological uniqueness means that predictions for the rest of world may not necessarily work here. Therefore, there is a need for specialist research to prepare New Zealand for the potential impacts of climate change.

The Ministry for Primary Industries (MPI) is charged with leadership of the New Zealand biosecurity system. A changing climate is likely to alter pest and disease risk profiles, as well as present new biosecurity risks to farmers, growers and New Zealand export markets. Proactive farmers and growers are already responding to changes in climate and investigating ways to develop long-term resilience (Kenny 2010). Some will be testing innovative new crops and forages ahead of current research.

The National Institute of Water and Atmospheric Research (NIWA) uses a range of general circulation models (GCM) to produce climate change predictions for New Zealand (Mullan et al. 2008), and these data provide the basis for predicting the effects on biological systems. Although climate change may affect organisms and ecosystems in a range of ways (Dukes & Mooney 1999, Walther et al. 2009, Robinet & Roques 2010), the most important driver of pest invasion is likely to be temperature, modified by rainfall, humidity and carbon dioxide concentration. Small changes in variables such as temperature, rainfall and humidity can have large influences on invertebrate populations (Poulin 2006, Lafferty 2009). In addition, changes in large-scale weather patterns (England et al. 2014) will influence the frequency and intensity of extreme weather events (e.g. flooding, drought, frosts) and regional winds and currents (e.g. westerly air flows across the Tasman) which in turn may affect the ability of potential invaders to reach New Zealand and establish.

2.2. PREVIOUS BIOSECURITY AND CLIMATE CHANGE RESEARCH IN NEW ZEALAND

To date, New Zealand research on the likely biological effects of climate change has been largely sector-based. Information from the forestry sector is the most comprehensive, with a number of reports on the potential effects of climate change on forest insects, pathogens and weeds. The work provides an overview of both direct and indirect effects. These include pest impacts on plantation forests under climate change (Watt et al. 2008, 2009b) as well as a large number of specific journal publications on current climatic suitability and expected suitability under climate change, direct and indirect pest impacts, and economic impacts of insects (e.g. pine processionary moth, Kriticos et al. 2013), pathogens (e.g. pitch canker, Ganley et al. 2009, 2011, Watt et al. 2011a; Swiss needle cast, Watt et al. 2010; *Dothistroma* needle blight, Watt et al. 2011a, 2011b, 2011e, 2011d, *Cyclaneusma minus*, Watt et al. 2012a, 2012b), and weeds (e.g. *Cytisus scoparius*, Potter et al. 2009; *Melaleuca quinquenervia,* Watt et al. 2009a; *Buddleja davidii*, Kriticos et al. 2011). In addition, studies have described more general impacts of climate change on key forestry crop species *Pinus radiata* (Kirschbaum et al. 2012) and Douglas fir (Watt et al. 2011f).

In horticulture, Beresford & McKay (2012) used validated disease risk models for four horticultural pathosystems to estimate impacts on disease risk for upper and lower limits of temperature and rainfall. Meanwhile, large scale FACE (free air carbon dioxide enrichment) experiments are ongoing in pastures (Newton et al. 2010, Rütting et al. 2010).

For the environment, McGlone and Walker (2011) provided a large review of the potential effects of climate change on New Zealand's terrestrial biodiversity and recommendations for mitigation. They recognised the need for both short- and long-term strategies for climate change, but one of their key recommendations was for surveillance of exotic weeds and invertebrates with potential for spread under a warming climate. Selected case studies are also available on the potential spread and increased invasion for ants (Harris & Barker 2007) and weeds (Sheppard et al. 2014). Biological control is an important tool for pest and weed control across all sectors. Potential climate change impacts on biocontrol systems have been reviewed by Gerard et al. (2010, 2013).

2.3. SCOPE OF THE CURRENT WORK

This aim of the current work is to synthesise current knowledge on the effects of climate change on current and potential biosecurity pests and diseases in New Zealand. A workshop was held in March 2014 involving experts from all of the land-based Crown Research Institutes, plus Lincoln University and the Ministry for Primary Industries (MPI).

This project provides information on how climate change is likely to change the risk of invasion by representative pests and diseases based on climate modelling, species distribution modelling of key pests both currently in New Zealand and not yet established, and the opinions and knowledge of researchers working with invasive species.

Section 3 describes the latest fine-scale projections for future climate scenarios. Sections 4 to 7 discuss potential trends in New Zealand's biosecurity risks as a result of projected climate change, based on the knowledge and expertise of some of New Zealand's most experienced

biosecurity researchers. In section 4, past trends in international import volumes to New Zealand are used as a basis for hypothesizing how future trade shifts might affect biosecurity risks on import pathways. The following sections then deal with climate change effects on the establishment of new exotic pests (Section 5), the use of new crops (Section 6), and changes in pest status of species already present in New Zealand (Section 7).

Section 8 describes experimental work based on the latest fine-scale projections of climate change for New Zealand. The climate data are used to project potential distributions for a range of species based on previously published CLIMEX models. Detailed projections are made for twelve species which are currently present in New Zealand, and compared to twelve species which are not present. An online tool is also described that enables quick and easy projection of species distributions under current and future climates.

Finally, we summarise and identify specific areas that we feel would benefit the most from further research.

3. Future climate predictions for New Zealand

Predictions of future climate depend on projections of future concentrations of greenhouse gases and aerosols. These depend on forecasts of emissions which, in turn, depend on changes in population, economic growth, technology, energy availability, and national and international policies. The starting point for all future climate projections is the specification of emission scenarios. In 2000, the International Panel on Climate Change (IPCC) produced a set of emission scenarios usually known as the 'SRES' scenarios, (Nakicenovic & Swart 2000), which formed the basis of climate model projections for the IPCC Fourth Assessment Report (AR4) released in 2007. In 2011, a new set of scenarios known as the 'RCP' (representative concentration pathway) scenarios were introduced (van Vuuren et al. 2011), and used in the IPCC Fifth Assessment Report of 2013.

3.1. DERIVATION OF CLIMATE PREDICTIONS

To identify likely future climate changes across New Zealand at high resolution (about 5 km), projected changes from General Circulation Models (GCM) must be downscaled from the global model resolution of 100 km or more. Mullan et al. (2008) described New Zealand projections from the IPCC AR4 models, based on one technique known as statistical downscaling. Historical observations are used to develop regression equations that relate local climate fluctuations to changes at the larger scale. These historical predictors are then replaced in the regression equations by the modelled changes to produce the fine-scale projections.

An alternative approach, known as dynamical downscaling (Ackerley et al. 2012), nests a high resolution regional climate model (RCM) within a global climate model (GCM), and the RCM is forced at its lateral and lower boundaries by data from the GCM. The RCM that NIWA currently runs has a spatial resolution of approximately 27 km, so its output in turn needs to be statistically downscaled to still finer resolution. A big advantage of the dynamical approach is that data are automatically created for a full set of climate variables at high temporal resolution (e.g., hourly or less, if required).

Dynamically downscaled climate projection data are available from NIWA for the three main SRES emission scenarios of B1 (low), A1B (mid-range) and A2 (high), as derived from four of the AR4 GCMs that validate well in the South Pacific region. Simulations covering the historical period from 1971 to 2000 are forced by historical emissions, and the future projection period of 2001 to 2099 are forced by SRES emission scenarios B1, A1B and A2. The final data sets are available on the same spatial grid as NIWA's Virtual Climate Station Network (VCSN, Tait et al. 2006); that is, a 0.05 degrees latitude and longitude grid (approximately 5 km by 4 km) of 11,491 points covering New Zealand. RCM simulations driven by Fifth Assessment (AR5) models are now underway, but processed data sets were not available for use in the current project.

When assessing the impacts on New Zealand of global warming, it is important to consider a range of projections. This means not just different future emission scenarios (B1, A1B, A2), but also different global models to account for internal variability of the climate system. With only four GCMs to choose from, the sample is too small to create probability distributions,

but will nevertheless give a more realistic perspective on future changes than focusing on a single model. The four models NIWA has downscaled are (Meehl et al. 2007): CM2.1-GFDL (from USA), MK3.5-CSIRO (Australia), ECHAM5-MPI (Germany), and HadCM3-UKMO (UK).

3.2.   PREDICTED CLIMATE TRENDS

For the annual mean projections under the A2 scenario, the MK3.5-CSIRO model has warmed the most by century end, and HadCM3-UKMO the least. The ECHAM5-MPI model has the strongest west-east rainfall changes (getting much wetter in west, much drier in northeast) of the four models, the MK3.5-CSIRO is the driest, and the CM2.1-GFDL model shows the least changes. Model comparison is helpful in estimating the range and regional patterns of seasonal change. The climates from different models for the A2 emission scenario depict large differences reflecting internal variability of the climate system. The seasonal variability of the models on the other hand is quite similar.

Temperature changes under the A1B scenario are comparable to those from A2 up to about mid-century, but thereafter the A2 results diverge with faster warming under the stronger A2 emission scenario. Precipitation changes are more variable, not showing clear trends relative to emissions.

Figure 3.1 shows the 50- and 100-year seasonal change in maximum temperature and precipitation derived from the HadCM3-UKMO model for the high end SRES-A2 scenario. This model generally gives intermediate to low end results in comparison to the other GCMs. Results from all GCMs are included in Appendix 1. The minimum temperature change patterns and variability (not shown) are similar to that of maximum temperature, though markedly weaker. The other (A1B and B1) scenarios show similar but weaker patterns of change.

The winter season warms the least for all models (with the exception of CM2.1-GFDL model in mid-century) and the summer season warms the most, thus increasing the annual temperature range. The mid-century warming is roughly half of that towards the end the century as indicated by the scales in Figure 3.1, though the trends are not linear, and increases are more rapid towards the end of the century. All models show the strongest warming at high elevations and in central to eastern regions of the South Island in the spring and summer seasons for both the 2040s and 2090s periods. In general, the North Island warms considerably less than the South Island at the end of century with a north-south warming gradient.
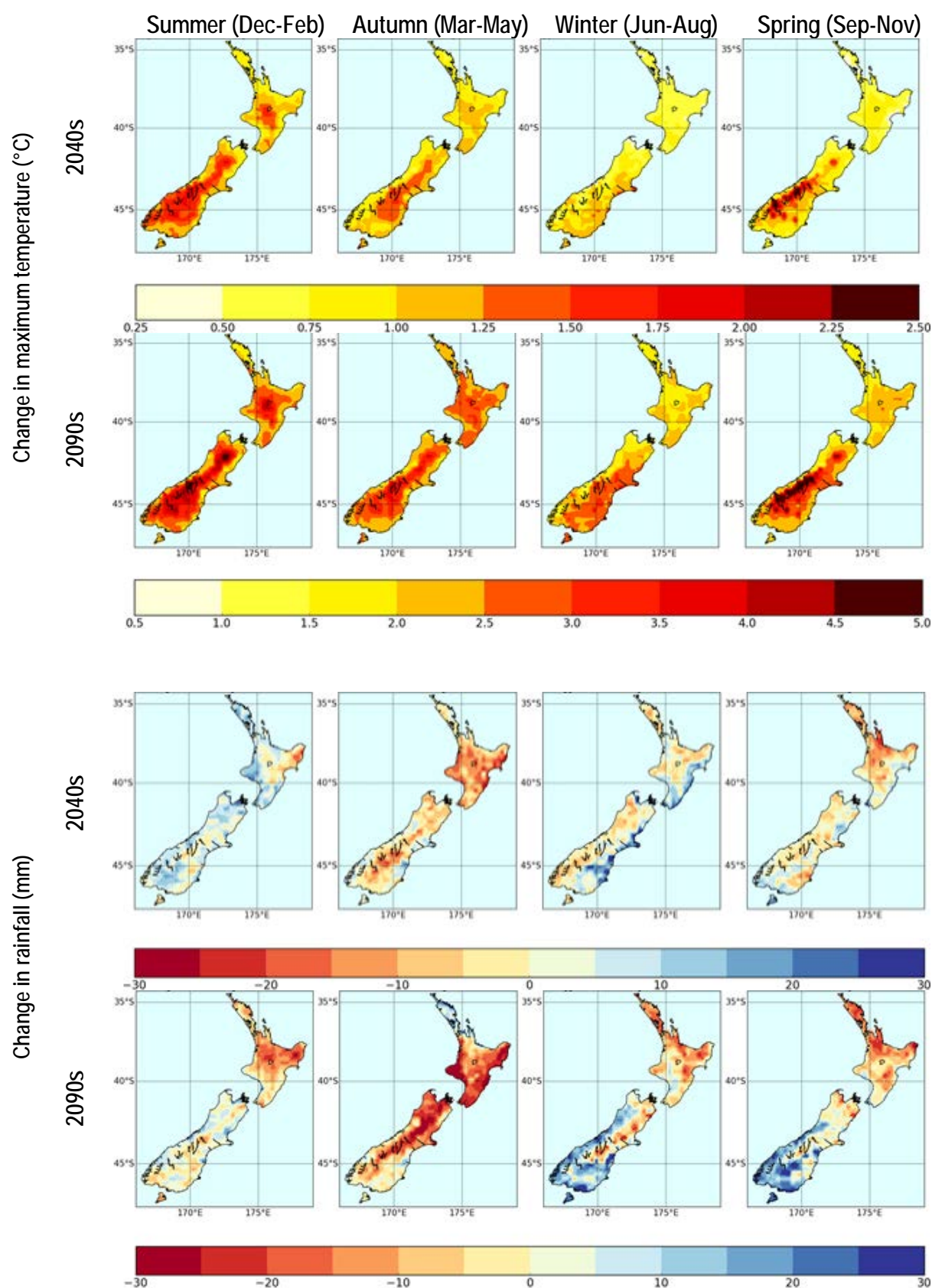
Figure 3.1. Projected 50-year (2040s) and 100-year (2090s) seasonal maximum temperature change (top) and seasonal rainfall change (bottom) forced by the HadCM3-UKMO model with A2 emission scenario.

The seasonal precipitation change on the other hand shows no obvious temporal trends, with the exception of the winter season. The climate in winter becomes increasingly wetter in the west and south of the South Island, and drier in the north and east of the North Island. The MK3.5-CSIRO model has overall the driest climate, whereby the North Island becomes drier in all seasons except in autumn. In general, the mid-century precipitation change is weaker than at the end of the century. A notable exception is precipitation decreases on the North Island in autumn, which are larger at mid-century than end of century.

Precipitation change is considerably more spatially variable than temperature, with both drier and wetter regions over New Zealand which change over time. Regional precipitation change is not directly related to emissions unlike temperature, but is related to changes in circulation patterns and climate indices. The precipitation change patterns reflect changes in wind fields for different scenarios, whereas the order of magnitude of change is similar for all scenarios.

3.3. KEY PREDICTIONS FOR CLIMATE CHANGE

- There are considerable differences between the projected climates from the different general circulation models. The MK3.5-CSIRO model predicts the greatest warming and drying of New Zealand, while the ECHAM5-MPI predicts the least.

- Most models predict the annual temperature range to increase, with summers warming more than winters, in general. Warming is likely to be greatest in the south and at high altitudes.

- Winters are likely to become wetter in the west and south of the South Island, and drier in the north and east of the North Island. However, there is considerable variability in rainfall predictions between locations and between models.

4.   Geographic sources of future pests

To anticipate future threats to New Zealand's biosecurity and to prepare for associated effects of climate change requires some understanding of the likely origins of pests and pathogens that will arrive in the future. Some of the main pathways for the arrival of pests and pathogens are associated with international trade. There are a wide range of pathways, and these differ significantly in volume, origins, and the likelihood of introduction for specific pests and diseases. This section reviews recent changes in trade patterns and considers future trends based on trade agreements and expert opinion.

4.1.   HISTORICAL CHANGES IN VOLUME AND ORIGINS OF IMPORTS AND FUTURE OUTLOOK

Trade data were obtained from several sources. We consulted the World Trade Organisation's International Trade Statistics (www.wto.org/english/res_e/statis_e/its2011_e/its11_charts_e.htm) for a global overview of trade growth. These indicate that international trade volumes have increased about 6% annually, on average, since 1950 (Figure 4.1). Over the last ca. 60 years, the volume of international trade has grown 800-fold for agricultural products and nearly 7000-fold for manufactured goods (Figure 4.1). These figures suggest that globalisation is resulting in ongoing increases in international shipping and air freight. Internet purchases are becoming increasingly important in the smaller volume mail and courier pathways. Although the financial crisis of 2007-2008 is clearly evident in Figure 4.1, growth has since resumed. Obviously, changes in trade and trading partners vary greatly among countries, and a New Zealand-specific analysis is needed.
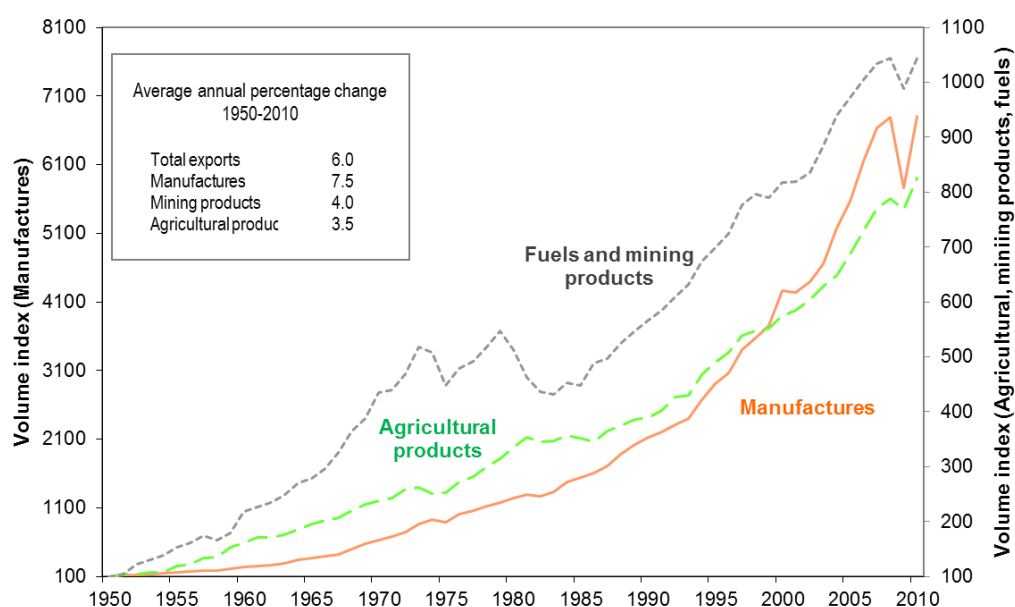
Figure 4.1. Change in global trade volume of agricultural products, fuels and mining products, and manufactured goods (Note:1950 = 100). Source: World Trade Organisation's International Trade Statistics (www.wto.org/english/res_e/statis_e/its2011_e/its11_charts_e.htm).

Time series of New Zealand-specific import data were obtained from Statistics New Zealand ("Global New Zealand – International trade, investment, and travel profile" for data post 2000, see www.stats.govt.nz/browse_for_stats/industry_sectors/imports_and_exports/ global-nz-dec-13.aspx) and for data going back to 1988, from Statistics New Zealand's Infoshare ("Infoshare: Harmonised Trade – Imports", see http://www.stats.govt.nz/ infoshare/Default.aspx). Longer time series could be obtained from other databases (e.g., the World Trade Atlas, www.gtis.com/english/GTIS_WTA.html) but there would be a charge for data access. These data are by import value, which is generally a less reliable indicator of biosecurity risk than import volume, but in combination with the international increase in trade volume (Figure 4.1) they indicate important trends. Volume data were not available for New Zealand, so value (= price × volume) were the next most indicative data, even though price and volume may change independently.

Since the 1980s, a considerable shift in trade patterns has occurred in New Zealand. The main origins of imports entering New Zealand, by value, used to be Australia, Europe, the USA, and Japan. However, these have largely remained static or declined, while imports from NE Asia have grown substantially and now constitute the greater share (Figure 4.2). While the total value of New Zealand's imports from the UK has remained at about $1 billion annually, the overall increase in import values means that the UK share actually decreased from about 9% in 1988 to less than 3% in 2013. Imports from the USA have remained at around $4 billion annually since the early 2000s, but the US share of all import value has declined from about 17% to about 9%. In contrast, the value of imports from China has grown substantially. In 1988, only 1% of New Zealand's imports by value originated in China, but in 2013 these represented more than 17%. By value, New Zealand now imports more from China than any other trading partner, including Australia (Figure 4.2). With China, Japan and South Korea, several other Asian countries have developed export economies. New Zealand's Reserve Bank now monitors economic activity also in Indonesia, Singapore, Malaysia, Taiwan, Hong Kong, Thailand, the Philippines and Vietnam. Together, these Asian countries now provide about half of New Zealand's imports by value, and current trends, such as the recent free trade agreement with South Korea, suggest that this may increase in the future.

There has been a slight increase in trade value with the emerging economies such as Brazil and other South American countries with whom New Zealand has not traded much historically. However, combined imports from Brazil, Argentina, Chile, Paraguay, Peru, Bolivia and Uruguay still represent less than 1% of New Zealand's imports by value (Figure 4.3). Nevertheless, this percentage is likely to increase in the future due to growing economic activity in South America and also because of new free trade agreements. Chile is part of the Trans-Pacific Partnership (TPP, along with Australia, Brunei, Canada, Japan, Malaysia, Mexico, Peru, Singapore, the USA, Vietnam, and New Zealand – see http://www.mfat.govt.nz/Trade-and-Economic-Relations/2-Trade-Relationships-and-Agreements/Trans-Pacific/index.php). Argentina, Brazil, Paraguay, Uruguay and Venezuela are part of the 'Mercosur' group which promotes free trade within the region. New Zealand currently has observer status with Mercosur.

Other countries with a notable and potentially increasing share of New Zealand's imports include Mexico (currently 0.5% of imports by value), South Africa (0.3%) and India (0.9%). A free trade agreement is currently being negotiated with India (http://www.mfat.govt.nz/ Trade-and-Economic-Relations/2-Trade-Relationships-and-Agreements/India/index.php) and if successful may lead to an increase in imports from there.

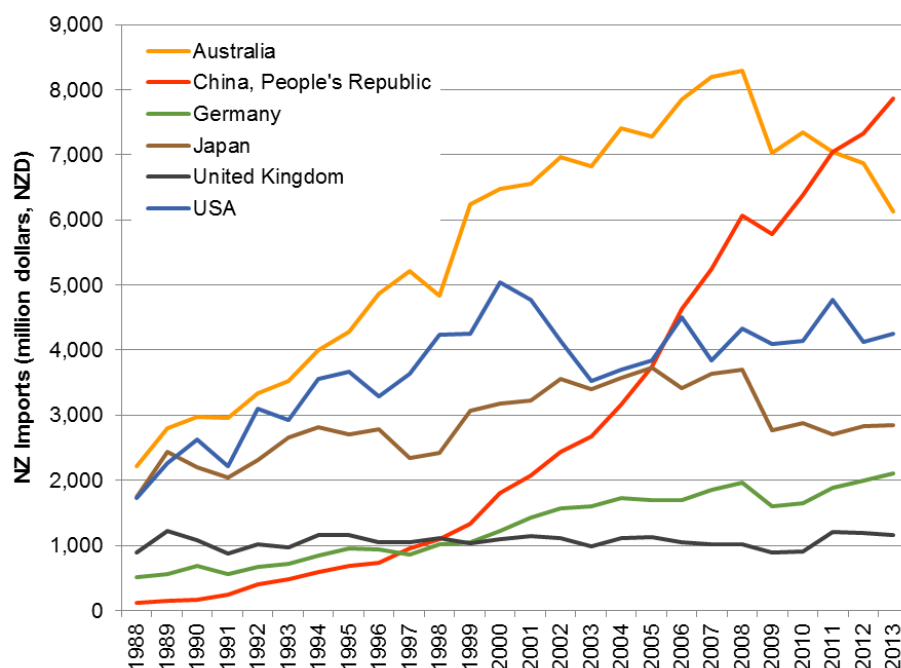**Figure 4.2.** New Zealand imports by value from several key trading partners, 1988-2013. Source: Statistics New Zealand ("Infoshare: Harmonised Trade – Imports", see http://www.stats.govt.nz/infoshare/Default.aspx).
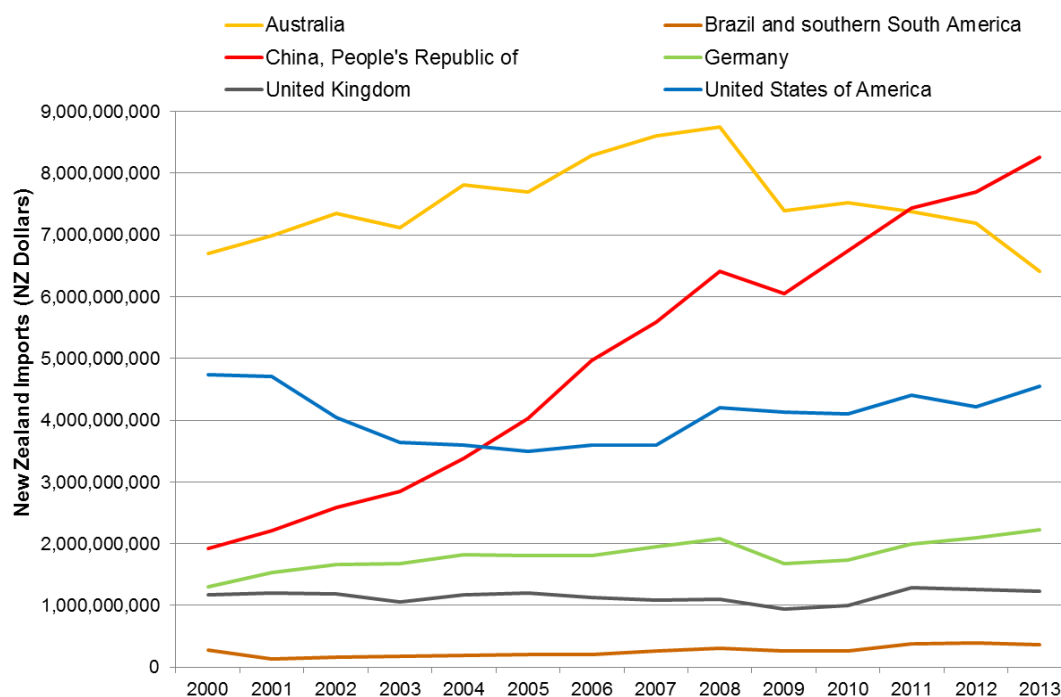

Figure 4.3. New Zealand imports by value from several key trading partners, 2000-2013, including imports from Brazil and southern South America. Source: Statistics New Zealand.

While the past data are indicative, we asked a range of New Zealand economists if they were aware of any efforts to predict future trends in the volumes and origins of New Zealand's imports. The responses suggest that little research has been published, but some internal analyses may have been done as needed. Natasha Abram from MPI's Sector Policy, Economic Information and Analysis team advised that they are concerned about the economic factors affecting exports and market access, but will also analyse imports as and when this is needed to contribute to the wider work programme of MPI. Victoria Yili Zhang from the Reserve Bank has published a relevant paper on changing trade flows (Zhang 2009) but indicated that there has been no comprehensive work at the Reserve Bank on this topic since then. Caroline Saunders and John Saunders, economists at Lincoln University's Agribusiness and Economics Research Unit, contributed to discussions about this project and are interested in the topic but have not undertaken any formal research in this area. Several resource economists at Crown Research Institutes are well placed to consider such issues; James Turner (AgResearch), Richard Yao (Scion) and Sandra Velarde (Scion) expressed interest but were unable to contribute to the current project due to other commitments. Based on these responses it appears that there may be scope for a comprehensive review of the likely characteristics of New Zealand's future imports.

4.2. EFFECTS OF CHANGES IN TRADE ON NEW ZEALAND'S BIOSECURITY RISK PROFILE

Changes in the origins of imported goods and passengers would be expected to result in changes in the profile of pest and pathogen threats. In fact, this has already been observed in several regions. For example, in North America and Europe there has been an increase in insect pest and pathogen incursions originating from NE Asia. Historically, the majority of forest insects invading North America originated from Europe but in the last two decades NE Asian species, including some high-impact invader such as Asian longhorned beetle (detected in 1998) and emerald ash borer (detected in 2002), became more prominent (Aukema et al. 2010).

While it is not possible to predict with any certainty the future changes in trade patterns and our likely trading partners in 2040 or 2080, it is possible to analyse current trends and expectations based on bilateral and multilateral trade agreements. Based on the import trends we analysed and the expected effects of trade agreements, one can assume that New Zealand's international trade, in general, will increase further. Furthermore, imports are likely to increase from NE Asia, SE Asia, South America and to a smaller extent several other non-traditional trading partners. At the same time, our traditional trading partners in Europe, Australia and North America are likely to remain important sources of our imports, even if their relative share of all imports will probably decrease. While it is too soon to know whether current widening of the Panama (http://www.pancanal.com/eng/expansion/) and Suez (http://worldmaritimenews.com/archives/140205/suez-canal-expansion-contracts-awarded/) canals will impact New Zealand's imports, it is at least feasible that these may increase imports from Mediterranean countries. If nothing else, such developments may accelerate the spread of some pests through other countries and thereby affect the pest profiles in import pathways from any of our trading partners. Internationally, climate change may also influence this spread (Figure 4.4).
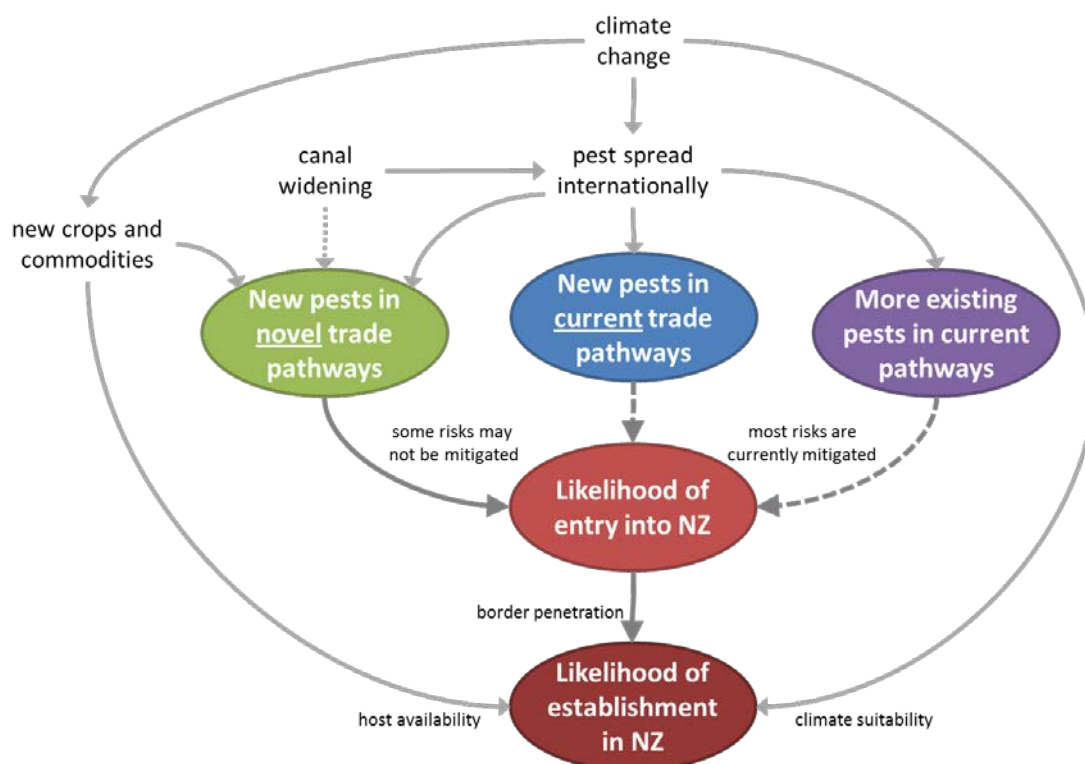
Figure 4.4. Conceptual summary of how some major future trends, including climate change, may affect biosecurity risk to New Zealand.

While trade may arguably present the greater risk of introducing unwanted pests and diseases, international passengers are another important pathway that may change in the future. New Zealand might attract greater numbers of visitors from currently developing countries as the number of individuals able to afford a visit increases. In addition, their method of arrival may change, affecting biosecurity risk. For example, the number of visitors arriving on cruise ships is expected to increase markedly in coming years (Tourism New Zealand 2012).

The volume of imports and the number of international visitors may be primary drivers of pest and disease propagule pressure, but several other factors will affect future biosecurity risk. For example, new and rapidly growing trading partners may have a disproportionate effect on biosecurity risk because they may host pests that have not previously had access to New Zealand's borders. Many of the most invasive species from our long-standing trading partners will have either established already in New Zealand or have had effective border protection measures put in place to exclude specific species or to mitigate specific entry pathways. This is not necessarily the case for newer trading partners in Asia, South America and Africa, though many pests may be excluded by generic and specific pathway measures. New risks are assessed prior to opening up novel pathways, for example for fresh produce and nursery stock. However, the greatest threat may be from new "hitchhiker" species, which are more difficult to manage because they are not necessarily associated with particular pathways in well understood ways.

Climatic similarity will also have important implications for the ability of pests and pathogens to establish and develop pest potential in New Zealand. As such, the SE Asian countries will

probably represent relatively less risk because pests from equatorial regions may not always be able to establish in New Zealand due to climatic limitations. However, temperate and some subtropical regions are of greater concern. Climate matching of current and future climates therefore suggests that parts of NE Asia, South America, and southern Africa, as well as cooler (e.g., montane) regions in subtropical countries may represent growing sources of species of biosecurity concern (Peacock & Worner 2006, Kriticos 2012). Finer-grained revision of previous analyses, and making the results readily available to MPI through an online GIS would potentially be useful, especially if combined with geospatial data on host plant distributions.

Another key factor that is likely to influence biosecurity risks is the similarity of plant phylogenies between the floras of exporting countries and New Zealand, including both native and valued exotic plants such as our major crop species. As most plant-feeding insects and plant pathogens are more or less host-specific, regions with plants that are more closely related to New Zealand's are expected to represent the greatest risk (Ridley et al. 2000, Beever et al. 2007, Bertheau et al. 2010). The native floras of southern South America (i.e., Chile and Argentina) and Australia and adjacent islands share many plant families and genera with New Zealand. For example, Nothofagaceae and Podocarpaceae occur mainly in parts of Australia, New Caledonia, New Guinea, Chile, Argentina, and New Zealand, and to a lesser extent in a few countries or regions further north. One would therefore expect that increasing imports from these countries, together with a warming climate in New Zealand, might increase the likelihood of arrival and establishment of such pests and diseases (e.g. Brockerhoff et al. 2010). As most of our crop plants have a northern hemisphere origin, an equivalent situation applies regarding increasing imports with some northern hemisphere countries.

It is clear from this brief review that climate change is only one of several interacting factors that will determine the risks of pest and disease introduction and establishment in the future. New Zealand's biosecurity systems will need to be flexible enough to adapt to such changes in risk profiles.

5.   Establishment of new pests

In New Zealand, the general warming of temperatures expected with climate change is expected to result in a southward extension of the habitable ranges of many crops and pests which are currently limited by winter cold. In addition, the reduced frequency or absence of frosts and increased temperatures in the northern North Island may create sub-tropical climates that allow some existing crops and new crops to be grown commercially (see Section 6). These local climates may also facilitate the establishment of new exotic pests and diseases that damage current and future crops and natural ecosystems. Of particular concern for agriculture and human health would be the establishment of vectors (e.g. ticks, mosquitoes, plant-sucking insects) that would facilitate the spread of animal and plant diseases.

5.1.   MAJOR SUBTROPICAL PESTS

In the future, northern New Zealand may be vulnerable to major subtropical pests and diseases that are not currently established. Auckland already shares a high proportion (78%) of its pest insect species with the analogous climates of western Europe and the east coast of the United States (68%) and traditionally is the point of entry for many high profile pests in New Zealand (Peacock & Worner 2006) because it has the largest sea port and international airport. It also currently averages less than 9 frosts per year, allowing subtropical plants and invertebrates to establish and thrive in sheltered urban habitats.

Peacock et al. (2006) identified that temperatures were the best classifiers for many non-established 'door knocker' insect species. With climate change, it is likely that northern North Island districts will become more suitable for subtropical species. From the species investigated in that study, the projected increase in autumn and winter temperatures will increase the likelihood of species such as the citrus pest *Diaphorina citri* and the grass pest *Spodoptera exempta* establishing in warmer regions. Increased summer temperatures will favour establishment of the polyphagous leafminers *Liriomyza sativae* and *L. trifoli*, and *Hypera postica*, a major pest of legumes overseas (Peacock 2005; Peacock et al. 2006).

Subtropical fruit flies are already considered major threats to the New Zealand horticulture industry and are 'Notifiable Organisms' (Kriticos 2007). An analysis of the impacts of climate change on the potential for permanent establishment by fruit flies suggested that risk to the summerfruit industry would increase for *Ceratitis rosa* and *Bactrocera dorsalis*, decrease for *C. capitata*, would not change for *B. tryoni*, and only increase under a 2090 scenario for *B. zonata* (Lindsay 2010).

Subtropical plant feeding invertebrates also pose risks to New Zealand native plants (Groenteman 2013), and climate change will increase the likelihood of their establishment and increase their potential distribution across New Zealand. For example, the giant whitefly *Aleurodicus dugesii* is a sap-sucking insect originating from Central America. This regulated pest is known to feed on over 200 host species in at least 35 plant families. Offshore, it is a known pest in horticulture, but a wide range of New Zealand native plants may also be susceptible to damage, including species of *Myoporum*, *Solanum*, *Pittosporum*, *Passiflora*, *Schefflera*, *Pseudopanax* and *Cordyline* (Groenteman 2013).

As well as being a potential major pest for the horticultural industry (Charles & Logan 2013), the glassy-winged sharpshooter (*Homalodisca vitripennis*) is also expected to have a significant impact on native plants. A recently published field survey of native New Zealand plants growing as ornamentals in southern California confirmed the susceptibility to the glassy-winged sharpshooter as a vector of a pathogenic bacterium (*Xylella* spp.). A large number of iconic New Zealand native species show signs of disease in California, including: pohutukawa (*Metrosideros excelsa*), tītoki (*Alectryon excelsus*), kauri (*Agathis australis*), *Coprosma* spp., New Zealand flax (*Phormium* spp.) and *Hebe* spp. (Groenteman et al. 2014). Similarly, *Klambothrips myopori* is an Australian gall-forming thrips that is causing severe damage to ngaio (*Myoporum laetum*) planted as ornamentals in California. The species is capable of killing a high proportion of mature ngaio trees. A warmer environment in New Zealand might facilitate *K. myopori* establishment along prevailing wind currents from Australia.

The potential for establishment of many invasive ants and social wasps is currently limited by New Zealand's temperatures (Ward 2007), but the risk of establishment will increase with climate change (Harris & Barker 2007). Climate comparisons suggest that the establishment and spread of several species will increase (red imported fire ant *Solenopsis invicta*, black imported fire ant *S. richteri* and crazy ant *Paratrechina longicornis*), while the yellow crazy ant *Anoplolepis gracilipes* and tropical fire ant *Solenopsis geminata* might also establish (Harris & Barker 2007). Interestingly, climate change is predicted to reduce the risk of invasion by the big-headed ant *Pheidole megacephala* in Oceania (Bertelsmeier et al. 2013). Likely social wasp species to establish with warmer temperatures in New Zealand include the Asian hornet *Vespa velutina nigrithorax* (which has recently invaded France and is impacting on beekeepers), the yellow paper wasp *Polistes olivaceus* and the oriental hornet *Vespa orientalis*.

5.2. DISEASE THREATS TO ANIMAL HEALTH

The key to predicting the likely effects of climate change on infectious diseases in New Zealand is understanding the response of disease vectors (Lafferty 2009), in particular the distributions of biting flies and ticks (Tompkins & Poulin 2006). A comprehensive cross-sectorial review of vector-borne disease threats to human, domestic animal and wildlife health in New Zealand was carried out in 2006-2007, based on a formal and objective risk assessment approach that built on independent assessments of agent and vector risk (Mackereth et al. 2007). Given the predicted relatively slow rate of climate change for New Zealand, the findings of this review may still hold. A range of agents were identified in that review as being of medium to high relative risk to human, domestic animal and wildlife health. These included agents that were already present in New Zealand by 2007 as well as several that were not known to be present. Those agents already present in the country assessed as having medium to high risk of increased impact to production animal health were *Anaplasma* sp., *Theileria orientalis* and *Theileria* sp., which all cause tick-borne diseases of livestock. Those agents currently absent from the country that were likewise assessed were West Nile virus (causing a primarily mosquito-borne disease of humans, livestock and wildlife), bovine ephemeral fever virus (causing a mosquito-borne disease of livestock), the

piroplasms *Babesia bigemina, B. ovata, B. major, B. ovis* (all causing tick-borne diseases of livestock), the rickettsia *Coxiella burnetii* (a likely tick-borne causative agent of Q fever in a range of animals including livestock), and other *Theileria spp.* (likewise causing tick-borne diseases of livestock).

Since 2007, two subsequent disease outbreaks have supported the predictions of the Mackereth et al. review. First, the review suggested that the already present tick-borne infectious agent *Theileria orientalis* would have medium to high likelihood of increasing its domestic animal health impact. Since then, infections of cattle have dramatically increased in both range and incidence (Lawrence et al. 2014). Second, the review similarly highlighted exotic tick-borne *Theileria* spp. as being of medium to high risk to domestic animal health. The subsequent outbreak in Northland of *T. orientalis* Type 2 (Ikeda) has spread to almost 1300 farms as of February 2015, and reached the west coast of the South Island in November 2014.

Mosquito vectors of West Nile virus are already present in New Zealand (Kramer et al. 2011), and are predicted to increase in both abundance and distribution with climate change (Tompkins et al. 2012). With multiple competent host species also present (Spurr & Sandlant 2004), critical to preventing West Nile virus emergence in New Zealand may be thus either or both of (1) the prevention of the virus from entering the country, and (2) the management of the existing mosquito populations at potential points of incursion. The identified transmission routes for the spread of West Nile virus across the Pacific from the America's (where it is continuing to emerge following initial emergence of WNV Lineage 1 in New York State in 1999; Tompkins et al. 2015) are (1) humans on aircraft, (2) wind-transported mosquitoes, (3) human-transported mosquitoes, (4) human-transported birds or other vertebrates, and (5) migratory birds (Kilpatrick et al. 2004). For introduction to Hawaii, the quantitative analysis of Kilpatrick et al. (2004) found risks (3) (human-transported mosquitoes) and (4) (human-transported birds or other vertebrates) to be primary. For management of existing mosquito populations, modelling exercises such as those recently conducted for Ross River virus (Tompkins et al. 2012; Tompkins & Slaney 2014), could inform on where in the country climate change is predicted to increase the potential for West Nile virus epizootics should the virus be introduced. Such exercises would identify whether or not there is (1) limited risk of climate change inducing greater vectorial capacity for West Nile virus epizootics, (2) the need for localized mosquito population management utilizing conventional tools such as surfactants, or (2) the need for landscape scale mosquito population management using approaches such as the in-development Trojan Female Technique (Gemmell et al. 2013).

The other mosquito-borne agent having medium to high risk to production animal health in New Zealand, bovine ephemeral fever virus, is currently present in Africa, Asia and Australia (Watts 2011). Far less is known about the incursion risk pathways for this agent into countries where it is not yet present, though MPI included it in their import risk analysis for cattle (MPI 2009). A quantified exercise such as that conducted by Kilpatrick et al. (2004) for West Nile virus may be informative. Similar to West Nile virus, mosquito vectors for this disease causing agent (*Culex quinquefasciatus*) are already present in New Zealand, thus the border biosecurity focus is on preventing incursion of the agent rather than on its vectors *per se*. Modelling could be used to assess whether the mosquito vector populations already present in New Zealand should be managed to prevent climate change increasing their capacity to vector disease, similar to that carried out for Ross River virus (Tompkins et al. 2012; Tompkins & Slaney 2014).

Apart from West Nile virus and bovine ephemeral fever virus, all other disease-causing agents assessed as having medium to high risks to production animal health in New Zealand, both either already present in New Zealand or not yet reported from the country, are vectored primarily by ticks. Tick-borne infectious agents of the genera *Anaplasma*, *Babesia* and *Theileria* have complex lifecycles in which the disease causing agents can frequently utilize multiple host and vector species (Mackereth et al. 2007). Thus, both pre-emptive and actual management of such diseases could be targeted to the impacted production animal species of concern (i.e. selection for resistance), wildlife reservoirs of the disease agents (e.g. the control of wild pig or deer populations), or vector management. With regards to vectors, a known or strongly-implicated vector for all of these disease causing agents (the cattle tick *Haemaphysalis longicornis*) is already well established in New Zealand (Heath 2002). Thus, again, border biosecurity efforts with regards to agents of concern not yet in the country should focus on the agents themselves rather than their vectors per se. As noted above for bovine ephemeral fever virus, a re-assessment of current border biosecurity mitigation actions could be guided by a quantified risk pathway analysis. For determining what combination of management of the impacted animal species, management of wildlife reservoirs, and or on- or off-farm management of vectors can best mitigate the risks associated with (or the current impacts of) such tick-borne infectious agents, guidance in the form of predictive modelling (as for Ross River virus noted above) can be very useful. Such modeling is likely to be confronted with a paucity of data with regards to tick dynamics in New Zealand, particularly in the off-farm context, and thus would likely require a program of field data collection to appropriately construct and parameterize such models to give accurate and robust guidance.

5.3.   RISKS FROM CURRENT TRANSIENTS

Long distance natural dispersal is a real and continual biosecurity risk. However, given New Zealand's isolation, Yen et al. (2014) identified only two pathways of potential high impact, namely from Africa and Australia. While the likelihood of a natural dispersal event from southern Africa was considered very low, the impact of incursion of a virulent pathogen could be high. In contrast, the likelihood of natural incursions from south east Australia is higher. New Zealand lies approximately 1800 km directly downwind of the prevailing wind currents and CLIMEX studies have shown that the two regions are climatically very similar (Peacock 2005). Peacock & Worner (2006) showed that New Zealand shares 90% of south east Australia's insect pests, and suggested that the remainder have potential to establish in New Zealand.

Accelerating trade winds in the Pacific (England et al. 2014) and intensification of 'bush fire' weather pattern (Pitman et al. 2007) associated with trans-Tasman migrations (Yen et al. 2014) may increase the range of taxa and propagule pressure of natural introductions from Australia and elsewhere. Suitable conditions for trans-Tasman insect migration were estimated to occur between 20-30 times per year in the 1960s and the most likely landing places at that time were judged to be Tasman Bay and the Waimea Plains in the South Island and low lying areas north of Hamilton in the North Island (Tomlinson 1973). Eddy effects were expected to produce similar down-draught effects about the Marlborough Sounds, the Picton-Blenheim area and near the Manawatu Gorge and near Mount Taranaki.

A number of Australian and island pests (exotic and indigenous) have been frequent 'doorknockers' in New Zealand but fail to overwinter in the field. Under climate change these species might persist year round and cause as much crop damage as they currently do in Australia and the islands.

While most reports of wind-assisted trans-Tasman migrations are for the more obvious Lepidoptera e.g. (Fox 1978; Harris 1990; Ryan & Harris 1990), there is a diversity of invertebrates and pathogens that utilise wind for dispersal and have made the crossing (Phillips et al. 2006). At least 18 species of thrips are thought to have dispersed naturally from Tasmania and SE Australia to New Zealand by westerly winds (Mound 2006). A Tasmanian species that could become a threat to our natural ecosystems under future climate change scenarios is *Klambothrips myopori*. This gall-forming thrips is causing severe damage to ngaio (*Myoporum laetum*) planted as ornamentals in California and is capable of killing a high proportion of mature ngaio trees.

Table 5.1 lists examples of Lepidoptera that are known or considered to have the ability to establish temporarily in New Zealand under current conditions, and therefore may become permanently established with milder frost-free winters. However, some have aspects of their life cycle that prevent this. For example, the bogong moth was trapped 4 out of 13 years of continuous trapping in the 1980s and 1990s at Pukekohe and larvae were found in a lettuce crop in 2005 (Bullians et al. 2006). However, the species has never established permanently, possibly because the adults require alpine boulder fields for aestivation.

Peacock (2005) analysed New Zealand incursion data collected 1993-1999 and from 117 incursions of species not established in New Zealand, identified 20 'door-knocker' species that had sufficient published data for further study. For these she assessed the existing known distribution and likelihood of establishment in New Zealand under current climate conditions (Table 5.2). All the species listed are Australian/Oceanian in origin and have suitable host plants in New Zealand. Nine of the 20 species had similar climate requirements, and since 2005 two of these have become established in New Zealand: circular scale *Chrysomphalus aonidum* (which was successfully eradicated) and citrus mealybug *Planococcus citri*.

Table 5.1. Examples of Australian Lepidoptera with potential to establish in New Zealand through increased westerly winds and warmer temperatures.

Pest	Plants attacked
bogong moth (*Agrotis infusa*)	beet, brassica, barley, lucerne, pea, wheat, *Pinus radiata*
Australian painted lady (*Vanessa kershawi*)	mainly Asteraceae (over 300 New Zealand indigenous spp)
Helicoverpa punctigera	polyphagous, damaging to tomatoes, maize, lucerne
tobacco looper (*Chrysodeixis argentifera*)	polyphagous including brassicas, tomato, silverbeet
meadow argus (*Junonia villida*)	polyphagous but plantain a favoured species
vine hawk moth (*Hippotion celerio*)	grapes, kumara, maize

Table 5.2. Summary climate match and available developmental temperature of frequent 'doorknocker' species data from Peacock (2005).

Species	Family	Climate match to NZ[2]	Lower threshold (ºC)	Degree days (ºC) required
Adoretus versutus rose beetle	Scarabaeidae			
Aleurodicus dispersus spiralling whitefly	Aleyrodidae			
Aonidiella citrina yellow scale	Diaspididae	Yes	14.8	449
Aspidiella hartii yam scale	Diaspididae			
Aspidiotus destructor coconut scale	Diaspididae	Yes	8.68-10.49	728-756
Chrysomphalus aonidum[1] circular scale	Diaspididae	Yes		
Fabrictilis gonagra passionvine bug	Coreidae			
Geococcus coffeae Coffee root mealybug	Pseudococcidae			
Helicoverpa assulta oriental tobacco budworm	Noctuidae	Yes	10.69-11.89	202
Hypera postica alfalfa weevil	Curculionidae	Yes	9.7	394
Liriomyza sativae vegetable leaf miner	Agromyzidae		8.8-9.4	272-296
Liriomyza trifoli American serpentine leafminer	Agromyzidae	Yes	9.7-10.6	282-314
Maruca vitrata legume pod borer	Pyralidae	Yes		
Nysius vinitor Rutherglen bug	Lygaeidae		14.5-15.0	350-360
Planococcus citri[1] citrus mealybug	Pseudococcidae	Yes		
Pseudaulacaspis pentagona mulberry scale	Diaspididae	Yes		
Saccharicoccus sacchari sugarcane mealybug	Coccidae			
Spodoptera exempta black armyworm	Noctuidae			
Thrips palmi melon thrips	Thripidae		7.4-10.1	82-194
Xyleborus perforans island pinhole borer	Scolytinae			

[1] established in New Zealand since the study, but has subsequently been eradicated

[2] climate match using principal component analysis

6.   Protecting new crop types

6.1.   INCREASED USAGE AND DEPENDENCE ON SUBTROPICAL PLANTS

Climate change projections indicate that in the northern North Island, temperatures are likely to be considerably warmer in future. By the end of the century Auckland, Waikato and Bay of Plenty are projected to have up to 60 extra days per year where maximum temperatures exceed 25˚C (MFE 2014). Frosts will be rarer in Northland, Auckland, Gisborne and coastal areas in Waikato, Bay of Plenty and Taranaki and will have reduced in frequency and severity in the inland districts in the latter regions. This will favour subtropical species over temperate species in these regions. Therefore, upper North Island farmers and growers are likely to increase their usage and dependence on existing subtropical plant species and introduce new commercial species. The increased usage of subtropical plants will make these regions more susceptible to invasion by subtropical pests and diseases and new host/pest associations.

In pastoral agriculture, warmer temperatures are likely to shift the competitive balance in pastures towards subtropical grasses having a C_4 photosynthetic pathway and it is expected that these species will spread and increase in dominance over large areas of the North Island in response to climate change (Field & Forde 1990). For example, modelling by Trolove et al. (2008) indicated that with climate change there would be economic benefits from using long-maturing or tropical maize hybrids in combination with winter forage. However, they noted that current disease and insect pressure was an issue in Northland and resistant forage cultivars would be needed.

No subtropical grass species were included among those selected by industry as being current priorities in a recent pasture-pest hazard identification project (MPI 2013). Broadleaf setaria (*Setaria sphacelata*) has been trialled in Northland with promising results and can withstand current northern North Island frost levels (Crush & Rowarth 2007). However, in the absence of alternatives, kikuyu grass (*Pennisetum clandestinum*) is likely to become the most prevalent forage grass as it spreads readily and forms dense swards, out-competing most other pasture species (Field & Forde 1990). Kikuyu is common in New South Wales and Victoria and given the proximity and frequency of trade and air travel, Australia would be the most likely source of invasive kikuyu pests. Table 6.1 lists examples of pests that might attack kikuyu. For example, *Rhopaea magnicornis* is a major pest in sugar cane crops in northern New South Wales, Australia and its northern distribution encompasses Brisbane. The adults fly late spring/early summer and are readily attracted to light. Therefore the most likely scenario for introduction is by adults being attracted to lights during imported cargo loading at night. It is one of a large group of closely-related Australian grass-feeding scarabs collectively known as cane grubs. *Sphenophorus* spp., commonly called billbugs, are weevils that attack grasses. Newly-hatched larvae feed for 2 to 3 weeks within stems before migrating to the crown and root zone of the plant and continue to feed on roots and underground stems. The adults feed on the foliage. Most turf species appear to have a one year life cycle, overwintering as adults in leaf litter in protected areas such as hedges, tall grass, and around houses. *Sphenophorus brunipennis* has been recorded on kikuyu in Northland (MAF Biosecurity 2001). *Sphenophorus venatus vestitus* is known as a kikuyu pest in Australia and of C_4 grasses in North Carolina (Doskocil & Brandenburg 2012).

Table 6.1. Examples of Australian grass pests and diseases with potential to establish on kikuyu. Source: www.tropicalforages.info/key/Forages/Media/Html/Pennisetum_clandestinum.htm

Potential pest	Specific pathway
Invertebrates	
Brown cockchafer (*Rhopaea magnicornis*)	Adults attracted to lights during cargo loading
Hunting billbug (*Sphenophorus venatus vestitus*)	Overwintering adults in protected litter
Lawn armyworm (*Spodoptera mauritia acronyctoides*)	Eggs laid on inanimate sheltered objects
Kikuyu grass bug (*Halticus chrysolepis*)	
Yellow sugarcane aphid (*Sipha flava*)	
Tarsonemus spp.	
Pathogens	
Verrucalvus flavofaciens	
Pyricularia penniseti	
Bipolaris setariae	
Phakopsora apoda	

With many districts in the northern North Island becoming frost free under climate change, the range of commercial subtropical horticultural crops will grow. It is likely that most will be 'boutique' crops for the gourmet markets rather than commodity export crops as production costs will be higher than in competitor countries. Examples of gourmet versions of world commodity crops currently grown successfully in New Zealand are olives for premium quality olive oil and Zealong Tea. With the proximity of Auckland, these boutique crops may provide better economic returns than pastoral agriculture in these northern districts. However, the target customers would also expect products to be produced using sustainable growing practices and these small producers may not have the resources to develop adequate integrated pest management systems if troublesome pests establish.

In the 1980s, Northland researchers investigated a range of subtropical crops considered to have market potential (MAF 1986; Anderson & Piggot 1981), some of which are now in commercial production (e.g. persimmon, macadamia). As examples of potentially significant subtropical crops of the future, these are listed in Table 6.2, along with major pests associated with each crop.

In contrast to the pastoral agriculture and horticulture industries, the forestry sector does not expect to invest in new subtropical crops. The long-term nature of forestry crops means that changes in the species grown can only be done very gradually. In addition, it appears that the main current crop, *Pinus radiata*, will probably perform even better in a warmer New Zealand climate than it currently does (Mike Watt, pers. comm.).

Table 6.2. Examples of subtropical horticultural crops and potential pests.

Crop (native country)	Native pests of note
pepino (Peru and Chile)	pepino fly (*Rhagoletis nova*) soil mealybug (*Symmetrischema tangolias*)
persimmon (China)	Japanese wax scale (*Ceroplastes japonicus*) persimmon budworm (*Stathmopoda masinissa*) persimmon bark borer (*Euzophera batangensis*) persimmon broad-winged planthopper (*Ricania sublimbana*)
cherimoya (Central America)	cherimoya fruit borers (*Talponia batesi, T. backer*) giant sphinx (*Cocytius antaeus*) Bephata maculicollis (unlisted) trunk borers *Bephratelloides cubensis, Cerconota anonella, Oenomaus ortygnus*
casimiroa (Mexico)	fruit flies
nashi (China, Taiwan, Japan, Korea)	summer fruit tortrix (*Adoxophyes orana*) Asiatic leafroller (*Archippus breviplicanus*) fruit tree borer (*Carposina sasakii*) apple blossom weevil (*Anthonomus pomorum*)
macadamia (Australia)	macadamia nut borer (*Cryptophlebia ombrodelta*) macadamia flower caterpillar (*Homoeosoma anaspila*, syn. *H. vagella*)
babaco (Ecuador)	relatively pest free, but mites cause problems especially as treatments are phytotoxic to babaco
peanuts (South America)	oriental tobacco budworm (*Heliothis punctigera*) vegetable leafhopper (*Austroasca viridigrisea*) lucerne leafhopper (*Austroasca alfalfa*) lucerne seed web moth (*Etiella behrii*)

6.2. INCREASED USAGE AND DEPENDENCE ON DROUGHT-TOLERANT PLANTS

The prevalence and severity of droughts are expected to increase in many regions (Mullan et al. 2008). To mitigate this risk in systems where irrigation is not an option, farmers and growers are likely to increase use of drought tolerant plant species. The 2014 emergence of two native moths (*Epyaxa rosearia* and *Scopula rubraria*) as major plantain pests demonstrates how a large increase in broad acre usage elevated previously innocuous species to pest status.

New Zealand pastoral farmers are already shifting towards more drought and heat tolerant forages for summer production following the recent spate of droughts in 2007, 2008, 2010, 2013 and 2014. Chicory *Cichorium intybus* and plantain *Plantago lanceolata*, both deep rooted pasture herbs, are now widely used throughout the country (Caradus et al. 2013). Lucerne *Medicago sativa* is anticipated to increase in popularity in the drier parts of New Zealand, mainly as a monoculture (Ward 2008). In regard to pasture legumes, the main

strategy appears to be to breed more drought-tolerant red and white clovers, or hybrids, that will have both productivity and persistence in grass/clover pasture systems (Williams et al. 2007). Therefore the potential economic impacts of exotic plantain, chicory and lucerne pests will become increasingly important with climate change whereas those for clovers are likely to remain the same.

Chicory is attacked by relatively few seriously damaging pests compared to many crops. The most notable chicory pests are already regulated, namely turnip moth *Agrotis segetum*, witloof chicory fly *Napomyza cichorii* and the fungus *Alternaria cichorii*. The yellowstriped armyworm, *Spodoptera ornithogalli* is a polyphagous pest known to attack chicory listed with USDA –APHIS-PQQ. This subtropical pest is common in eastern USA down into South America. *Aphis intybi*, a common pest of chicory in Europe, is now in North America (Durante et al. 2012). Other pests that appear on websites dedicated to cultivating chicory are darkling beetles (*Eleodes* spp., *Blapstinus* spp. and *Caelus* spp.) and flea beetles (*Epitrix* spp. and *Phyllotreta* spp.).

Sagar & Harper (1964) provide a long list of invertebrates and pathogens damaging to plantain in the UK and Table 6.3 lists those not currently known from New Zealand. Lucerne is grown extensively throughout North America and Europe and resistant cultivars have been developed to combat some of the many pests and diseases. Those present in NSW, Australia (both exotic and native) but not in New Zealand are listed in Table 6.4.

Table 6.3. Examples of plantain pests not known to be present in New Zealand

Pest	Order: Family	Distribution
Homoeosoma sinuella	Lepidoptera: Pyralidae	Europe
Aphelia paleana	Lepidoptera: Tortricidae	Europe, Russia, China
Junonia coenia	Lepidoptera: Nymphalidae	USA, eastern Canada, Central America
Junonia villida calybe	Lepidoptera: Nymphalidae	Australia
Mecinus pyraster	Coleoptera: Curculionidae	USA and Canada, Europe and Northern Asia
Chrysolina staphylaea	Coleoptera: Chrysomelidae	Eurasia, Europe, Canada
Longitarsus pratensis	Coleoptera: Chrysomelidae	Palaearctic, North America

Table 6.4. Lucerne pests and diseases in New South Wales not known to be established in New Zealand. Sources: Agfact P2.2.25 Lucerne for pastures and fodder, NSW Department of Primary Industries http://www.dpi.nsw.gov.au/?a=164738; Pests of Field Crops and Pastures: Identification and Control - PT Bailey – 2007.

Pest or pathogen	Invasion risk
Mediterranean snail (*Cernuella virgata*)	Known invasive
lucerne seed-web moth (*Etiella behrii*)	Infest pods and seeds of legumes
lucerne crown borer (*Corrhenes stigmatica, Zygrita diva*)	Larvae and pupae in stems
wingless grasshopper (*Phaulacridium vittatum*)	Egg pods in soil
lucerne leafhopper (*Austroasca alfalfae* and *A. viridigrisea*)	Eggs on leaf material
bacterial wilt (*Pseudopeziza medicaginis*)	

7.   Changes in status of existing pests

The previous sections focus on the implications of climate change on border biosecurity issues. However, not all of the serious pests of the future will arise from afar; many currently innocuous species that are already present in New Zealand may become pestiferous under the perturbation of climate change. Although this report is focused mostly on border risks, it is important to recognize that many of tomorrow's pests and disease problems are currently "sleeping" in New Zealand, awaiting some perturbation, such as climate change, to allow them to spread and flourish. This section deals briefly with the issue of sleeper pests and diseases; more comprehensive treatments are available elsewhere (e.g. Groves 2006, Cripps et al. 2013, Duursma et al. 2013).

The concept of 'sleeper weeds' has been used in weed science to describe introduced species that remain relatively scarce for a considerable period after they have become naturalized, with the implication that some species will subsequently become more highly invasive (Grice & Ainsworth 2003). Weed invasions often have a lag-phase when the population remains at low numbers for several years after introduction followed by a period where numbers increase rapidly. A retrospective analysis of records of 105 New Zealand weed species showed nearly all had a lag-phase, which averaged 20-30 years (Aikio et al. 2010). For any given weed species there is a range of factors that influence whether it becomes a significant invasive weed and the length of the lag phase, from life history traits and propagule pressure to ecosystem features and human activities. In their study of alien plant invasions in northern Italy, Marini et al. (2012) found a consistent positive effect of temperature and human population and that the high resistance to alien plant invasion of high-elevation areas appeared to be primarily related to low human pressures and not directly to harsh climatic constraints.

Reviews suggest that in at least some cases, the lag phase in weed invasions is terminated by some change in conditions which favours growth and spread (e.g. Williams et al. 2010). Therefore, the concept of sleeper weeds can be generalized to include those weeds, pests and diseases that might suddenly become problematic as a result of climate change.

There are several mechanisms whereby this might occur. First, pests might experience shortened generation times that allow their populations to grow faster or achieve more generations per year. Alternatively, climate change might upset regulation by natural enemies, allowing pests to escape control and exceed economic damage levels. Herbivores may become more pestiferous if their host plants are grown more widely, or as monocultures, in response to climate-induced land use changes. Climate change may also alter the effectiveness of control strategies, especially IPM and biological control (Hellmann et al. 2008). Indeed, climate change disruptions to biological control systems (reviewed by Gerard et al. 2010) are equally valid for crop-pest relationships.

7.1. SLEEPER WEEDS

In their assessment of potential effects of climate change on New Zealand's terrestrial biodiversity, McGlone & Walker (2011) quoted publications (e.g.Heenan and Williams 2004) reporting that already within New Zealand is a large (>30,000) reservoir of exotic plant species grown in gardens and as crops that could become weeds in our indigenous estate, and over 180 aquatic plants that have yet to naturalise. Many of the aquarium species were weeds elsewhere in the world and 35 were subsequently designated unwanted organisms, including Eurasian milfoil *Myriophyllum spicatum* and water chestnut *Trapa natans* (Champion 2004). Historically, 10-20 of these exotic species naturalised every year (i.e. established self-sustaining populations) (Esler 1988), and this rate may be increasing (Howell 2008, Sullivan et al 2009). Typically there can be decades of delay between the first introduction of a plant species, its naturalization, and the increase in abundance required to reach weed status. This delay is often called the "lag phase" with the plants that will eventually become weeds being referred to as "sleeper weeds", although the processes and causes underlying "lag phases" are usually unclear (Groves 2006). Nevertheless, climate change was recognised quite early as having potential to allow previously benign plant species to become weedy in New Zealand: to end their "lag phase" (Panetta & Mitchell, 1991). More recently, detailed modelling in Australia has predicted hotspots which may be under particular threat from incursions by naturalised plants under climate change (Duursma et al 2013). These hotspots can then be prioritised for surveillance and, if necessary, pre-emptive management (Duursma et al 2013).

New Zealand certainly has species that are currently not weedy but that could respond to climate change, but to date there have been no analyses like the Australian example. One such species is *Psidium cattlianum* Sabine (strawberry guava) that is a major forest weed in high altitude forests in Hawaii and Mauritius (Huenneke & Vitousek 1990; Florens et al., 2010), and is currently the target of an eradication programme on Raoul Island (West 2002). Strawberry guava is widely grown in gardens in Auckland and Northland. Whether the predicted increase in temperature in these areas will be sufficient to allow this plant, or other species, to naturalise and then become weedy could be modelled following the methodology used in Australia. As in Australia, such models could guide surveillance to detect the early emergence of new weeds, and allow pre-emptive management: in the case of strawberry guava the biocontrol agents released in Hawaii could be deployed prior to the problem reaching the devastating levels of infestation it has on those islands (Huenneke & Vitousek 1990; USDA 2005; Dean & Block, 2014). Also on the positive side, there may be practical opportunities to restrict the southward movement of weed populations, which in Australia is predicted to be up to 1000 km (Scott et al., 2008). With sufficient surveillance, small new infestations of many southerly-moving weeds could be detected and eradicated, which is a more cost-effective management tool than tackling large-scale weed infestations (Harris & Timmins, 2009).

The potential of introduced ornamental plants to become future invasive weed is already acknowledged and managed through the National Pest Plant Accord (NPPA http://www.biosecurity.govt.nz/nppa). This is a cooperative agreement between the Nursery and Garden Industry Association, regional councils and government departments with biosecurity responsibilities. All plants on the NPPA are present in New Zealand and are unwanted organisms under the Biosecurity Act 1993. These plants cannot be sold, propagated or distributed in New Zealand. Two examples of species on the NPPA that will become more widely invasive with climate change are:

- Alligator weed *Alternanthera philoxeroides*. This aquatic weed is widespread in Northland and Auckland. Frost and ice kill exposed stems and leaves. It forms extensive floating mats, blocking waterways, and is also invasive in terrestrial areas affecting crops and pasture. It is toxic to livestock.

- Mickey Mouse plant *Ochna serrulata*. Found in Northland, Auckland and coastal Waikato districts. Can only withstand light frosts. Prefers semi shade of the understory of forests where it forms a dense monoculture that prevents regeneration of native species.

7.2. SLEEPER PESTS AND DISEASES

In contrast to exotic weeds, invasive invertebrate species appear to have much shorter lag phases. While it may be argued that invertebrates are almost impossible to detect at initial establishment, this is counteracted by the rapidity that high profile, easily recognised invasive species have spread (e.g. glassy-winged sharpshooter, *Homalodisca vitripennis* through Pacific islands nations) and how introduced biological control agents can build up from relatively small release populations to levels that suppress target pest populations (e.g. the biological control agents for Argentine stem weevil *Listronotus bonariensis* and clover root weevil *Sitona obsoletus* were providing widespread control in New Zealand within five years of release (Barker & Addison 2006; Gerard et al. 2011)).

Currently in New Zealand >2000 exotic invertebrates are considered to have established (Brockerhoff et al. 2010). While relatively few are currently major pests, other species are potential pests under climate change. However, to date there are an insufficient number of analyses on non-pest species in order to draw generalisations about potential new pests under climate change.

Examples of sleeper invertebrate pests include:

- Migratory locust *Locusta migratoria* is found in rough grassland from Christchurch north. Because existing temperatures are usually not high enough to trigger swarming behaviour, the insect currently is not regarded a pest. However, the locusts have retained the capacity to swarm with a small swarm and the gregarious phenotype observed near Ahipara, Northland in the 1980s (Messenger 1988).

- Tropical armyworm *Spodoptera litura*. While this pest can be found through many lowland North island districts, epidemic outbreak populations, when caterpillars move 'like an army' through crops and pastures, are rare. However, the combination of events that precipitate outbreaks will be more common under predicted climate change scenarios and include above average summer and autumn temperatures allowing for additional generations to develop.

In forestry, the range of potential pests and diseases is well known due to pines being very widely grown around the world. Only occasionally are new pests and diseases detected that were not previously known to affect pines. One example is the fungal pathogen *Neonectria fuckeliana*, which was known in association with spruce (*Picea*) in Scandinavia, but has

unexpectedly colonized pines in New Zealand. One of the best known cases of climate change – pest interactions in forestry concerns the mountain pine beetle, *Dendroctonus ponderosae*, which had a spectacularly severe outbreak in western Canada and the western USA. Although climate change is not the sole factor that contributed to this (decades of fire prevention and control created overmature forests that were more susceptible to the beetle), several mechanisms are known by which a series of warmer years, including warmer winters, contributed to the outbreak. The mechanisms include increases in voltinism, leading to a greater reproduction, combined with reduced winter mortality due to the lack of severe frosts that would normally kill a large proportion of overwintering beetles.

These kinds of mechanisms may affect other species in similar ways. However, so far very few important pests of forest trees are present in New Zealand and most key pathogens do not occur here either. The challenge therefore is to prevent the arrival and establishment of new forest pests and pathogens, and this may become more difficult as climate change is likely to change the suite of species that may find New Zealand's climate suitable and allow more or different pest and pathogen species to become problematic. Nevertheless, climate change will not affect the ability to manage the risks of these new species entering on managed pathways. Indeed, future improvements in technology to detect and treat pests may decrease risks on managed import pathways.

7.3. MITIGATION

There may be value in predicting the potential impacts of these sleeper weeds and pests, and considering pre-emptive action. In particular, if biocontrol has already been successful in other parts of the world then such programmes can be relatively inexpensive to transfer to New Zealand. The successful biological control of mist flower in New Zealand could be regarded as an example of this type of action (Barton et al. 2007). Although mist flower biocontrol was primarily undertaken because of threats to indigenous ecosystems, experience in Hawai'i showed it's potential as a pasture weed (Trujillo 1985). Future climate change scenarios would almost certainly have led to mist flower becoming an invasive pasture weed over a wide geographic range in New Zealand, a threat that has probably been mitigated by successful biocontrol.

In cases where the potential for biocontrol of a weed or pest appear poor (e.g. because of lack of success elsewhere), then a high priority ought to be to develop alternative management plans based on good quality surveillance and local eradication/management. A good place to start is to use species distribution models like CLIMEX to assess whether climate change is likely to affect the potential distribution of a weed or pest. This is dealt with in detail in the following section.

8. Projecting potential distributions of pests

A range of species distribution models are available for projecting the potential naturalized geographic range of species, based on their realized distributions within their native range. One popular tool for this is CLIMEX (Hearne Scientific Software). CLIMEX is semi-mechanistic, so that the functions which determine climate suitability may be based on biological data collected in laboratory and field studies, together with statistical model fitting. Hundreds of CLIMEX models have been published over the past three decades, mostly for invasive pests and weeds. These models predict the potential distribution of a species based on climate, but do not consider the likelihood of that species reaching the area. Therefore CLIMEX analyses should be regarded as only one part of a species risk assessment.

8.1. MODELLING POTENTIAL DISTRIBUTIONS OF PESTS

New Zealand has a characteristic envelope of meteorological conditions. There will also be a CLIMEX parameter value space that simulates the unique New Zealand climate. Is it possible to identify at least part of this CLIMEX parameter value space for New Zealand in order to assess the likelihood that an arriving species may establish long-term in New Zealand? Further, with knowledge of the parameter value space, is it possible to predict what species will establish in New Zealand given predictions of climate changes. Here we selected a suite of CLIMEX models for established and non-established species and carried out a preliminary assessment.

Models for a range of arthropod species were collected from refereed papers and from unpublished literature. Parameter files for each of 24 species (n=12 present and n=12 species not present in New Zealand, Table 8.1) were added to CLIMEX V 2.0 and response to current and future climates simulated. The taxa were a biased sample of species. Some species are highly invasive and polyphagous and most (23/24) are threats to agricultural, horticultural and forest production or a risk to human health. As such most of the modelled species represent a class of arthropods of interest to NZMPI (key pests that need to be excluded). Further description of each species and the source for models is given in Appendix 12.2. The parameter values for the models are listed in Tables 12.1 and 12.2 of Appendix 12.3.

Downscaled climate data (section 3) were converted to CLIMEX format. There are 36 possible climate datasets (combination s of 4 GCMs, 3 emission scenarios and 3 time periods) however as data for each of the three emission scenarios (B1, A1B and A2) are the same for the period 1980-1999 only 28 climate datasets were used for each species. Data were generated for map grid cells of 0.05° or ca. 5 km enabling a representation of the climate response at a relatively high geographic resolution.

Table 8.1. Species selected for assessment of CLIMEX parameterisation in relation to response to climate change. Values for model parameters are provided in Appendix 12.3.

Present in New Zealand		Absent from New Zealand	
Species	Significance	Species	Significance
Cydia pomonella	horticultural pest	*Anopheles arabiensis*	human health risk
Danaus plexippus	iconic/flagship species	*Anopheles gambiae*	human health risk
Epiphyas postvittana	horticultural pest	*Bactrocera tryoni*	horticultural pest
Essigella californica	forestry pest	*Contarinia nasturtii*	horticultural pest
Frankliniella occidentalis	horticultural pest	*Cerotoma trifurcata*	ag/hort pest
Helicoverpa armigera	ag/hort pest	*Diaphorina citri*	horticultural pest
Plutella xylostella	ag/hort pest	*Drosophila suzukii*	horticultural pest
Latrodectus hasseltii	human health risk	*Harmonia axyridis*	hort/environ pest
Penthaleus major	agricultural pest	*Homalodisca vitripennis*	horticultural pest
Rhopalosiphum padi	agricultural pest	*Spodoptera exigua*	agricultural pest
Sirex noctilio	forestry pest	*Solenopsis invicta*	health/environ pest
Uraba lugens	forestry pest	*Thrips palmi*	horticultural pest

Organisms may respond in several ways to climate change. These include range expansion or contraction, change in survival and changes to phenology and annual generations. Not all types of response are amenable to the compare locations function in CLIMEX. Effects of climate on phenology and the consequences for suitability of a particular location for long-term population development as measured by the Ecoclimatic Index (EI) may be modelled using the Compare Years function. Here we used the compare locations function only and selected CLIMEX outputs to indicate some of the effects of climate change:

1. Change in the overall suitability of a site (measured by proportion of map grid cells with EI scores >19 indicating a high probability that the site is suitable for long-term population persistence)

2. Change in the number of annual generations (measured by the median annual number of generations)

3. Change in the over-wintering mortality (measured by changes to cold stress score >100)

Values for these indicators were generated for the selected 24 arthropod species for all 28 climate datasets (672 model runs). The goal was to produce set of a comparable CLIMEX outputs and screen them to identify possible common trends. The indicators generated for each GCM and period were plotted to show general trends with change in climate. Maps of EI were generated for the A1B scenario (which generates mid-range predictions) for each of the three time periods for each species. Finally some preliminary assessment was made using scatterplots of CLIMEX temperature and moisture parameter values and the proportion of map grid cells with EI > 19.

8.2. GENERAL TRENDS IN PROJECTED RANGE SHIFTS

Based on the three indicators (EI > 19, median generations and cold stress), the general response for the species studied was an increase in the overall suitability of New Zealand for projected climates compared with the historic climate, i.e. more grid cells had EI values above 19, there was an increase in the median number of generations and a decline in cold stress (e.g. Figure 8.1). The size of the changes varied with species and with location and can be assessed qualitatively by viewing maps (Figures 8.2, 8.3 and Appendix 12.4). A typical pattern was for suitable area to expand into inland areas from the coast in the North Island and on the east coast of the South Island. Species such as *Solenopsis invicta* with subtropical distributions, and tropical ones like *Anopheles* spp. may not be threats or may be limited to warm microclimates under projected climates in 2080-2099. One New Zealand species (*Penthaleus major*) was predicted to have a polar shift in distribution.

General patterns were investigated by plotting CLIMEX growth and stress parameter values for temperature and moisture against one of the climate response indicators, proportion of area with EI > 19 (e.g. Figure 8.1). Only the outputs from model runs based on the A1B scenario and the CM2.1-GFDL GCM were plotted. There were no trends for an association of moisture variables and EI > 19 (Figure 8.5). However species established in New Zealand tended to have lower values for limiting low temperature (DV0) and lower optimal temperature (DV1) than those not present (e.g. Figure 8.4). By fitting a regression to the proportion of grid cells with EI > 19 and model values for the parameters DV0 (limiting low temperature) and DV1 (lower optimal temperature) it is possible to estimate an upper limit for these parameters for species that are established in New Zealand. The maximum limit for DV0 was estimated to be 12.2 °C under historical climate and increased to 13.4 °C in the projected period 2080-2099 (Table 8.2). The limit for DV1 increased from 24.4 to 26.8 °C for the same period. In a comparable study Peacock and Worner (2008) compared two groups of insects that were regularly intercepted at the New Zealand border and found that those species that were already established had a lower average developmental threshold (7.4 °C) than those that were not recorded as established (11.3 °C). The difference between the estimates (7.4 versus 12.2 °C) is that the former is an average and the latter is an upper limit for a lower developmental threshold (the CLIMEX DV0 parameter is equivalent to the lower developmental threshold). Further assessment of DV0 and DV1 may be useful to develop rules of thumb to assess the likelihood that an arthropod species will become established in New Zealand.

Table 8.2. The estimated limiting and lower optimal temperatures (CLIMEX parameters DV0 and DV1 respectively) for arthropod species that are established in New Zealand, and projected changes to those values with climate warming. Values are average x-intercepts and their standard deviations from linear regressions of 12 DV0 and DV1 parameter values and proportion of the New Zealand landmass suitable for long-term persistence of populations (i.e. model outputs for EI>19) for the A1B scenario and four different GCM-derived climate datasets.

Period	Limiting low temperature (DV0)	Lower optimal temperature (DV1)
1980 - 1999	12.20 ± 0.02	24.41 ± 0.09
2030 - 2049	12.48 ± 0.08	25.10 ± 0.14
2080 - 2099	13.39 ± 0.35	26.84 ± 0.48

This study is preliminary only and further analysis of data may be useful, as well as the assessment of other models. It is clear that model quality varied and this was to be expected. For example, models of the distribution and abundance of some species (e.g. *H. armigera*) did not closely correspond with New Zealand experience. Errors are likely in the parameterisation of CLIMEX models and the estimation of the fundamental niche because of the imperfect knowledge of physiological response and geographical distribution and this differs between species. Whether or not model development or validation included New Zealand may also be important to consider as there may be some responses that are unique to the New Zealand climate.

In conclusion, temperature response, particularly low temperature response, is a better indicator than moisture response when considering potential establishment of arthropods in New Zealand. Based on a limited data set, a limiting low temperature DV0 = 12.2 ºC and a lower optimal temperature DV1=24.4 ºC are estimates defining part of the CLIMEX parameter value space that simulates the New Zealand climate.
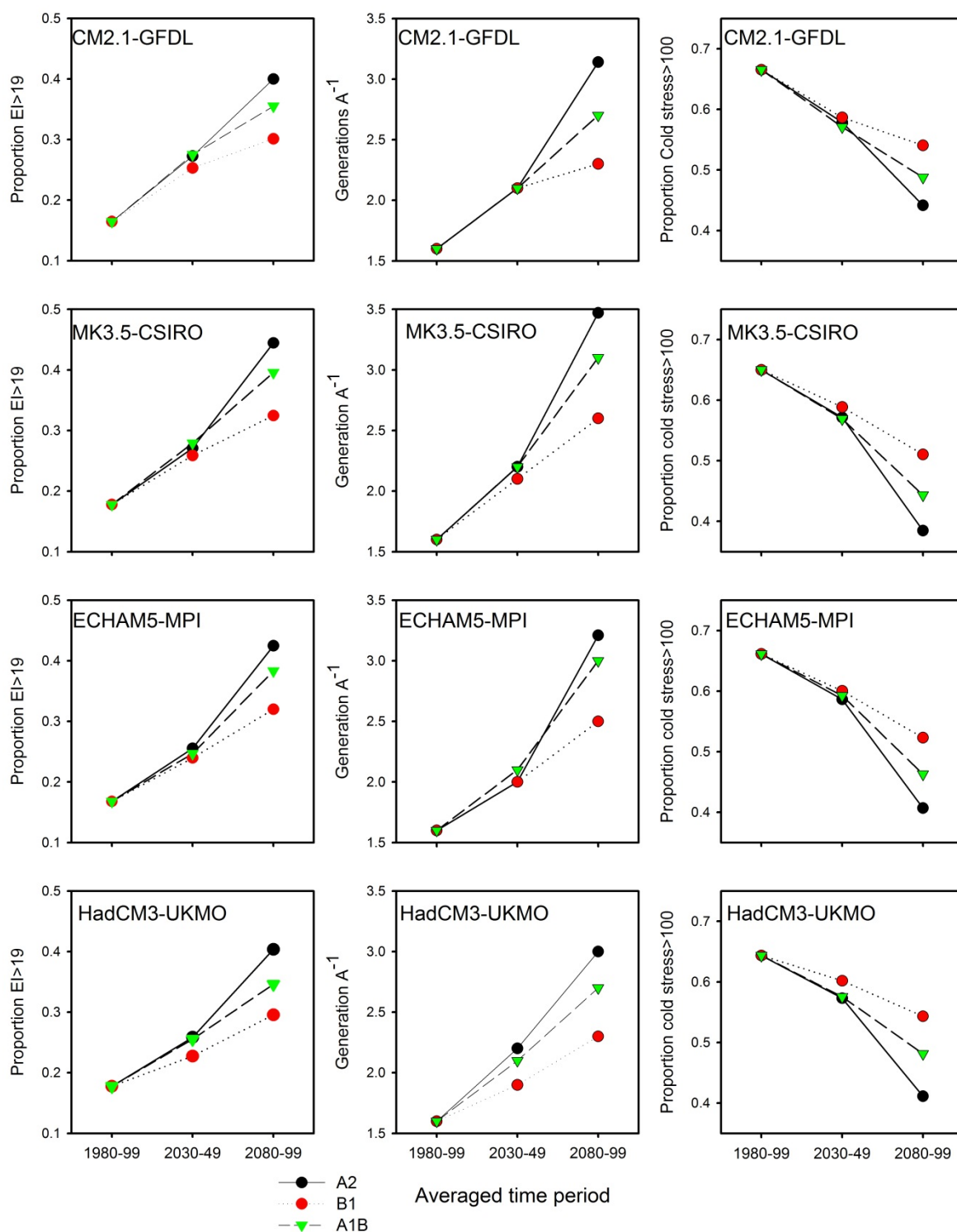
Figure 8.1. Response of *Diaphorina citri* to historical and projected climates for three SRES scenarios (A2,B1 and A1B), and four GCMs (CM2.1-GFDL, MK3.5-CSIRO, ECHAM5-MPI,HadCM3-UKMO). Three climate response indicators were used to summarise output from CLIMEX models. Proportion of map grid cells with EI>19 indicates sites with potential for long-term establishment. Median annual generations is an indicator of the potential for changes to abundance and the proportion of grid cells with cold stress above 100 is an indicator of areas where over-wintering mortality is likely.
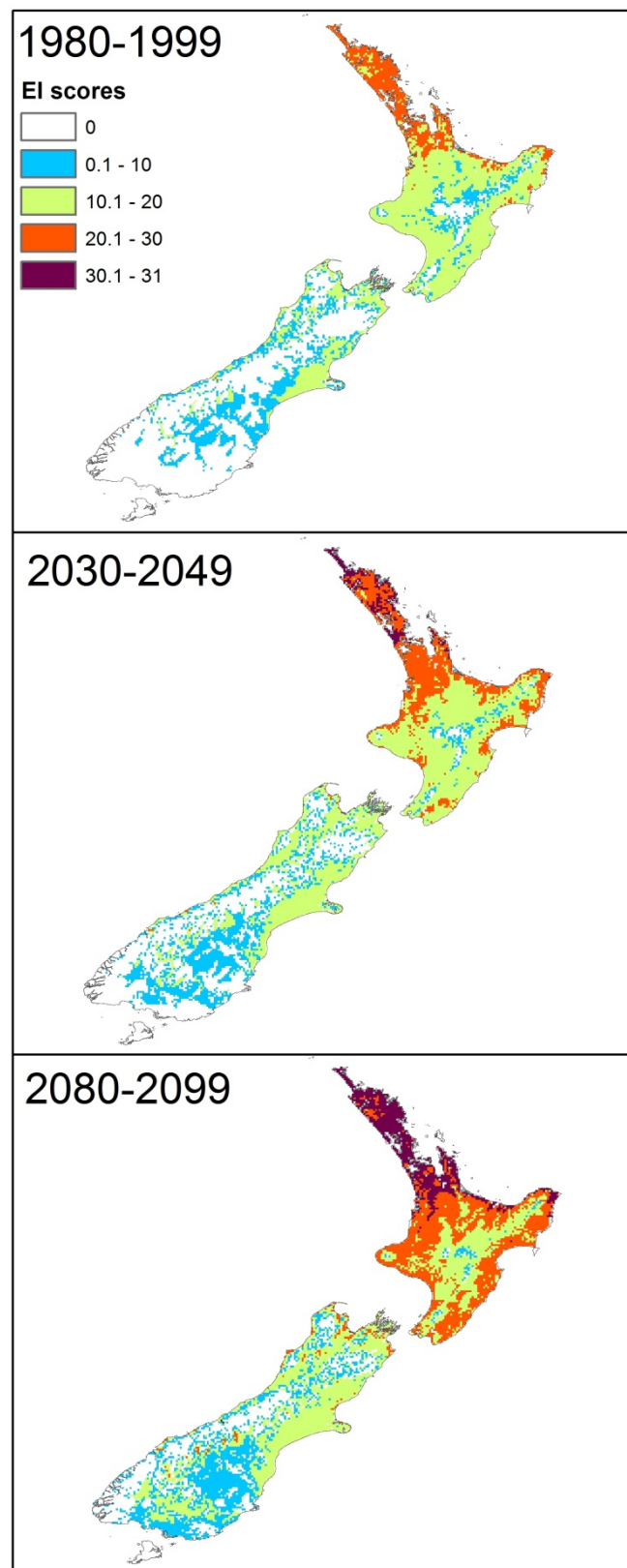
Figure 8.2. Ecoclimatic Index scores for the Queensland fruitfly, *Bactrocera tryoni*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
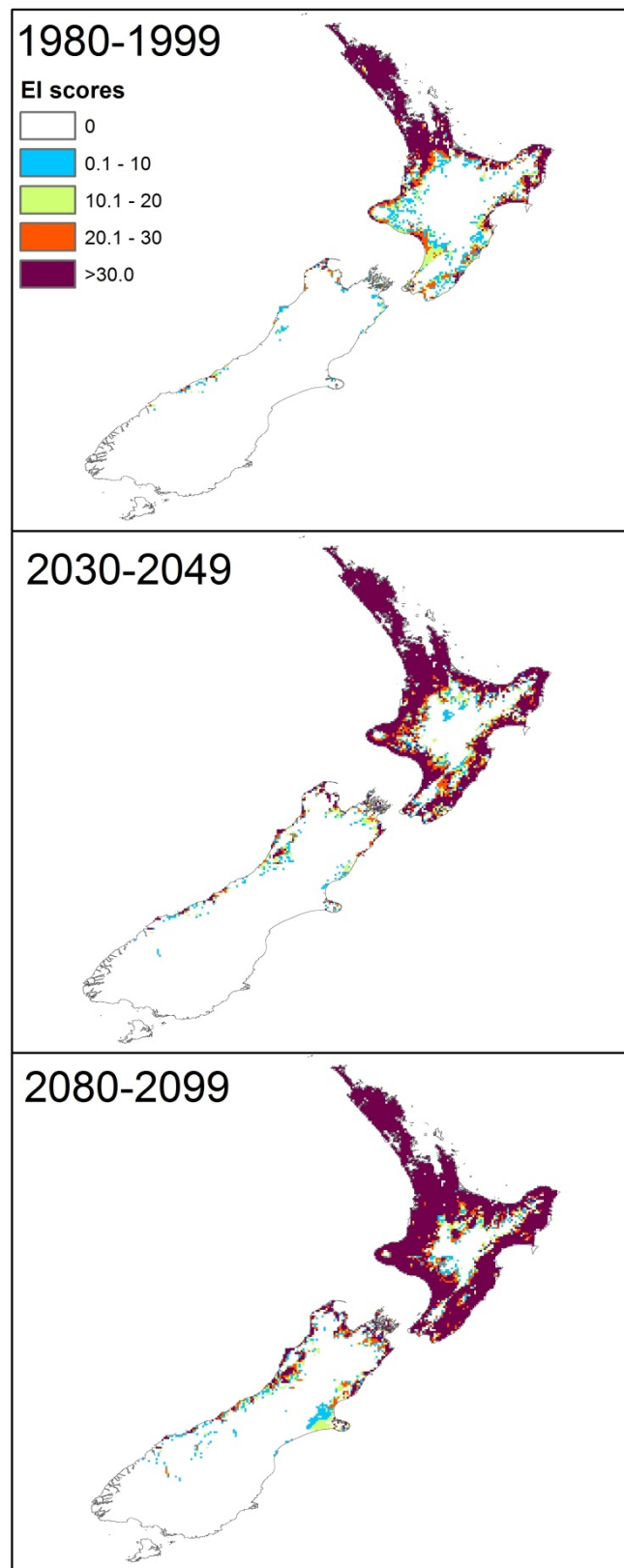
Figure 8.3. Ecoclimatic Index scores for Glassy-winged sharpshooter, *Homalodisca vitripennis* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
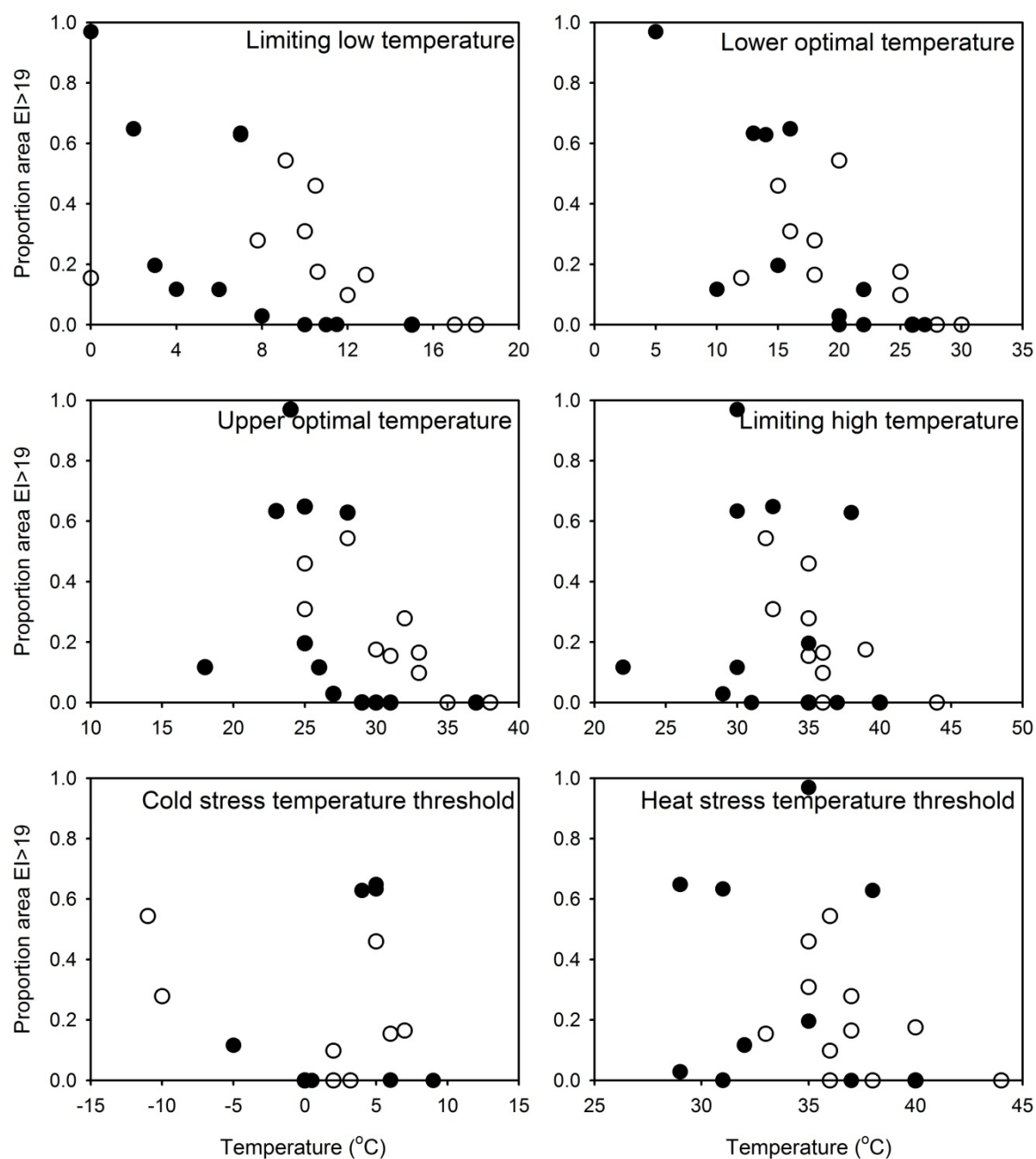
Figure 8.4. Selected temperature parameters for 24 modelled arthropod species(● present in New Zealand, ○absent from New Zealand) and the proportion of New Zealand land mass where long-term populations persistence is likely under historic climate (as indicated by the grid cells with an Ecoclimatic index of 20 or more). Climate data set is the A1B scenario based on the gfdl_CM20 GCM.
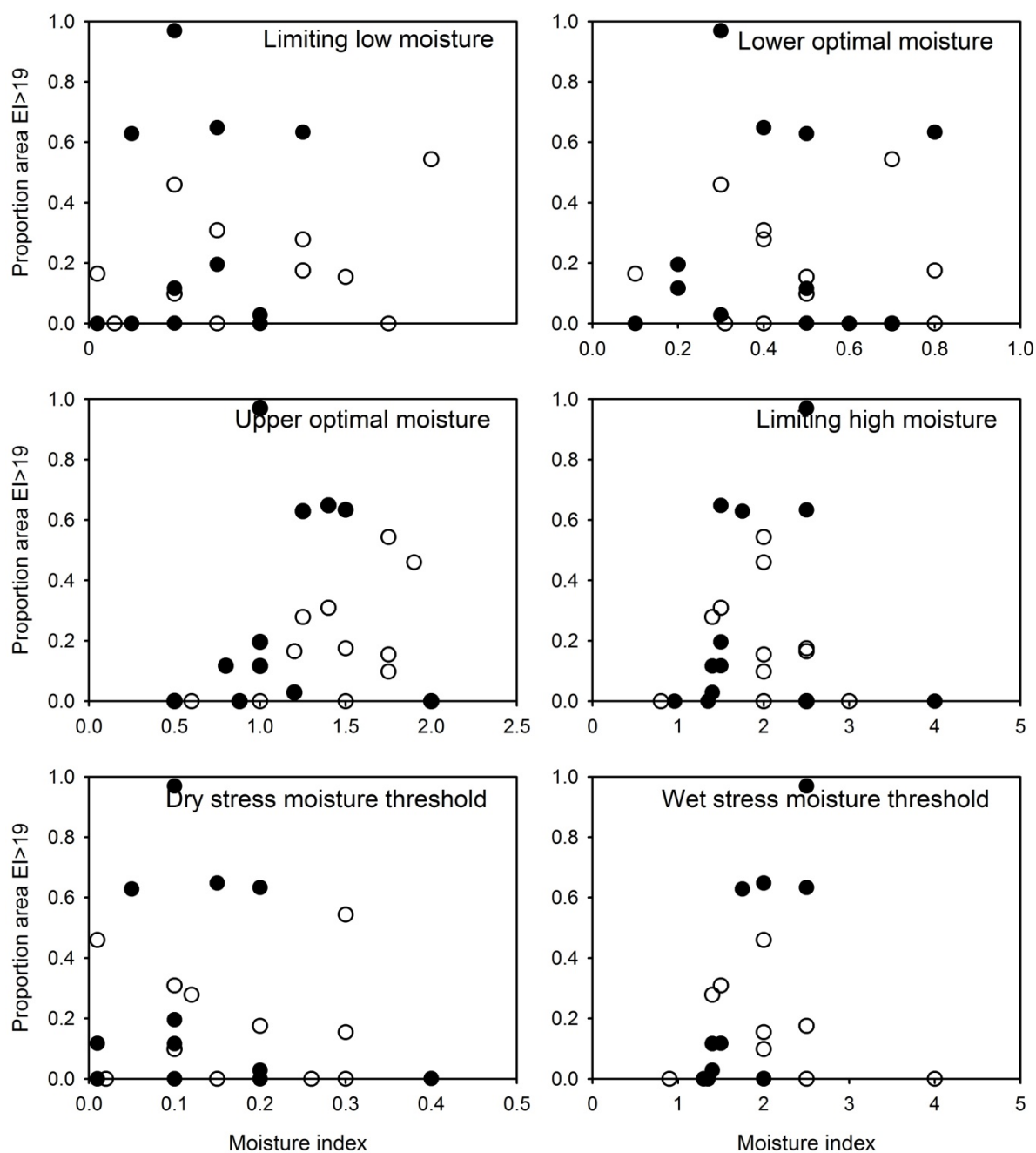
Figure 8.5. Selected moisture parameters for 24 modelled arthropod species (● present in New Zealand, ○ absent from New Zealand) and the proportion of New Zealand land mass where long-term populations persistence is likely under historical climate for 1960-1999 (as indicated by the grid cells with an Ecoclimatic index of 20 or more). Climate data set is the A1B scenario based on the gfdl_CM20 GCM.

8.3. THE CLIMENZ ONLINE TOOL

We implemented an online resource, the CLIMENZ website (http://b3.net.nz/climenz), that allows authorised users to generate high resolution (0.05° arc, approximately 5×4 km per pixel) maps for the projected climate suitability of New Zealand for particular taxa under current and future climates. Projections are made from published CLIMEX models.

The website implements the CLIMEX algorithms to generate potential New Zealand distribution maps from a database of published CLIMEX models, based on the NIWA climate projection data described above. Users can select which species to project, from the online database of CLIMEX models, which global circulation model and IPPC carbon emission scenario to use, and what year to project for. The website then presents a summary report for the projected suitability of New Zealand.

Access to the CLIMENZ website is white-list protected, so that it is only available from particular IP addresses. Given that modern servers typically use dynamic IP values that are changed regularly, the whitelist sometimes goes out of date and prevents access by legitimate users. However, the IP addresses of all access attempts are logged, allowing the administrator to update the white list.

Currently, the CLIMENZ website holds a database of 182 published CLIMEX models covering 178 different species, including 118 plants, 55 invertebrates, 4 pathogens and 1 other taxa. This is by no means an exhaustive list of all of the CLIMEX models that have been published, but it does include a wide range of species of biosecurity interest. Further models can be added online, for example, from newly published studies. Each model is linked to the source publication, its Document Object Identifier (DOI), the publisher's website, and may be annotated. CLIMEX parameter files (.cxp) are generated on the fly for download and use in the titular software.

The website cannot be used for fitting new models; for this, the CLIMEX software is required. CLIMEX v.3 is available from Hearne Scientific Software at http://www.hearne.com.au/Software/CLIMEX/Editions. Version 4 is expected to be released soon.

The website generates climate suitability projections using the published CLIMEX algorithms (Baskerville & Emin 1969, Maywald et al. 2007, Sands & Hughes 1976, Sutherst & Maywald 1985, Sutherst 2003, Sutherst et al. 2007). However, CLIMEX v3's algorithms for estimating weekly evaporation and relative soil moisture differ from those described in Sands & Hughes (1976) and the DYMEX documentation. The documentation for the upcoming CLIMEX v.4 will have complete details. Meanwhile the CLIMENZ website uses an empirically fitted formula for weekly evaporation that gives a close approximation to CLIMEX's results under most New Zealand situations.

CSIRO, who developed CLIMEX, has sanctioned the website and is currently issuing a license for its use. Part of that agreement will be full disclosure of the CLIMEX algorithms so that they can be implemented accurately. In the meantime, results should be regarded as provisional. Validation trials suggest that the ecoclimatic index (EI) values generated by CLIMENZ are within 1% of those from CLIMEX for >99.5% of New Zealand sites, and the climate suitability categories mapped online should match those from CLIMEX for >95% of New Zealand sites.

For each CLIMEX model, a total of 5 GCMs × 3 emission scenarios × 101 projection years = 1515 unique projections are available. Given the number of CLIMEX models available, there are hundreds of thousands of potential projections available to users. However, not all of these will be needed. In practice, the website generates projections as required, a process that takes around 20 seconds, and stores the results. Subsequent requests can be served up instantly using the stored data.

Figure 8.6 shows a screen shot from CLIMENZ, projecting the climate suitability of New Zealand for Mediterranean fruit fly in 2015 under the HadCM3 model and scenario A1B. Full details of the model parameters and source are given next to a categorized map of the results. Clicking on the map opens a full-scale version of the image that may be copied or saved. The categories (favourable, suitable, marginal etc) are somewhat arbitrary, but are based on published ranges and in consultation with a CLIMEX expert (Darren Kriticos, pers. comm.). The CLIMEX software itself cannot generate maps of this type, data must be exported to a GIS and mapped there.

A button at the bottom of the page allows the raw data to be downloaded as a delimited ASCII file. A second button will rerun the model; results are stored on the server to speed subsequent access. Running a model normally takes 20-30 seconds, but previously run models are available instantly. The third button at the bottom of the report allows comparison of these results with a different scenario.

Two different scenarios can be compared using the "comparisons" option from the main menu. For example, analysts may wish to compare projections for different years (e.g. 2015 versus 2040), or different species (e.g. Medfly versus Queensland fruit fly). They may also want to assess the robustness of projections by comparing results for the same species and year from different general circulation models or climate change scenarios.

Figure 8.7 shows the results from comparing Mediterranean fruit fly in 2015 and 2040 under the HadCM3 model and scenario A1B. Projections are shown for each of the two scenarios, and clicking on these maps opens a full-scale version of the image. Below these, a graph plots the ecoclimatic index values for one scenario against the other, with red points indicating an increase in climate suitability and blue a decrease. In the example given, almost all locations were projected to increase in climate suitability in 2040 compared to 2015. Next to the graph, a map shows where the changes occur, with red shades indicating the greatest increase and blue shades the greatest decrease in ecoclimatic index values. Here, the greatest increases in climate suitability are expected to be in South Canterbury and Taihape. At the bottom of the report, a matrix reports the differences in land areas of each suitability category.

· climenz · CLIMEX model projections for New Zealand

about   algorithms   climate data   models   projections   comparisons

· simulation results ·

species:	*Ceratitis capitata*
authority:	(Wiedemann)
order:	Diptera
family:	Tephritidae
common name:	Mediterranean fruit fly, Medfly

simulated year: 2015

climate change scenario: A1B: globalisation, balanced energy sources, moderate warming

general circulation model: HadCM3: Hadley Centre Coupled Model, version 3

model parameters:

SM0 = 0.1; SM1 = 0.3; SM2 = 1; SM3 = 1.5; DV0 = 12; DV1 = 22; DV2 = 30; DV3 = 35; DTCS = 5; DHCS = -0.0015; TTHS = 39; THHS = 0.01; SMDS = 0.02; HDS = -0.05; SMWS = 1.6; HWS = 0.0015; PDD = 622 (more details)

model source:

Vera MT, Rodriguez R, Segura DF, Cladera JL, Sutherst RW 2002. Potential geographical distribution of the Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae), with emphasis on Argentina and Australia. Environmental Entomology 31: 1009-1022. DOI: 10.1603/0046-225X-31.6.1009
[WEB] [PDF 1158 Kb]

map categories* and total area:

- Favourable (EI >= 20): 16367 km²
- Suitable (EI 5 to 20): 80641 km²
- Marginal (EI 0.5 to 5): 6755 km²
- Seasonally suitable (EI < 0.5, GI >= 5): 58722 km²
- Seasonally marginal (EI < 0.5, GI 0.5 to 5): 51174 km²
- Unsuitable (GI < 0.5): 46428 km²

*Note that these categories are somewhat arbitrary and may be context-specific.

These results were generated on 14 January 2015 at 1:32 pm.

[download results] [recalculate] [compare]

(legend)
- Favourable
- Suitable
- Marginal
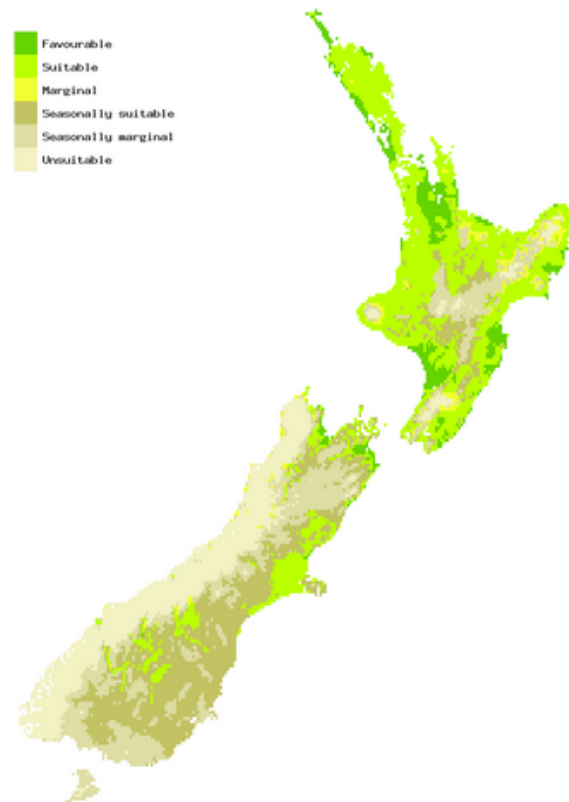- Seasonally suitable
- Seasonally marginal
- Unsuitable

Figure 8.6. Screen shot of a CLIMENZ climate suitability projection.
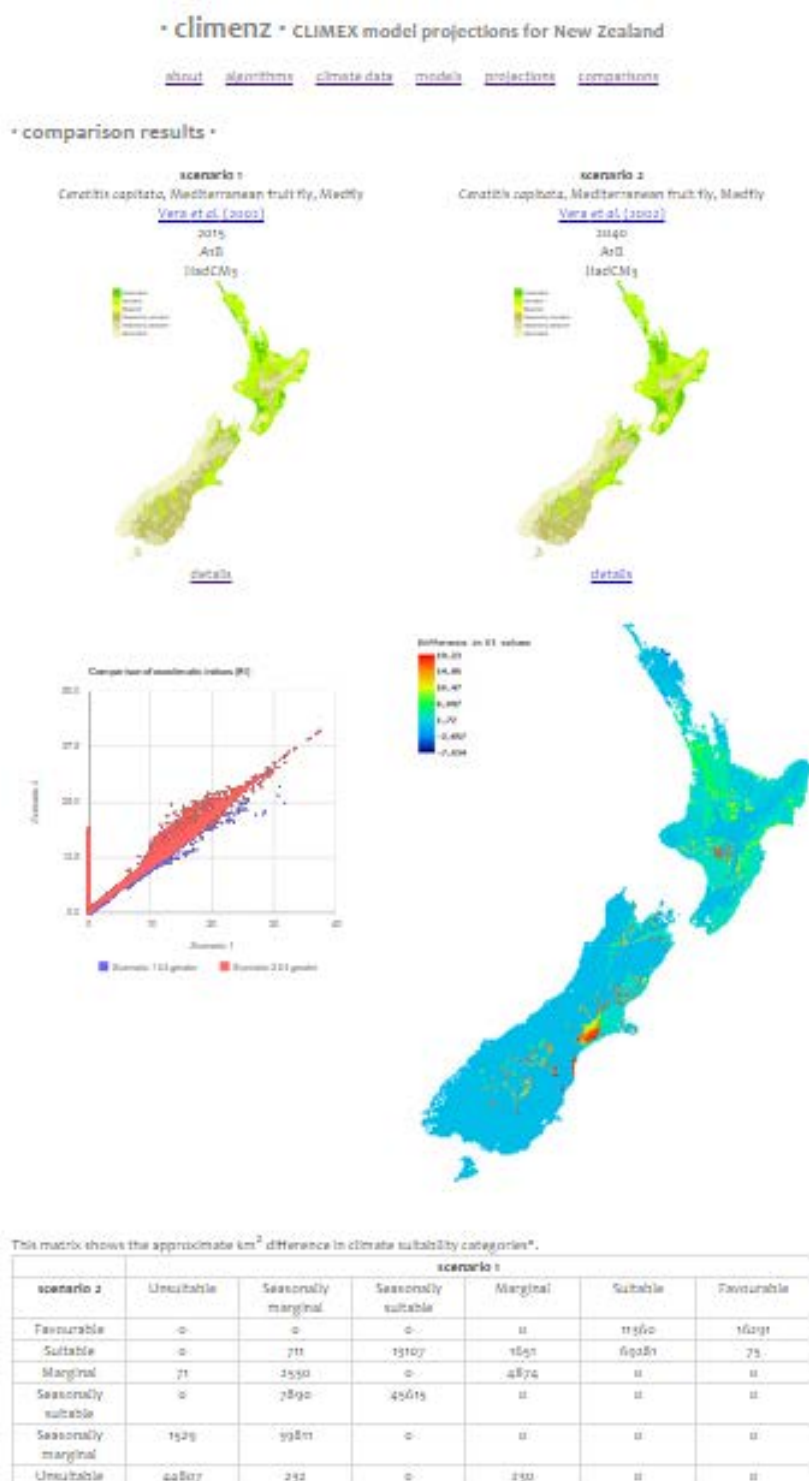
Figure 8.7. Screen shot of a CLIMENZ comparison.

More advanced comparisons may be done by exporting the data for individual projections and analyzing them in a GIS. For example, Figure 8.8 shows results for comparing climate suitability from 2015 to 2090 for 17 different fruit fly species (including *Drosophila suzukii*). For each location, the number of potential fruit fly species that might establish was tallied as the number of species for which the ecoclimatic index >=5. Then the tallies for 2015 were subtracted from those for 2090. The results suggest that the greatest increase in potential for fruit fly establishment (in terms of number of species) is likely to occur around Auckland, the Coromandel, East Cape and Wairarapa. The results suggest that coastal Westland is likely to be less suitable for fruit flies in 2090 than it is in 2015.
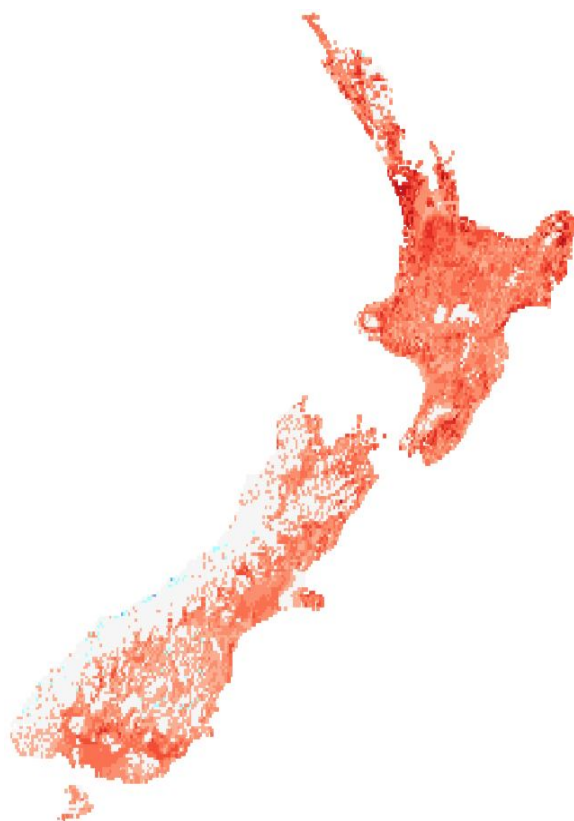
Figure 8.8. Change in climate suitability from 2015 to 2090 for 17 different fruit fly species. Darker shades of red indicate the greatest increase in the number of species that might establish; blue indicates locations projected to be suitable for fewer species in 2090 than in 2015.

8.4. OTHER APPROACHES FOR GEOSPATIAL PROJECTION OF BIOSECURITY RISK

It is assumed that the exotic species originating from overseas areas with New Zealand-like climates are most likely to become abundant and potentially damaging in New Zealand because of their pre-adaptation to the climate (e.g. Sexton et al. 2009). CLIMEX provides a species-independent index for the similarity in climates between two (or more) sites, the Climate Match Index (CMI). This has previously been used to identify New Zealand-like climates overseas (Peacock & Worner 2006) under current and future climates (Kriticos 2012). However, past studies did not have access to the relatively fine-scale data now available for New Zealand (~5 km resolution; Mullan et al. 2008) and the world (~20 km resolution; Kriticos et al. 2012). Many niche crops, such as avocados, are grown in microclimates which are currently rare in New Zealand and unlikely to be represented in the climate data used in previous analyses. Therefore, previous work may not have captured the full range of risks to New Zealand.

It would be possible to compare New Zealand's current and projected future climates to the current climate elsewhere in the world. As global climate change proceeds, New Zealand's climate will become less well matched with the current climates of some foreign regions and better matched with others. Thus, one could ask "how might New Zealand's climate suitability for pests from different foreign regions change as climate change proceeds?"

Such analyses would be particularly relevant to exotic pests already established in New Zealand, because exotic species that experience a New Zealand climate which is trending towards the climate of their natural geographic origin might be likely to increase their population densities and geographic distributions in New Zealand. However, this analysis would also be applicable to exotic pests not present in New Zealand because identifying foreign regions with current climates that match New Zealand's future climates would enable pests of concern to New Zealand that are currently present in those regions to be identified. Then future changes in their distributions might be monitored to track changes in the most probable geographic sources of New Zealand's potential future pests.

Rather than comparing the projected future climates of all of New Zealand's land area with current overseas climates, it would be more informative to subdivide New Zealand into land uses that are relevant to MPI risk analysts such as agriculture, plantation forestry, urban areas and native vegetation, then conduct separate analyses for each land use. This would assume that broad patterns of land use in New Zealand will remain moderately static over time, despite climate change. Conducting separate analyses for different land uses would minimise climate matches between foreign locations and New Zealand locations that we expect should be at low risk of pest invasion, such as the high alpine zone.

Due to resource constraints, this work could not be conducted within the current project, but it would be a high priority for future funding. The results could be presented as web-accessible maps that can be searched, scrolled and zoomed to facilitate rapid use and interpretation by biosecurity risk analysts. Two such maps produced by Phillips and Vink (unpublished) are already being used by MPI risk analysts. The new climate change maps would be useful for identifying the foreign regions that are likely to become increasingly important as potential sources of pests for New Zealand.

9.   Synthesis and potential research

This report summarises potential impacts of climate change on pests (including weeds) and diseases of relevance to New Zealand's biosecurity systems. It reviews a range of factors that may interact to help determine the future distributions and impacts of pests and diseases, based on the best current information from experts in the Crown Research Institutes and Lincoln University.

Figure 9.1 synthesises these factors and shows their main interactions. The two most basic drivers for change in biosecurity risks are shifts in introduction pathways and climate change. Section 3 of this report summarised current expectations for the latter. Though there are differences between the projected climates from the different general circulation models, New Zealand is likely to become warmer in general, especially in the south and at high altitudes, with most models predicting the annual temperature range to increase as summers warm more than winters. There is still uncertainty about future trends in rainfall, but it is likely that winters are likely to become wetter in the west and south of the South Island, and drier in the north and east of the North Island. Obviously, there is need to continue to monitor and revise future climate projections to enable long-term planning for adapting to climate change, though biosecurity risks are subject to other influences that may be more difficult to predict beyond one to two decades.
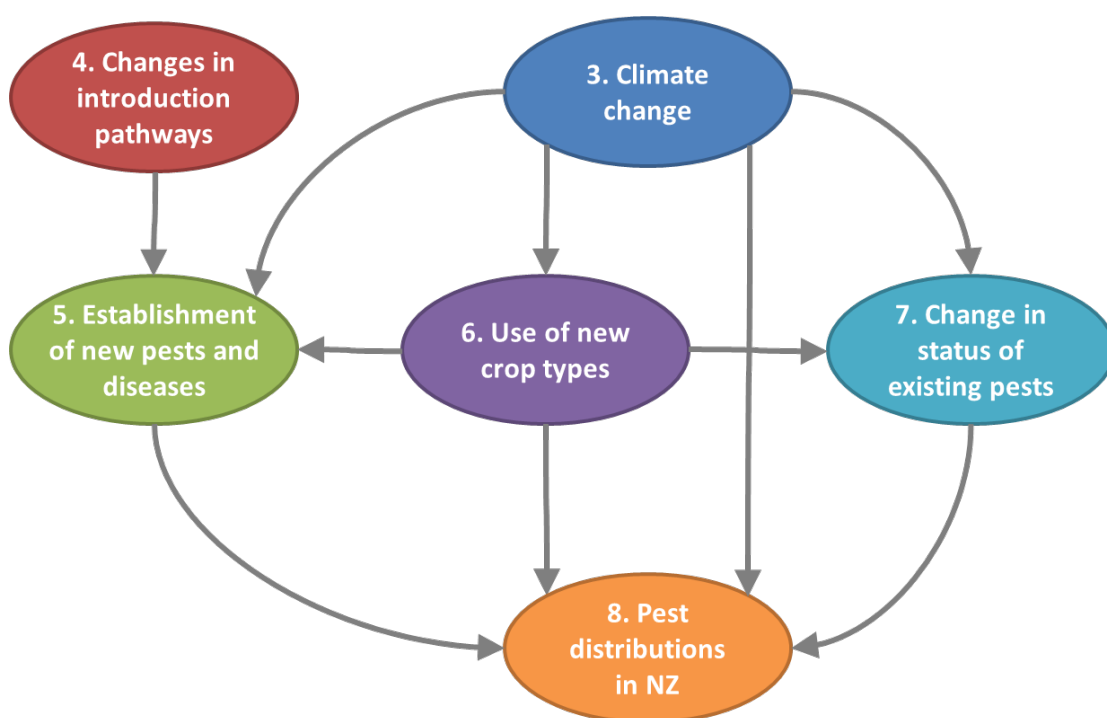
Figure 9.1. Major inter-relationships between the pest and disease risk factors discussed in this report (numbers refer to sections in the report).

Another major factor that is likely to affect biosecurity risk is shifting patterns of introduction pathways. Section 4 conducted a brief analysis of current trends in the value of global and New Zealand trade, and speculated that import pathways from north-east Asia are likely to be of particular importance in the future, with increasing pest risks associated with India, South America and other emerging economies. There is scope for a more detailed economic and political forecast of likely future import sources and volumes to inform future biosecurity risk. There may be benefit in MPI maintaining a formal process to monitor the risk dynamics of trading partners to inform biosecurity risk assessments, import health standards and planning; the Emerging Risks System (ERS) (Reed 2014) represents a suitable vehicle for this.

Pathways risk management interventions may successfully exclude many of the pests and diseases with increasing propagule pressure, but there may be need for specific consideration of some new taxa, especially "hitchhiker" species, which are more difficult to manage in this way. Detailed climate matching analyses between current and future New Zealand climates and current and future international climates might support risk assessments, recognising that climate match is just one of several factors influencing the likelihood of entry and establishment. Novel threats from new geographic sources might be identified by monitoring valued plants (e.g. crops, New Zealand native species) growing overseas in botanical gardens and arboreta (Britton 2010).

Climate change in New Zealand may allow the growing of new crops and increase the economic importance of some currently minor crops (section 6). For example, greater areas of pastoral agriculture in the north may rely on the C_4 grass kikuyu, while farmers in the increasingly dry east are expected to make greater use of drought-tolerant forages like lucerne, chicory and plantain. To help protect such crops from exotic pests and diseases, MPI will benefit from close relationships with the agricultural sectors, such as those currently forming through the Government-Industry Agreement (GIA) process. GIA partners may also benefit from the science sector to help identify crop species that will become increasingly important under climate change.

Introduction pathways (propagule pressure), host availability and climate suitability are the major factors influencing pest and disease establishment (Theoharides & Dukes 2007, Magarey et al. 2011), while the latter two may also affect the status of existing pests. Section 5 reviewed the potential impacts of climate change on the establishment of new pests in New Zealand, focusing on three main risks: new subtropical pests, vectored animal diseases, and self-introduced species with current transient establishments. There are many potential areas for research here, especially for predictive modelling of high-risk taxa such as pathogens vectored by ticks (e.g. *Theileria orientalis*) and mosquitoes (e.g. West Nile virus and bovine ephemeral fever virus). Vectored diseases may be especially responsive to climate change because many of the required vectors (ticks, mosquitoes) are currently restricted in New Zealand due to temperature, and the diseases show explosive outbreak behaviour under favourable conditions. Older (e.g. Tomlinson 1973) and more recent (Yen et al. 2014) work has looked at propagule pressure from natural trans-Tasman dispersal of pests and pathogens, and such work will need to be updated as climate change alters the weather patterns of the southern hemisphere.

Though not strictly relevant to border biosecurity, section 7 considered how the risk profiles of currently established species might change under future climates. Arguably of most concern are those "sleeper" species which are currently benign or have limited impacts, but which might "awake" to cause significant impacts under climate change. The key need here is

methods to accurately predict which taxa might behave this way and thereby enable proactive management, such as containment or introduction of biocontrol agents. This can only be achieved by analysing past cases to draw generalisations about which have the greatest potential to cause damage, and this relies on the ongoing collection and maintenance of distribution records for exotic species in New Zealand.

Finally, section 8 used CLIMEX modelling software to consider the potential distributions of a range of invertebrate pests under climate change. A preliminary examination of 24 arthropod species (twelve already present in New Zealand, twelve currently absent) suggested potential range increases for most and that lower temperature limits may be useful as a general indicator of the potential for establishment in New Zealand where host plants are available. We also created an online database of previously published CLIMEX models that allows potential species distributions to projected at high (~5 km) resolution under a range of current and future climate scenarios. The results are presented in a meaningful way that facilitates their use for biosecurity risk analysis. Other approaches are available for assessing biosecurity risks under climate change, such as climate matching between New Zealand and the world under current and future climates. This has been done previously, but not with the high resolution climate data now available, not on a meaningful sector-by-sector basis, and not with the results made readily available for exploration by risk analysts. MPI has indicated that this would be useful to them and we were unable to resource it from the current project, so this would potentially be a high priority for further funding.

10. Acknowledgements

11. References

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12. Appendices

12.1. COMPARISON OF CLIMATE CHANGE PREDICTIONS FROM DIFFERENT GCMS

See figures 12.1 to 12.4.

12.2. DESCRIPTION OF SPECIES USED IN THE COMPARISON OF CLIMEX MODELS

Species present in New Zealand:

Cydia pomonella (L.) (Lepidoptera: Tortricidae) codling moth originates in south-eastern Europe and currently occurs throughout New Zealand wherever pome fruit are grown. It is reported to have a single annual generation from Manawatu south and 2 generations north, sometimes with a partial 3rd generation. We used a model available from the library available with the CLIMEX software. Both this model and the modified model of Rafoss & Saethre (2003) grossly over -estimate the number of generations in New Zealand (approx. 80% of cells have at least 3 generations). The error is likely to be a poor model of diapause.

Danaus plexippus (L.) (Lepidoptera: Nymphalidae) monarch butterfly is an iconic butterfly species with a native distribution in central and North America. Monarch butterflies are well-known migrants and spread throughout the Pacific in the 19th century reaching New Zealand in the 1870s. We used the model developed by Zalucki & Rochester (1999).

Epiphyas postvittana (Walker) (Lepidoptera: Tortricidae) light-brown apple moth is an Australian leaf-roller that is a pest of fruit crops and is widespread in New Zealand. We used the model developed by He et al. (2012).

Essigella californica (Essig) (Hemiptera: Aphididae) Monterey pine aphid is native to western USA and Mexico and feeds on *Pinus* spp.. It is a pest of *Pinus radiata* plantations in Australia however is currently not considered of economic importance to New Zealand commercial forestry. We used the model of Wharton & Kriticos (2004).

Frankliniella occidentalis (Pergande) (Thysanoptera: Thripidae) western flower thrips is a native of south-western USA and has spread to Europe, South America, Australia and New Zealand. It has a large host range and causes feeding damage to fruit, vegetables and cultivated flowers, and is a vector for TSWV. A pesticide-resistant strain is widespread on glasshouse vegetable and flower crops in New Zealand (Teulon & Nielsen 2005) and a second strain occurs on lupins and other flowers outdoors from Auckland to central Otago (Mound & Walker 1982). We used the model of Cheng et al. (2006).

Helicoverpa armigera (Hübner) (Lepidoptera: Noctuidae) is widespread pest distributed in the Afrotropic, Australasia and warmer areas of the palaearctic. We used the model developed by Zalucki & Furlong (2005) although it provides a relatively poor simulation of *H. armigera* in New Zealand.
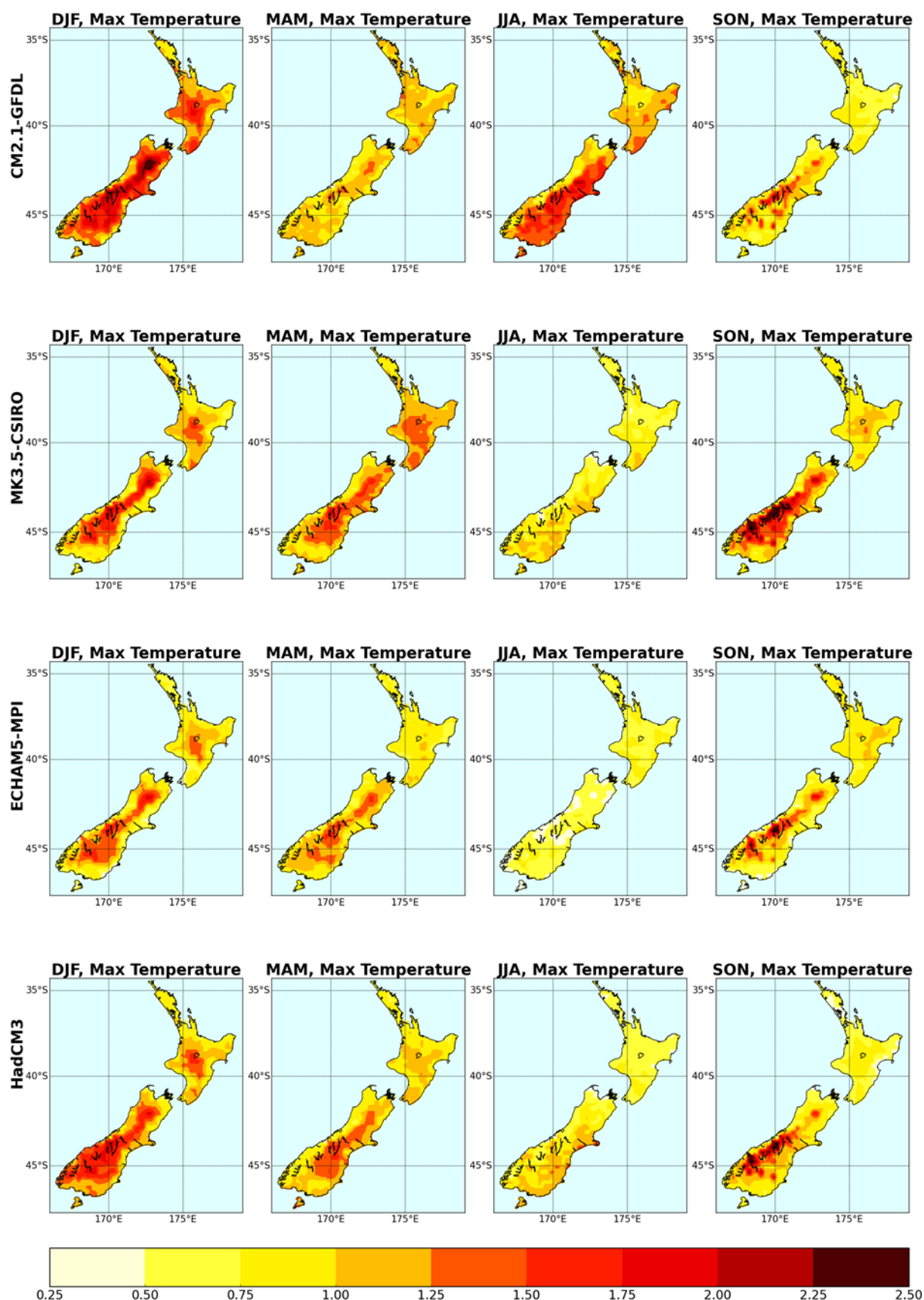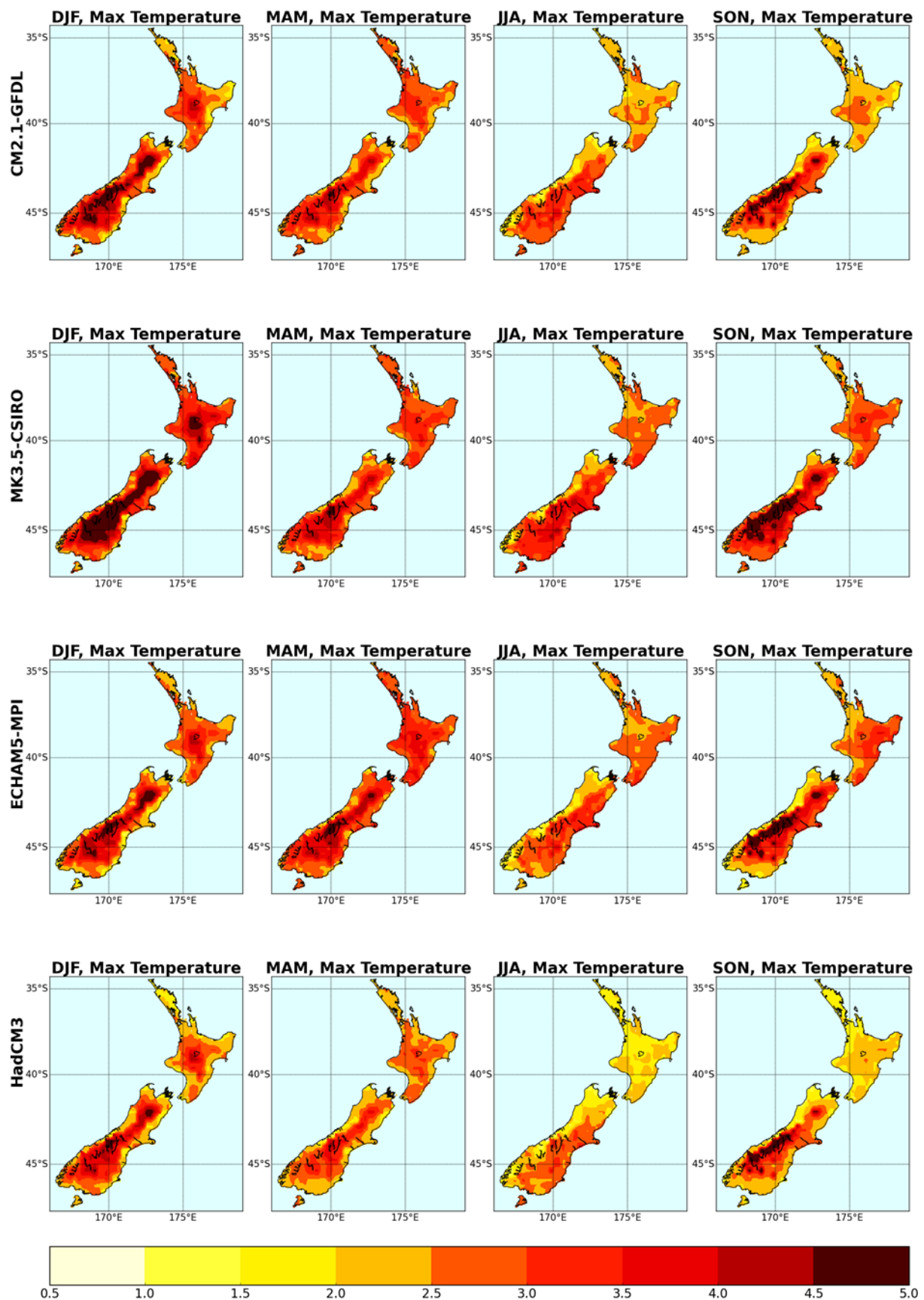
Figure 12.1. Projected 50-year (2040's) seasonal maximum temperature change forced by IPCC-CMIP3 models for A2 emission scenario

Figure 12.2. Projected 100-year (2090's) seasonal maximum temperature change forced by IPCC-CMIP3 models for A2 emission scenario
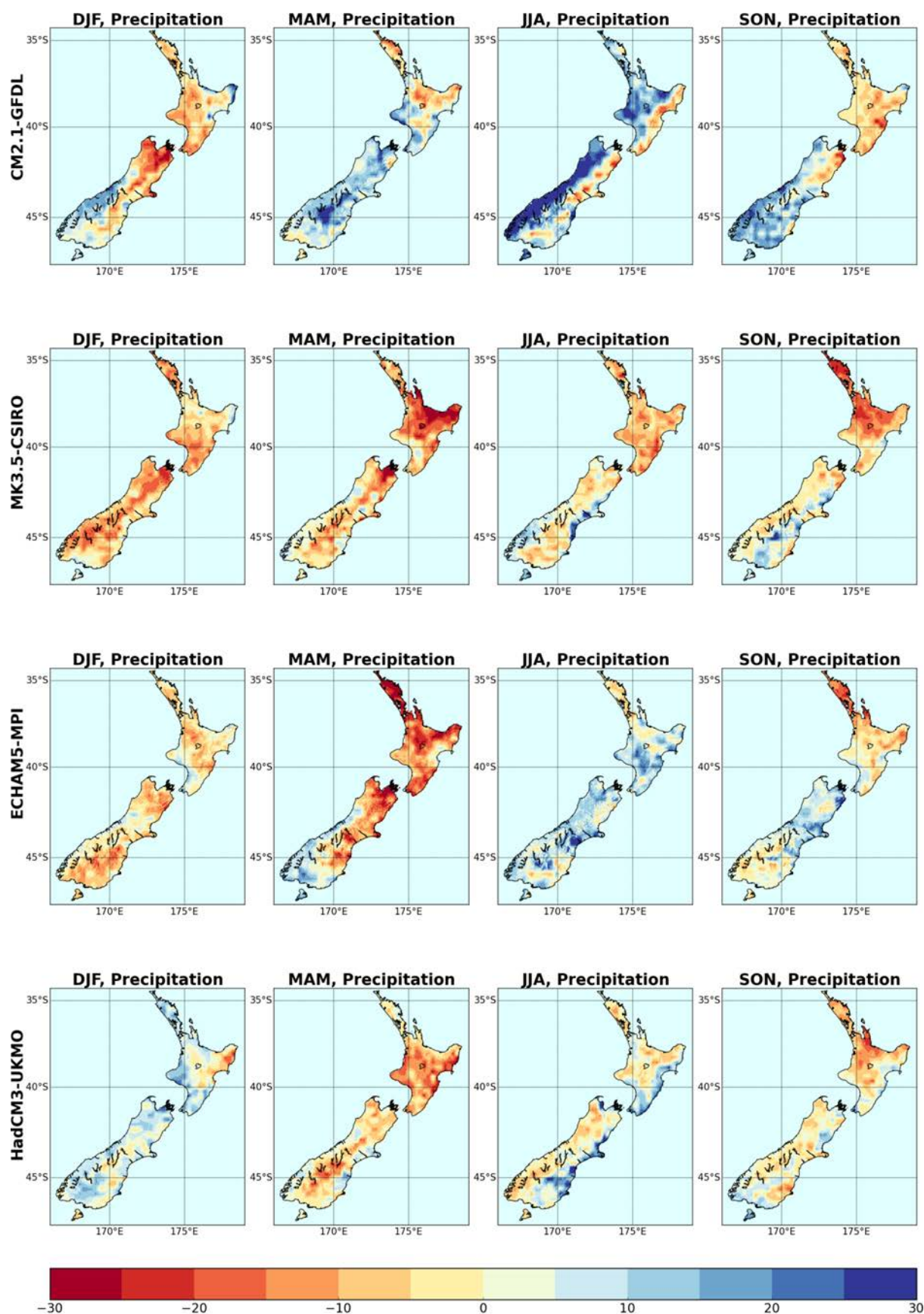
Figure 12.3. Projected 50-year (2040's) seasonal precipitation change forced by IPCC-CMIP3 models for A2 emission scenario
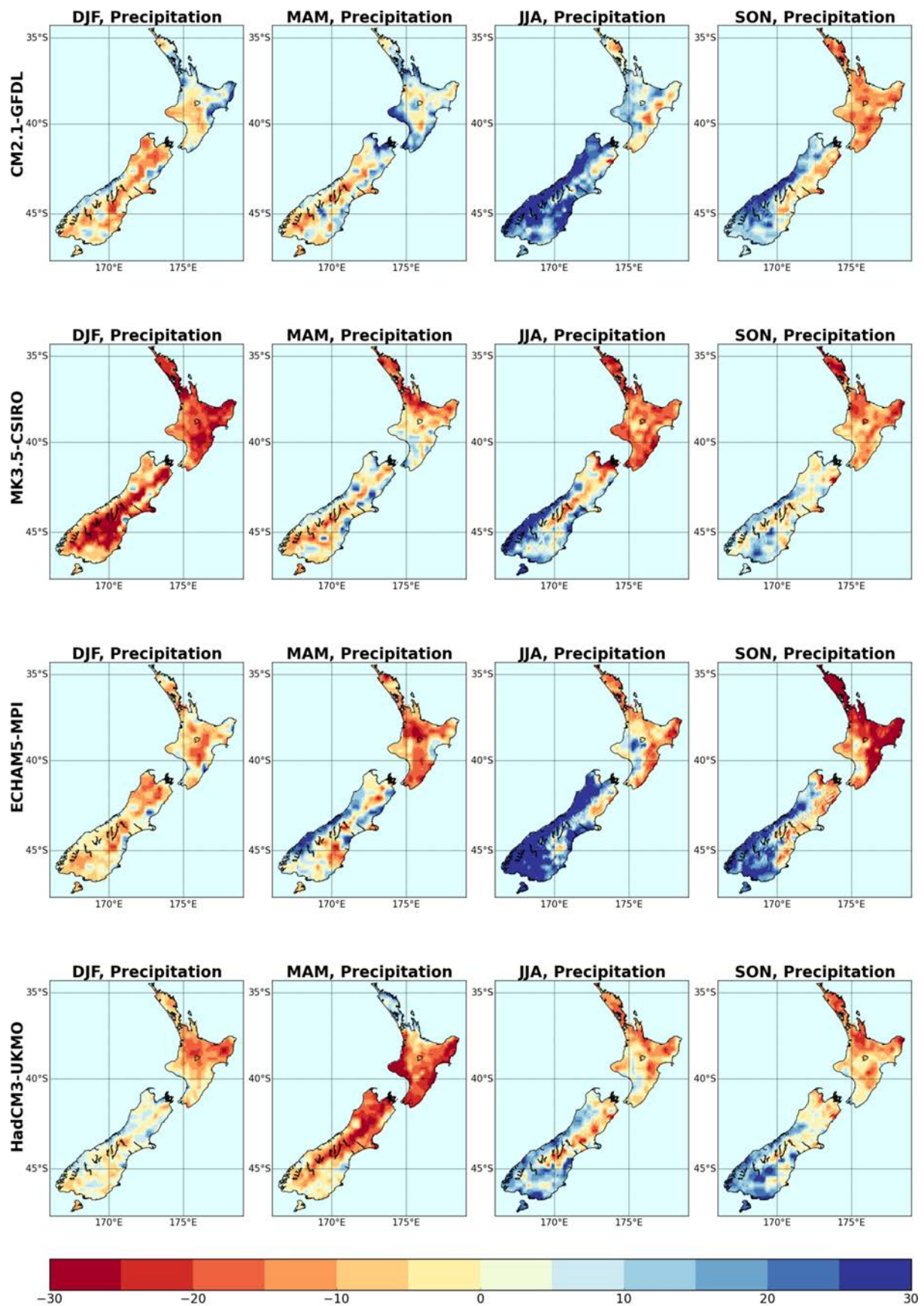
Figure 12.4. Projected 100-year (2090's) seasonal precipitation change forced by IPCC-CMIP3 models for A2 emission scenario

Latrodectus hasseltii Thorell (Aranaeae: Theridiidae) redback spider occurs in Australia, Papua New Guinea, the Philippines and India and has invaded several more countries including New Zealand relatively recently (Vink et al. 2011). It currently has a restricted distribution in New Zealand being recorded as established in five locations. We used the general model, not the one modified for peri-urban areas, developed by Vink et al. (2011).

Penthaleus major (Dugés) (Acarina: Penthaleidae) blue oat mite or winter grain mite is a cosmopolitan pest of temperate crops and pastures. In New Zealand *P.major* damages oat crops and pastures in the South Island. We used the model of Robinson & Hoffmann (2001).

Plutella xylostella L. (Lepidoptera: Plutellidae) diamondback moth is a major and cosmopolitan pest of brassicas. It was introduced to New Zealand in the 19th century and is widespread here. Moths are capable of long-distance dispersal and recolonise areas where overwintering is poor. We used the CLIMEX model of Zalucki & Furlong (2011) with a modification (removal of the cold-stress degree-day threshold and rate) to allow *P. xylostella* to occur in New Zealand.

Rhopalosiphum padi L. (Hemiptera: Aphididae) cereal aphid is a cosmopolitan pest of cereals and is widespread on grasses and cereals in New Zealand. We used the model of the asexual form by Macfadyen & Kriticos (2012).

Sirex noctilio Fabricius (Hymenoptera: Siricidae) sirex woodwasp is native to the temperate palaearctic and has spread to other temperate areas in North and South America, South Africa, Australia and New Zealand. It is a pest of *Pinus* spp., particularly infesting weakened trees. Well-managed stands tend to have negligable damage. We used the model of Carnegie et al. (2006).

Uraba lugens Walker (Lepidoptera: Nolidae) gum-leaf skeletoniser is a pestof plantation eucalypts in Australia. In New Zealand *U.lugens* also attacks other trees including silver birch (*Betula*) and brushbox (*Lophostemon*). We used the model of Kriticos et al. (2007).

Species not present in New Zealand:

Anopheles arabiensis Patton (Diptera: Culicidae) is a major vector of malaria in sub-saharan Africa where it prefers dry, savannah environments. We used the model developed by Tonnang et al. (2010).

Anopheles gambiae s.s. Giles (Diptera: Culicidae) is a major vector of malaria in sub-saharan Africa. We used the model developed by Tonnang et al. (2010).

Bactrocera tryoni (Froggatt)(Diptera: Tephritidae) Queensland fruit fly is a pest of many fruit crops and some vegetables. It occurs in eastern Australia and has invaded New Caledonia, French Polynesia and Pitcairn islands. We used a model developed by Yonow & Sutherst (1998).

Cerotoma trifurcata (Forster) (Coleoptera: Chrysomelidae) bean leaf beetle is a pest of cucurbits and legumes in North America where it is endemic. We used the model developed by Berzitis (2013).

Contarinia nasturtii (Kieffer) (Diptera: Cecidomyiidae) swede midge occurs on brassicaceous plants in Europe and south-west Asia. Larvae feed within the growing tips and

can cause severe crop loss. Recently *C. nasturtii* invaded North America (Kikkert et al. 2006, Hallett & Heal 2001). We used the model reported by Mika et al. (2008).

Diaphorina citri Kuwayama (Hemiptera: Psyllidae) Asian citrus psyllid is a pest of citrus world-wide because it vectors *Candidatus* Liberibacter asiaticus, the causal agent of the deadly disease of citrus Huanglongbing. *D.citri* is widely distributed in southern Asia, and occurs in the Middle East, Caribbean, southern USA, Brazil and several Indian Ocean and Pacific islands. We used the model developed by Logan & Narouei Khandan (2014).

Drosophila suzukii (Matsumura) (Diptera: Drosophilidae) spotted wing drosophila is a temperate to subtropical species native to Southeast Asia that is a fruit crop pest and a serious economic threat to soft fruit such as stonefruit and berries. We used the model developed by Damus (2009).

Harmonia axyridis (Pallas) (Coleoptera: Coccinellidae) originated in northwestern Asia and is now established in Europe and North and South America partly due to releases for the control of scale insects, psyllids and aphids. *H. axyridis* is also considered a pest because it feeds on fruit, predates other aphidophagous coccinellids and causes a nuisance by overwintering in aggregations in buildings (in USA and Canada) (Roy & Wajnberg 2008). We used the model reported by Poutsma et al. (2008).

Homalodisca vitripennis (Germar) (Hemiptera: Cicadellidae) glassy winged sharpshooter is a pest of some horticultural crops and ornamentals, primarily because it vectors the plant pathogenic bacterium *Xylella fastidiosa* Wells. It is native to Central America and south-eastern USA and has established in California and some western Pacific islands. We used the model of Hoddle (2004).

Solenopsis invicta Buren (Hymenoptera: Formicidae) red imported fire ant is native to South America and an invasive pest of the southern USA, the Caribbean, southern China, Taiwan and Australia. We used a model developed by Sutherst & Maywald (2005).

Spodoptera exigua (Hübner) (Lepidoptera: Noctuidae) beet armyworm is a southeast Asian species also found in North America. Larvae are serious pests of many vegetable and field crops. We used the model developed by Zheng et al. (2012).

Thrips palmi Karny (Thysanoptera: Thripidae) melon thrips is a pest of glasshouse crops probably originating in Indonesia and has been widely introduced to other Asian countries, Australia, Pacific islands, west Africa and the Americas. We used the model developed by Park et al. (2014).

Table 12.1. Parameter values for CLIMEX models of selected arthropod species present in New Zealand

| CLIMEX parameters	C. pomonella[1]	E. postvittana[2]	E. californica[3]	F. occidentalis[4]	H. armigera[5]	P. xylostella[6]	R. padi asexual[7]	U. lugens[8]	L. hasseltii[9]	P. major[10]	S. noctilio[11]	D. plexipus[12]
Temperature												
DV0	10	7	3	10	11	7	6	8	15	4	0	11.5
DV1	16	13	15	27	20	14	22	20	22	10	5	26
DV2	25	23	25	30	31	28	26	27	37	18	24	29
DV3	32.5	30	35	31	37	38	30	29	40	22	30	35
PDD	200	673.6		264	500	268	150	610				
Moisture												
SM0	0.15	0.25	0.15	0.2	0.05	0.05	0.1	0.2	0.01	0.1	0.1	0.1
SM1	0.4	0.8	0.2	0.6	0.7	0.5	0.5	0.3	0.1	0.2	0.3	0.5
SM2	1.4	1.5	1	0.88	2	1.25	1	1.2	0.5	0.8	1.0	1.5
SM3	1.5	2.5	1.5	0.96	4	1.75	1.4	1.4	1.35	1.5	2.5	2.5
Diapause												
DPD0	14				11					12		
DPT0	10				15					20		
DPT1	0				16					18		
DPD0	0				-69					40		
DPSW	0				0					1		
Cold stress												
TTCS	5	5		0.5	9	4	-5		0			6
THCS	-1e-5	-5e-4		-0.002	-3e-4	-5e-4	-0.001		-0.005			-0.005
DVCS			23			12[a]	8	18				
DTCS		-1.8e-4				-5e-4[a]	-0.001	-5.5e-4				
TTCSA												
THCSA												
Heat stress												
TTHS	29	31	35	31	37	38	32	29	40	32	35	31
THHS	0.006	0.01	0.002	0.0038	0.0005	0.001	0.01	0.0011	0.005	0.005	0.05	0.00125
DTHS						1						
DHHS						0.005						
Dry stress												
SMDS	0.15	0.2	0.1	0.2	0.1	0.05	0.1	0.2	0.01	0.01	0.1	0.4
HDS	0.01	-0.01	-0.01	-0.0001	-0.005	-0.005	-0.25	-0.015	-0.005	-0.005	-0.01	-0.001
Wet stress												
SMWS	2	2.5		1.3	2	1.75	1.4	1.4	1.35	1.5	2.5	2
HWS	0.002	0.002		0.006	0.005	0.05	0.001	0.009	0.01	0.005	0.002	0.0005
Hot-Dry stress												
TTHD											23	
MTHD											0.1	
PHD											0.1	
Hot-Wet stress												
TTHW		28				30					32	
MTHW		0.3				1.25					1.5	
PHW		0.0012				0.05					0.5	

[1]CLIMEX software model library, [2]He et al. (2012), [3]Wharton & Kriticos (2004), [4]Cheng et al. (2006), [5]Zalucki & Furlong (2005), [6]Zalucki & Furlong (2011), [7]Macfadyen & Kriticos (2012), [8]Kriticos et al. (2007), [9]Vink et al. (2011), [10]Robinson & Hoffmann (2001). [11]Carnegie et al. (2006), [12]Zalucki & Rochester (1999). [a]omitted to fit New Zealand.

Table 12.2. Parameter values for CLIMEX models of selected arthropod species not present in New Zealand

CLIMEX parameters	C. nasturtii[1]	C. trifurcata[2]	D. citri[3]	D. suzukii[4]	H. axyridis[5]	H.vitripennis[6]	S.exigua[7]	S.invicta[8]	T.palmi[9]	A. gambiae[10]	A. arabiensis[10]	B.tryoni[11]
Temperature												
DV0	10	7.8	12.85	9.1	10.5	0	15	17	10.6	15	18	12
DV1	16	18	18	20	15	12	26	26	25	28	30	25
DV2	25	32	33	28	25	31	29	30	30	35	38	33
DV3	32.5	35	36	32	35	35	36	35	39	40	44	36
PDD	200	1000	230	268	330		265.6	510	183.3			380
Moisture												
SM0	0.15	0.25	0.01	0.4	0.1	0.3	0.03	0.15	0.25	0.35	0.15	0.1
SM1	0.4	0.4	0.1	0.7	0.3	0.5	0.31	0.8	0.8	0.7	0.4	0.5
SM2	1.4	1.25	1.2	1.75	1.9	1.75	1	2	1.5	1.5	0.6	1.75
SM3	1.5	1.4	2.5	2	2.0	2	2	3	2.5	2.5	0.8	2
Diapause												
DPD0	14	12			14							
DPT0	10	10			16							
DPT1	6	9			7.3							
DPD0	150	0			40							
DPSW	0	0			0							
Cold stress												
TTCS	-18	-10	7	-11	-5	6	3.2	0		2	2	2
THCS	-8e-5	-0.002	-5e-4	-5e-4	-2e-5	-0.001	-0.2	-4.47e-3		-1	-1	-2.5e-4
DVCS			30			2		6		25	15	
DTCS			-2.5e-4			-0.001		-5.5e-4		-0.002	-0.001	
TTCSA						0			4.4			
THCSA						-0.001			-0.002			
Heat stress												
TTHS	35	37	37	36	35	33	36	38	40	40	44	36
THHS	0.005	0.005	0.00015	0.0007	0.005	0.001	0.0163	0.0018	0.0005	0.001	0.0002	0.005
DTHS						10						
DHHS						0.001						
Dry stress												
SMDS	0.1	0.12		0.3	0.01	0.3	0.02	0.15	0.2	0.26	0.3	0.1
HDS	-0.01	-0.07		-0.001	-0.001	-0.006	-0.005	-0.008	-0.005	-0.006	-0.001	-0.005
Wet stress												
SMWS	1.5	1.4			2	2	2.5	4	2.5	2.5	0.9	2
HWS	0.0005	0.05			0.01	0.002	0.002	0.002	0.002	0.2	0.003	0.002
Cold-Wet stress												
DTCW		10		30						30		
MTCW		1.1		0.3						0.1		
PCW		0.01		0.001						0.001		

[1] Mika et al. (2008), [2] Berzitis (2013), [3] Logan & Narouei Khandan (2014), [4] Damus (2009), [5] Poutsma et al. (2008), [6]Hoddle (2004), [7]Zheng et al. (2012), [8]Sutherst & Maywald (2005), [9]Park et al. (2014), [10]Tonnang et al. (2010), [11] Yonow & Sutherst (1998).

12.4. SELECTED RESULTS FROM CLIMEX SIMULATIONS
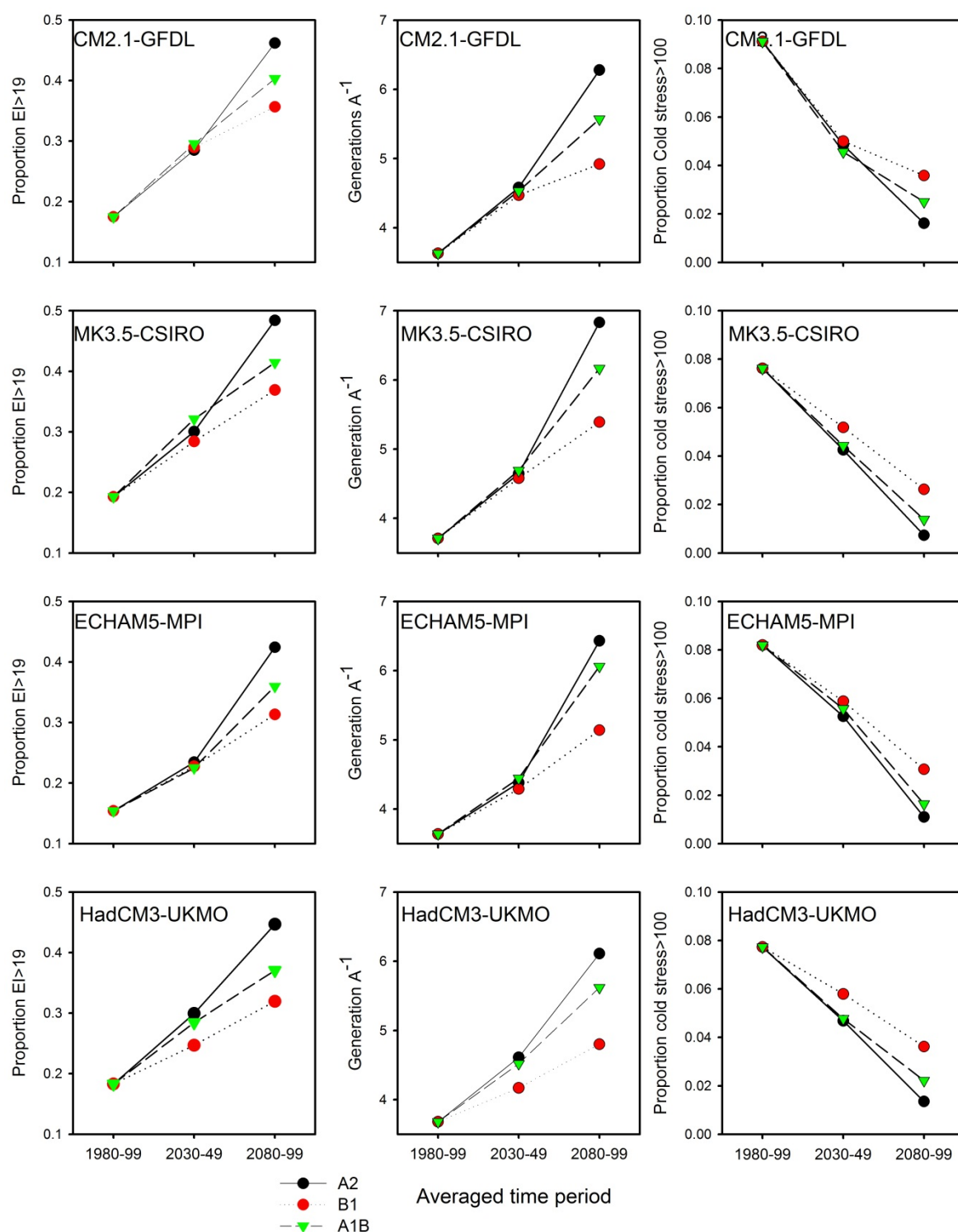
Figure 12.5. Response of *Thrips palmi* to historical and projected climates for three SRES scenarios (A2,B1 and A1B), and four GCMs (CM2.1-GFDL, MK3.5-CSIRO, ECHAM5-MPI,HadCM3-UKMO) as indicated by three indicators. See figure 1 description for explanation of indicators.
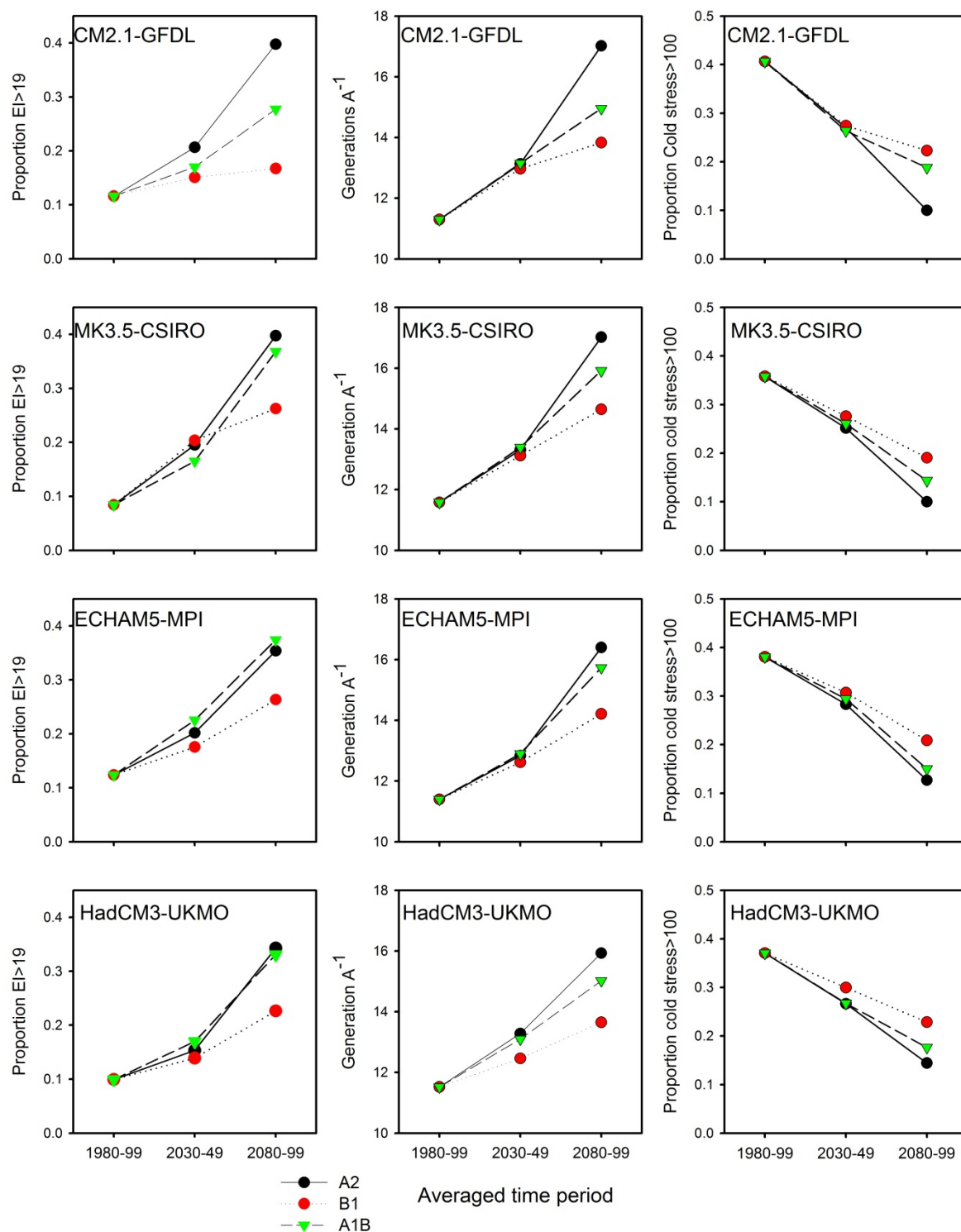
Figure 12.6. Response of *Rhopalosiphum padi* to historical and projected climates for three SRES scenarios (A2,B1 and A1B), and four GCMs (CM2.1-GFDL, MK3.5-CSIRO, ECHAM5-MPI,HadCM3-UKMO) as indicated by three indicators. See figure 1 description for explanation of indicators.
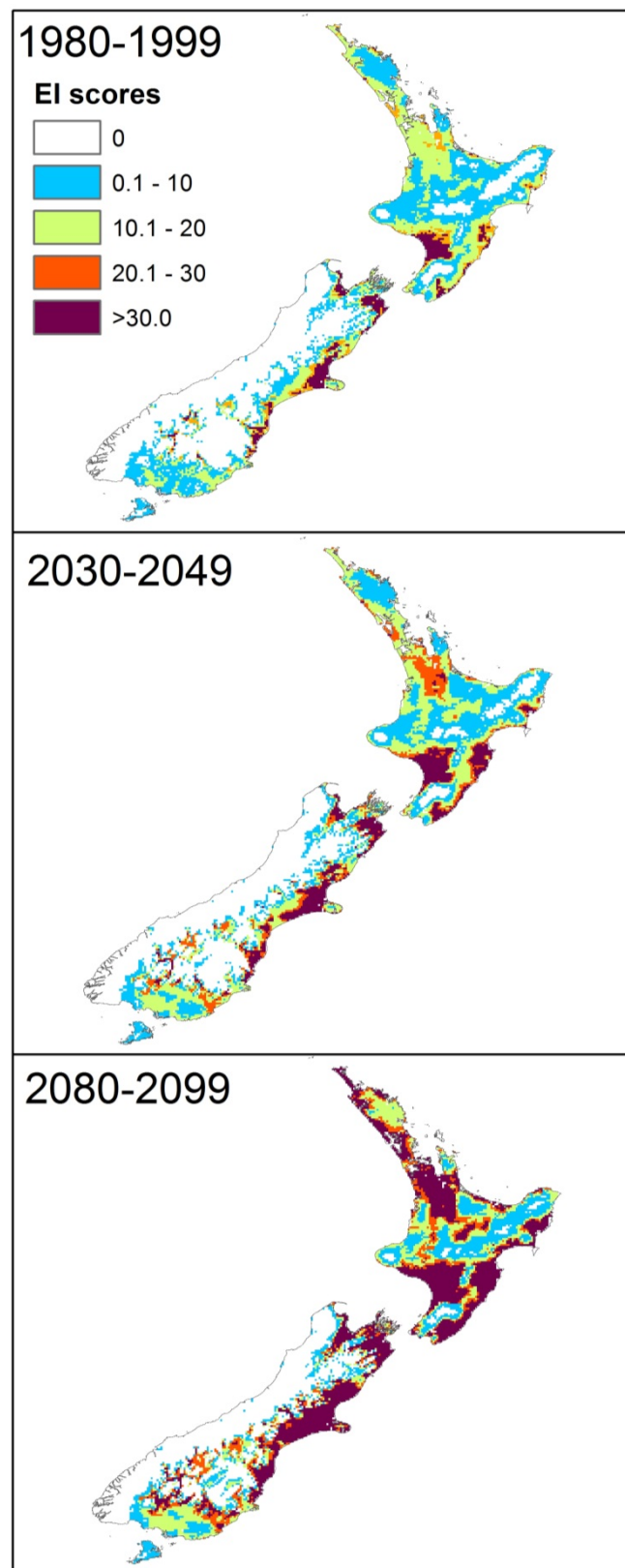
Figure 12.7. Ecoclimatic Index scores for the lightbrown apple moth, *Epiphyas postvittana*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
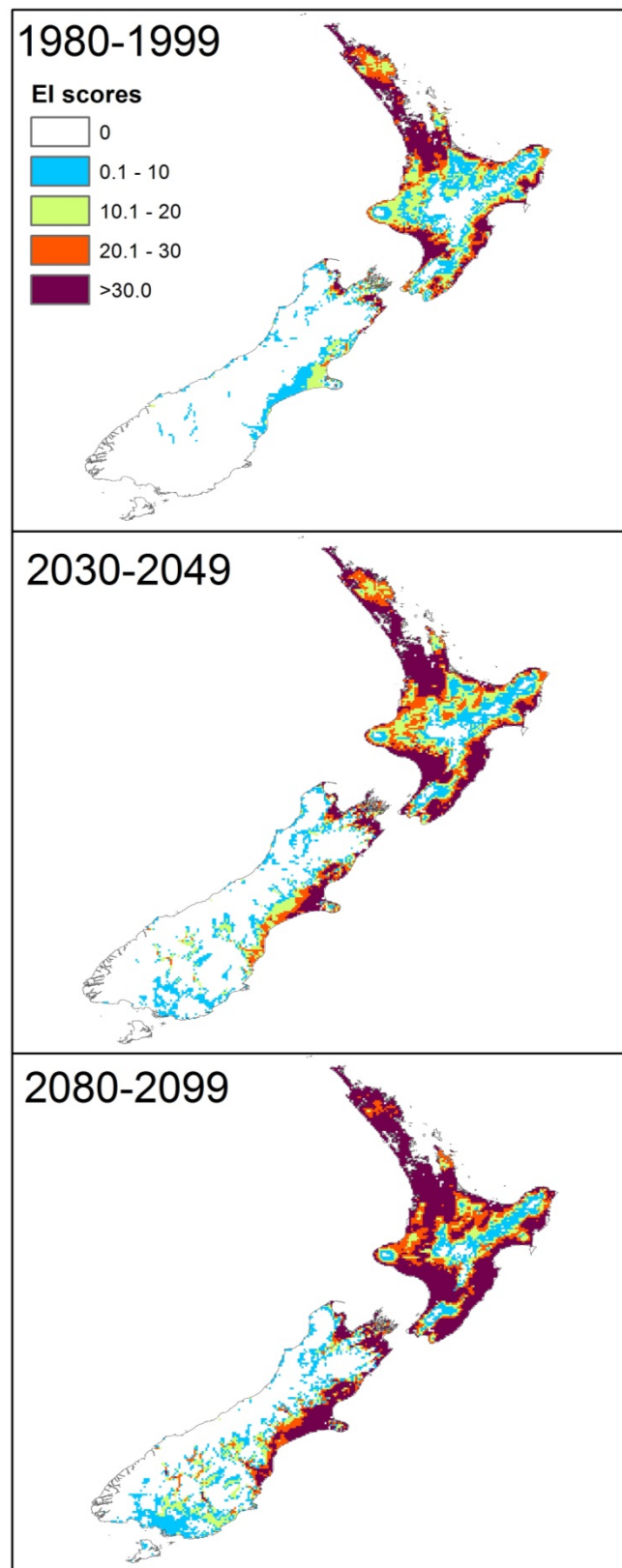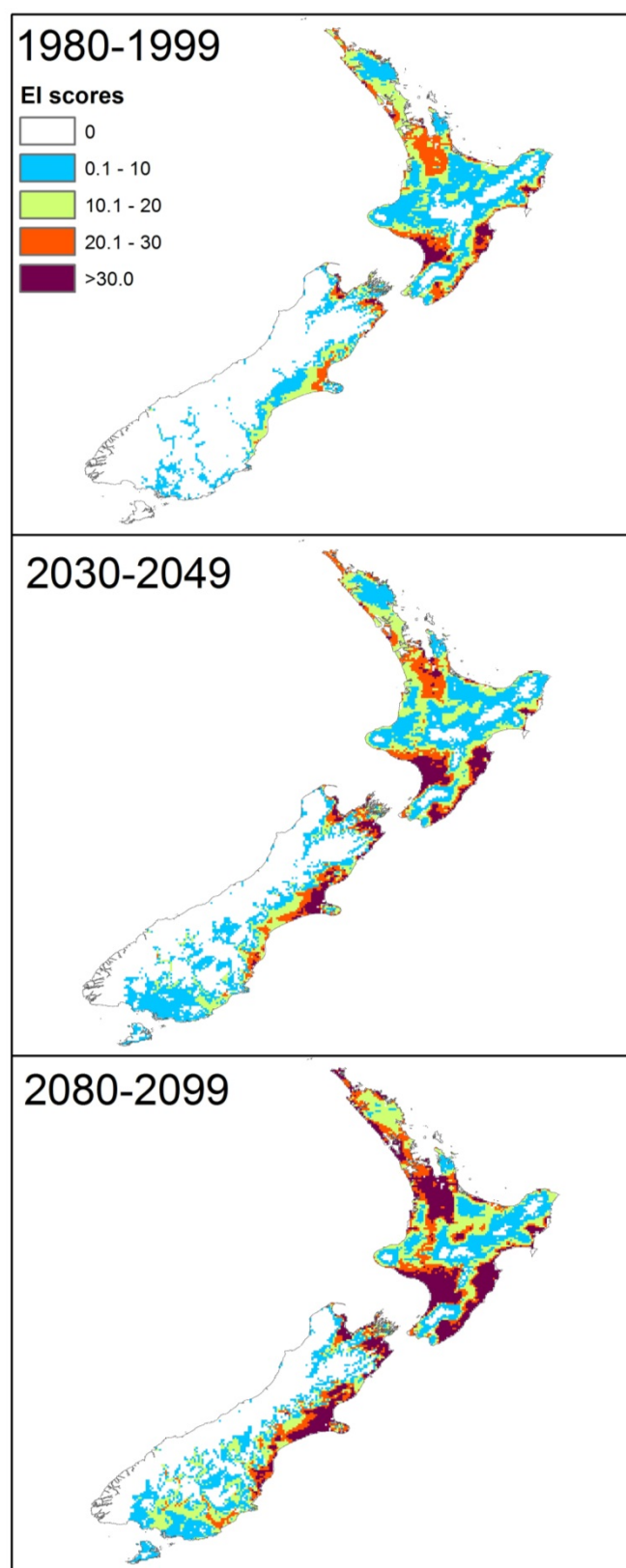
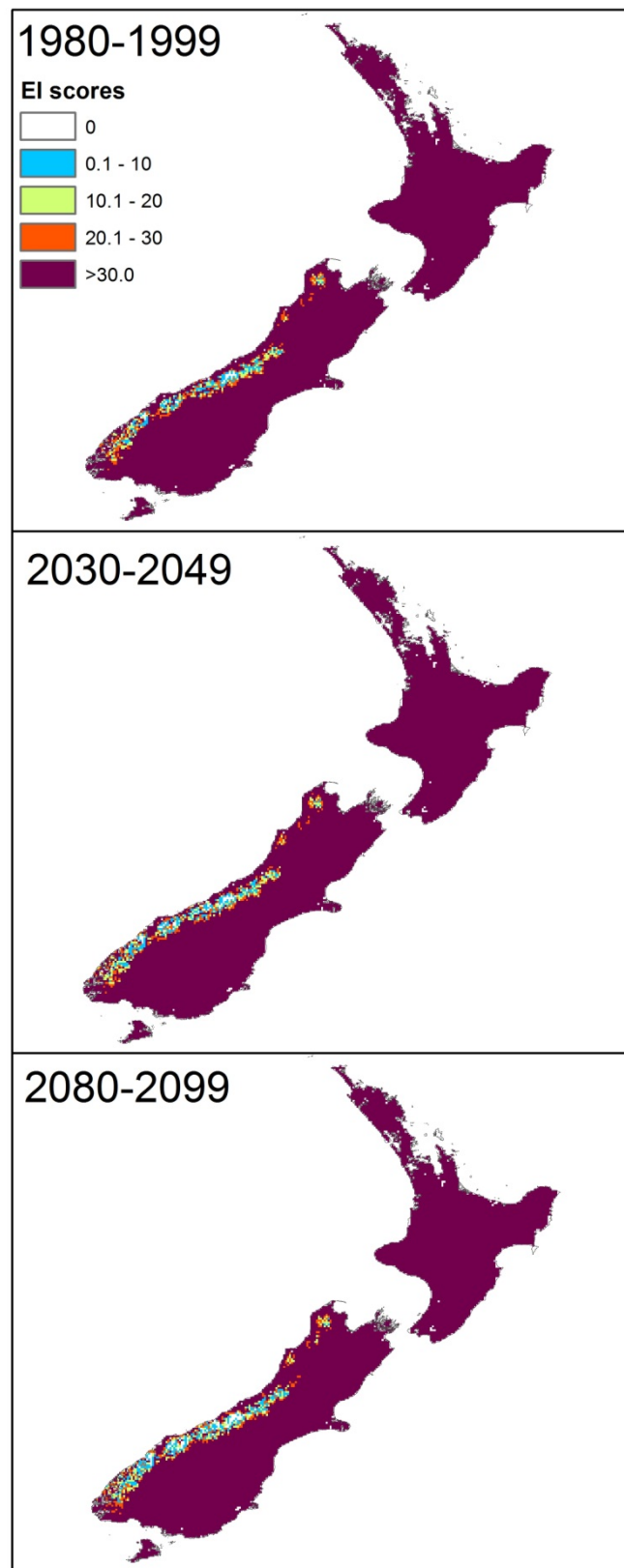**Figure 12.8**. Ecoclimatic Index scores for the Monterey pine aphid, *Essigella californica*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
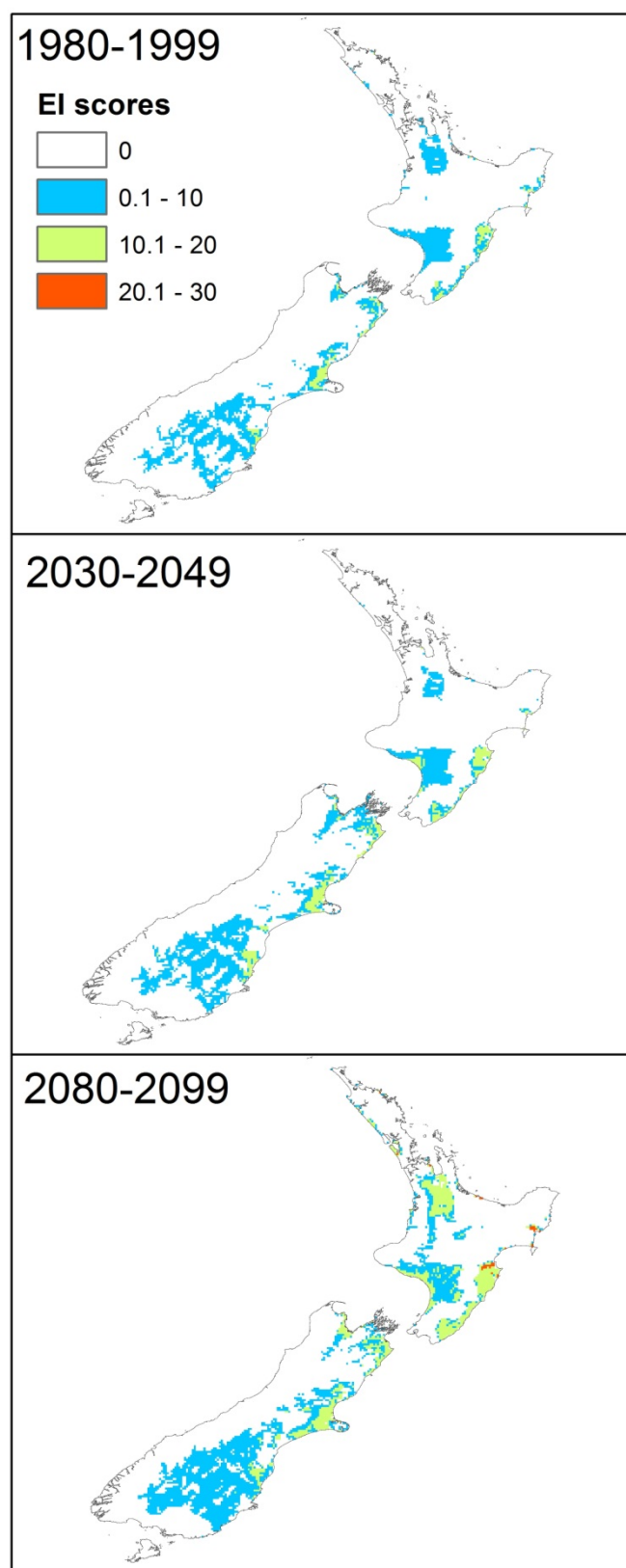
Figure 12.9. Ecoclimatic Index scores for the Western flower thrips, *Frankliniella occidentalis*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
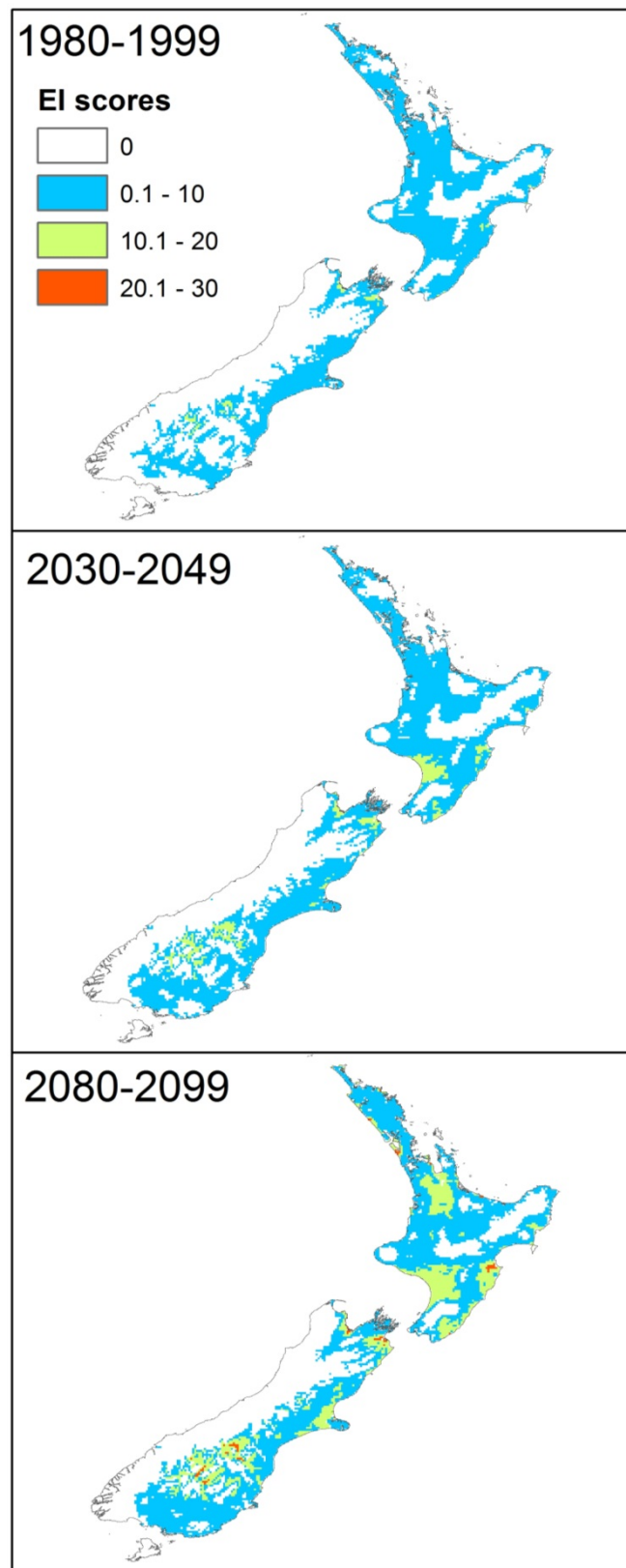
Figure 12.10. Ecoclimatic Index scores for the Redback spider, *Latrodectus hasseltii,* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
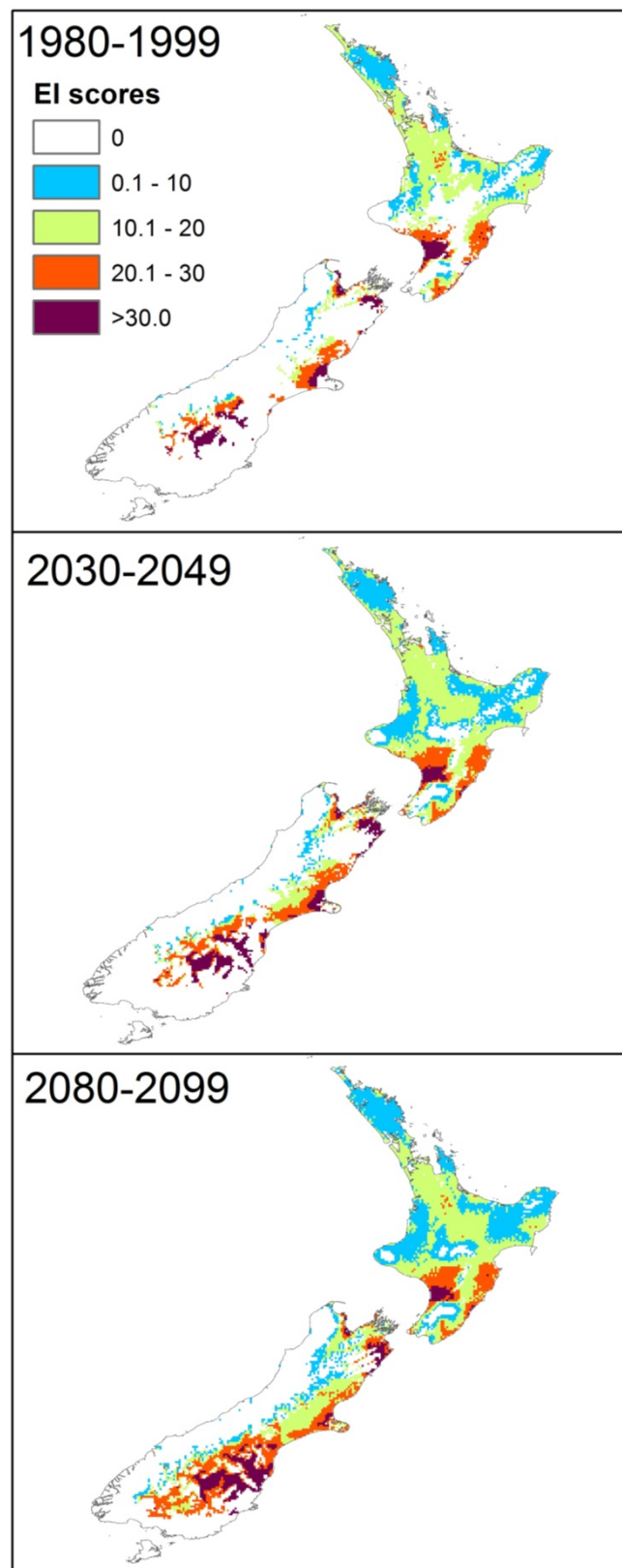
Figure 12.11. Ecoclimatic Index scores for the Blue oat mite, *Penthaleus major,* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
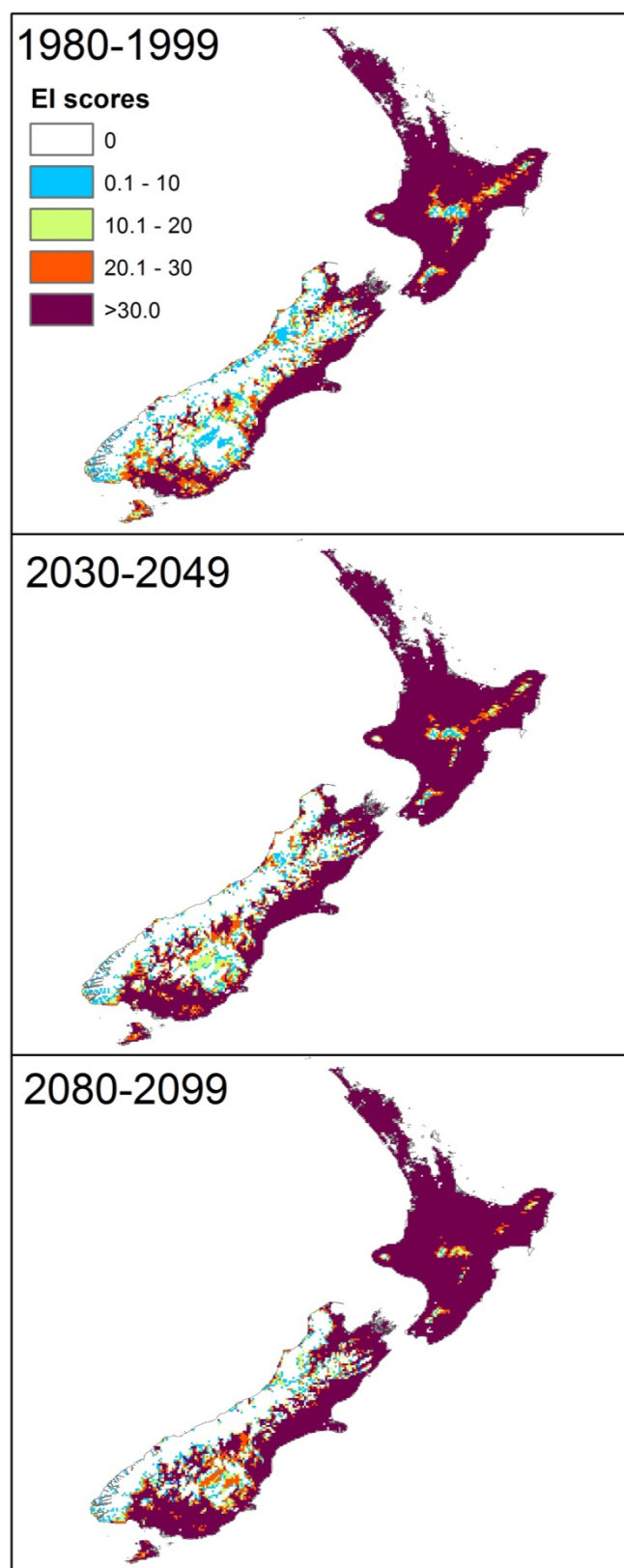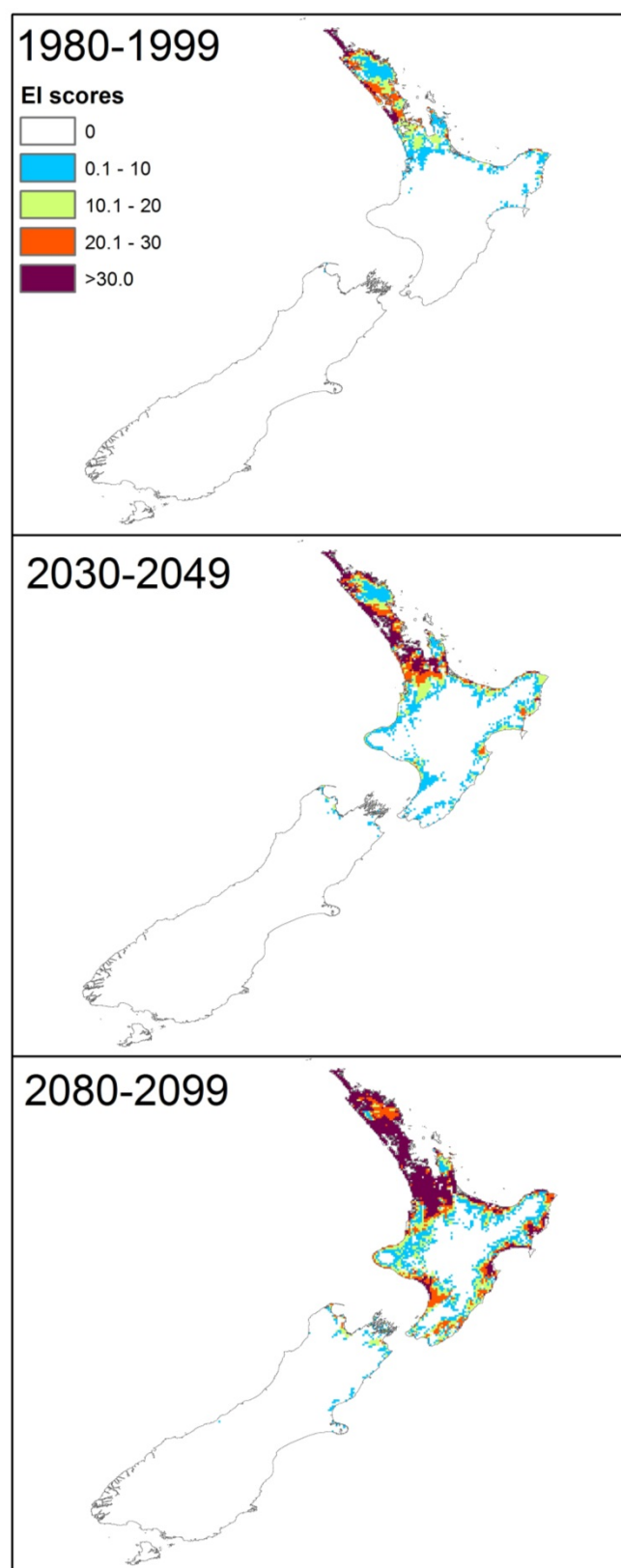
Figure 12.12. Ecoclimatic Index scores for the Diamondback moth, *Plutella xylostella*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.

Figure 12.13. Ecoclimatic Index scores for Cereal aphid,*Rhopalosiphum padi,* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
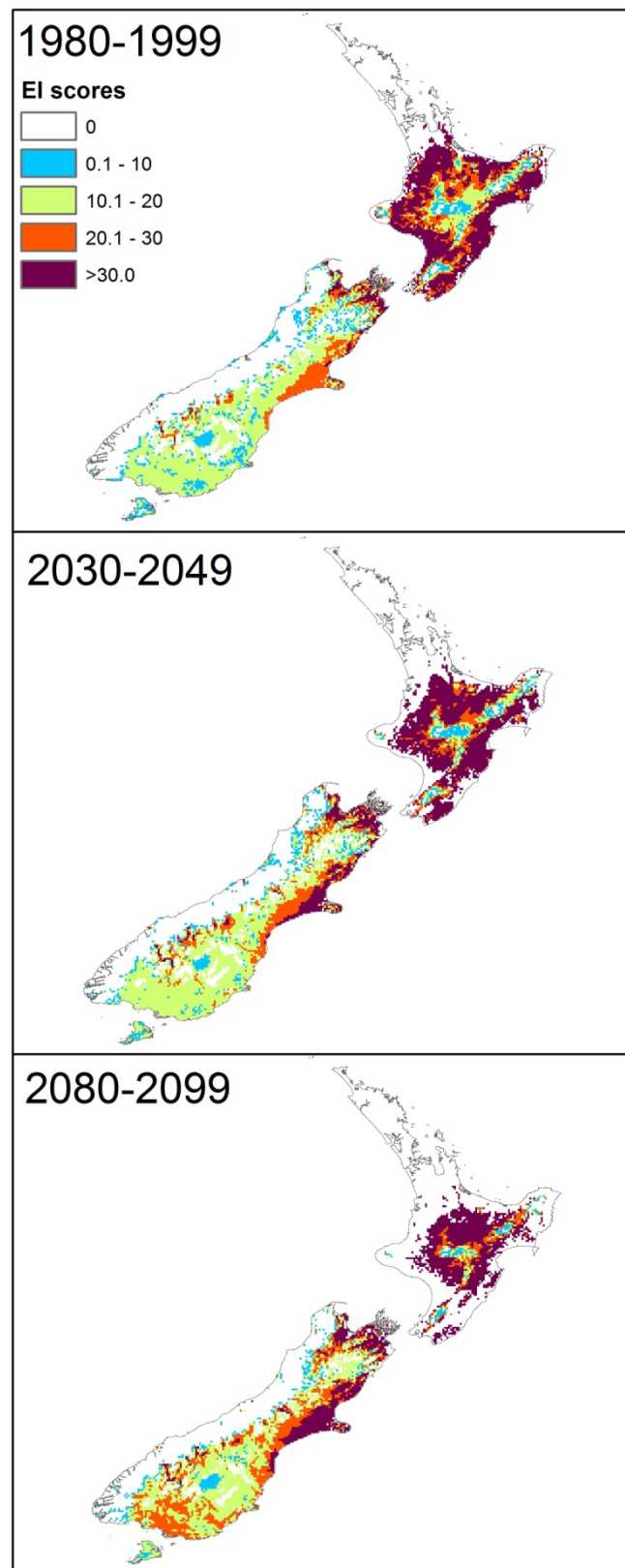
Figure 12.14. Ecoclimatic Index scores for the Sirex woodwasp, *Sirex noctilio*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
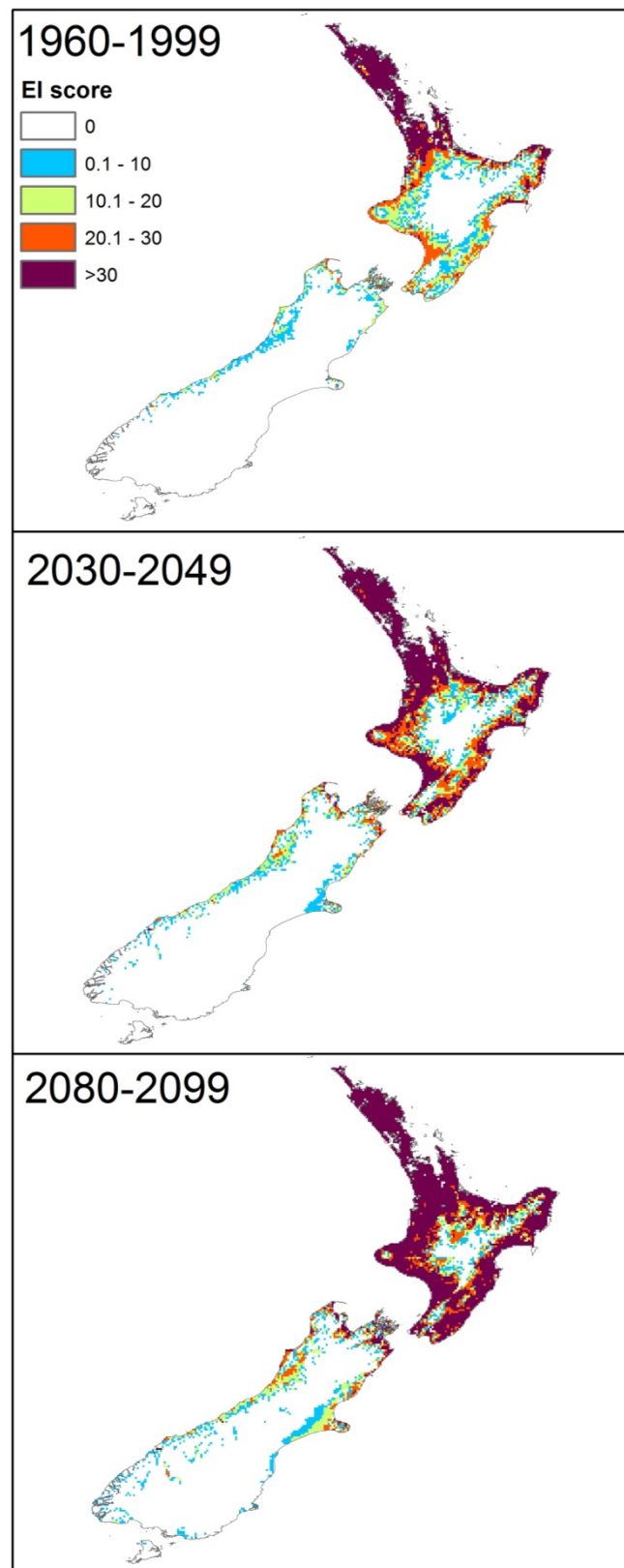
Figure 12.15. Ecoclimatic Index scores for Gum-leaf skeletoniser, *Uraba lugens*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
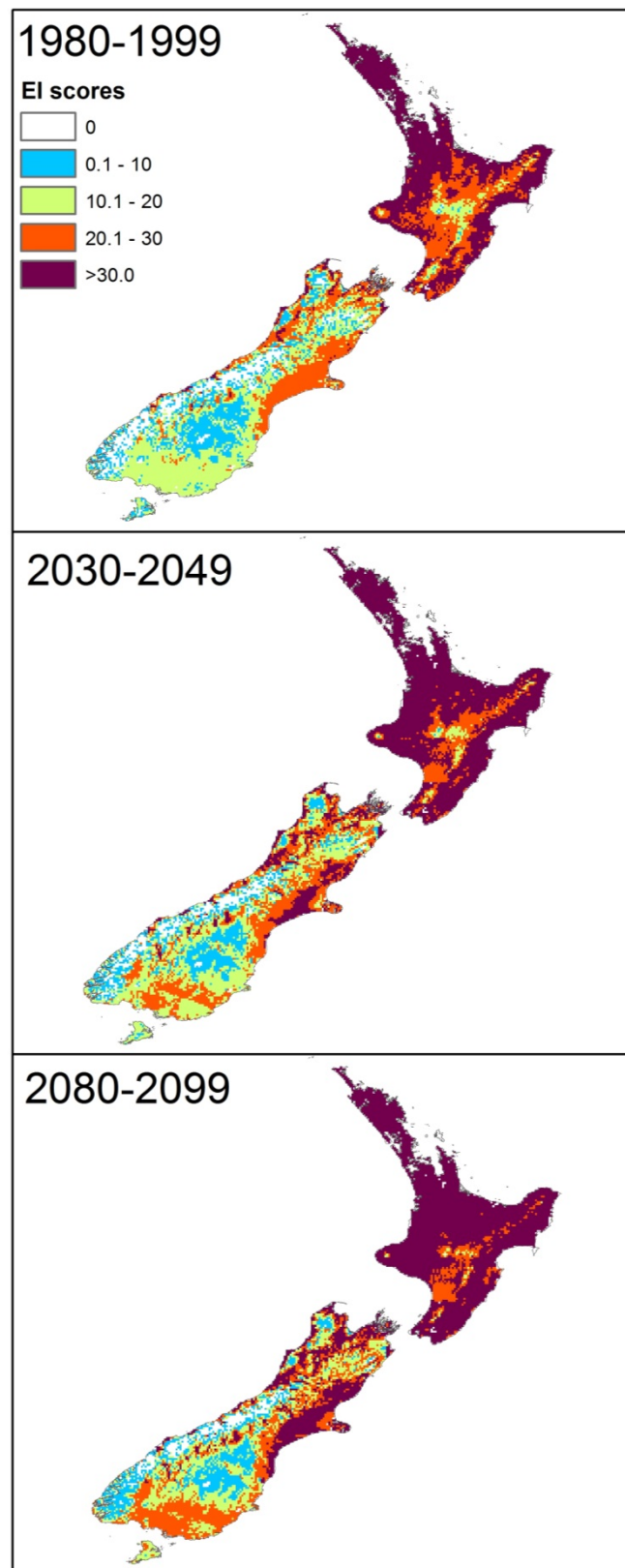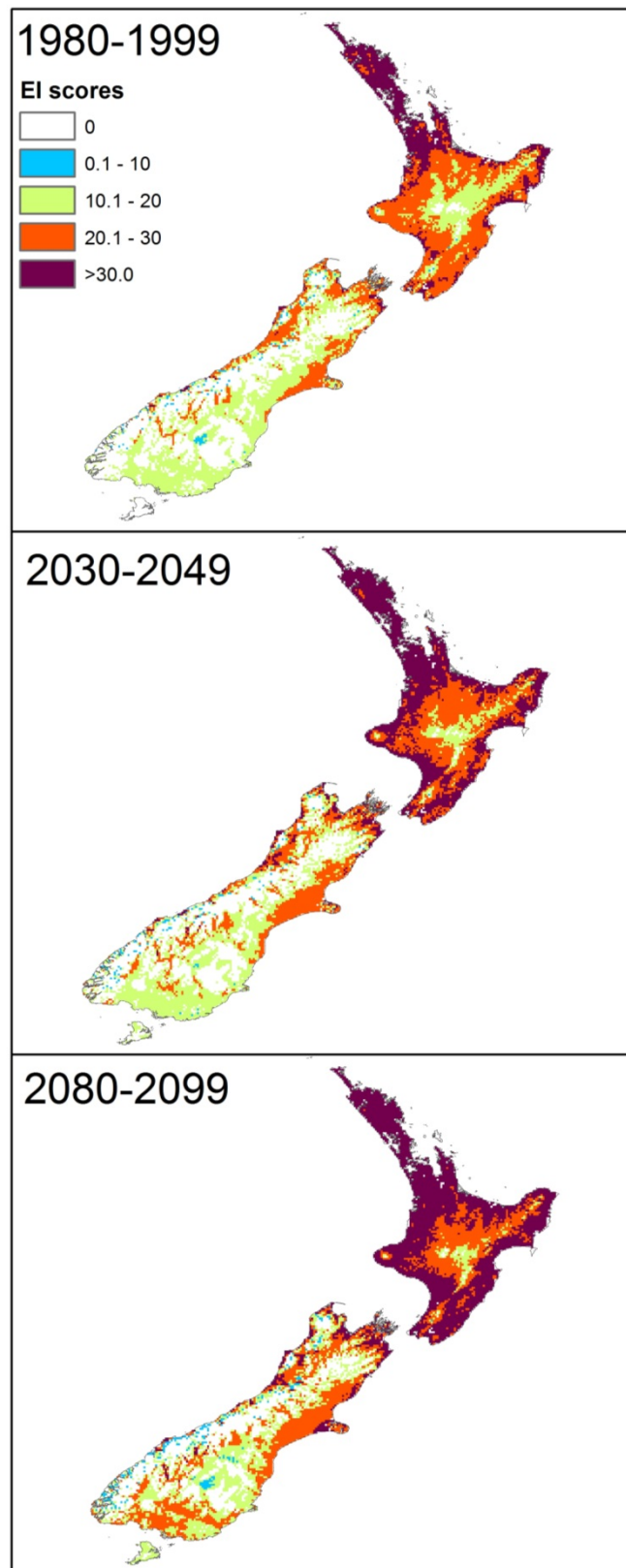
Figure 12.16. Ecoclimatic Index scores for the Swede midge, *Contarinia nasturtii,* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
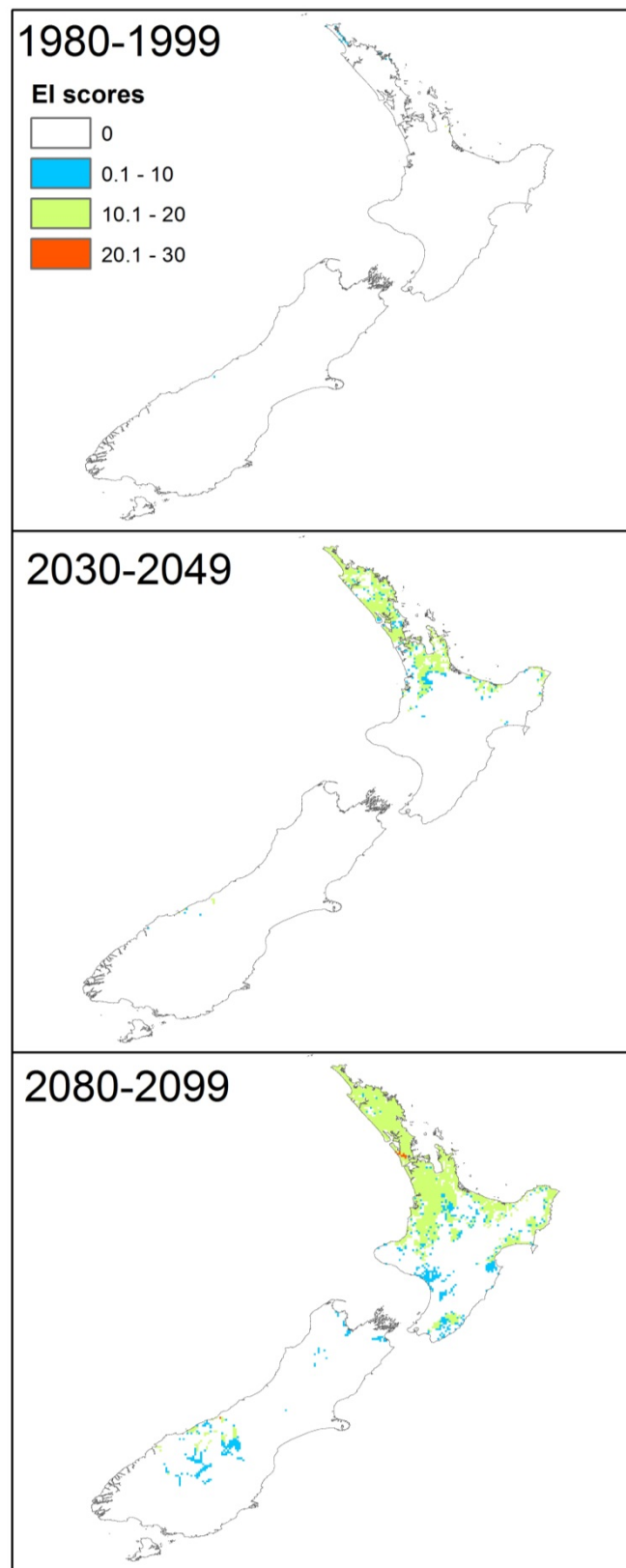
Figure 12.17. Ecoclimatic Index scores for the Asian citrus psyllid, *Diaphorina citri*, for three periods 1980-1999,2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.
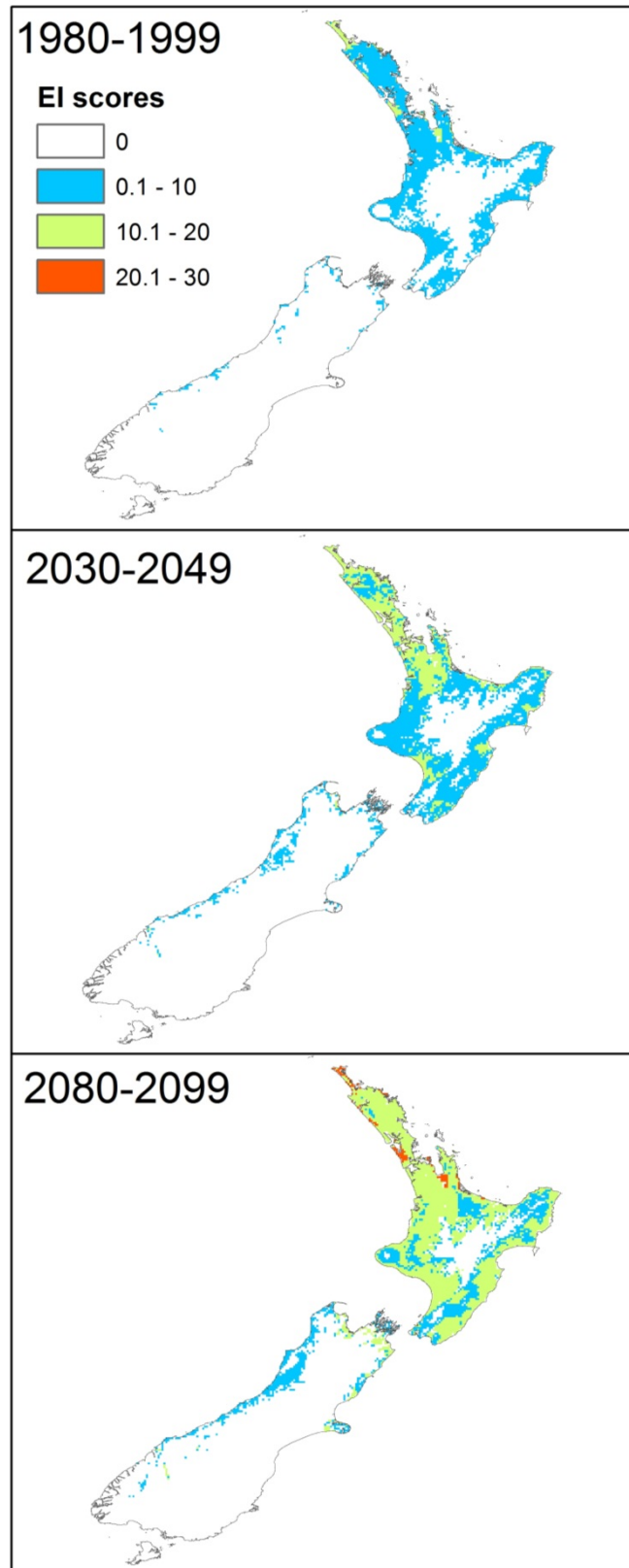
Figure 12.18. Ecoclimatic Index scores for Spotted-wing drosophila, *Drosophila suzukii* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.

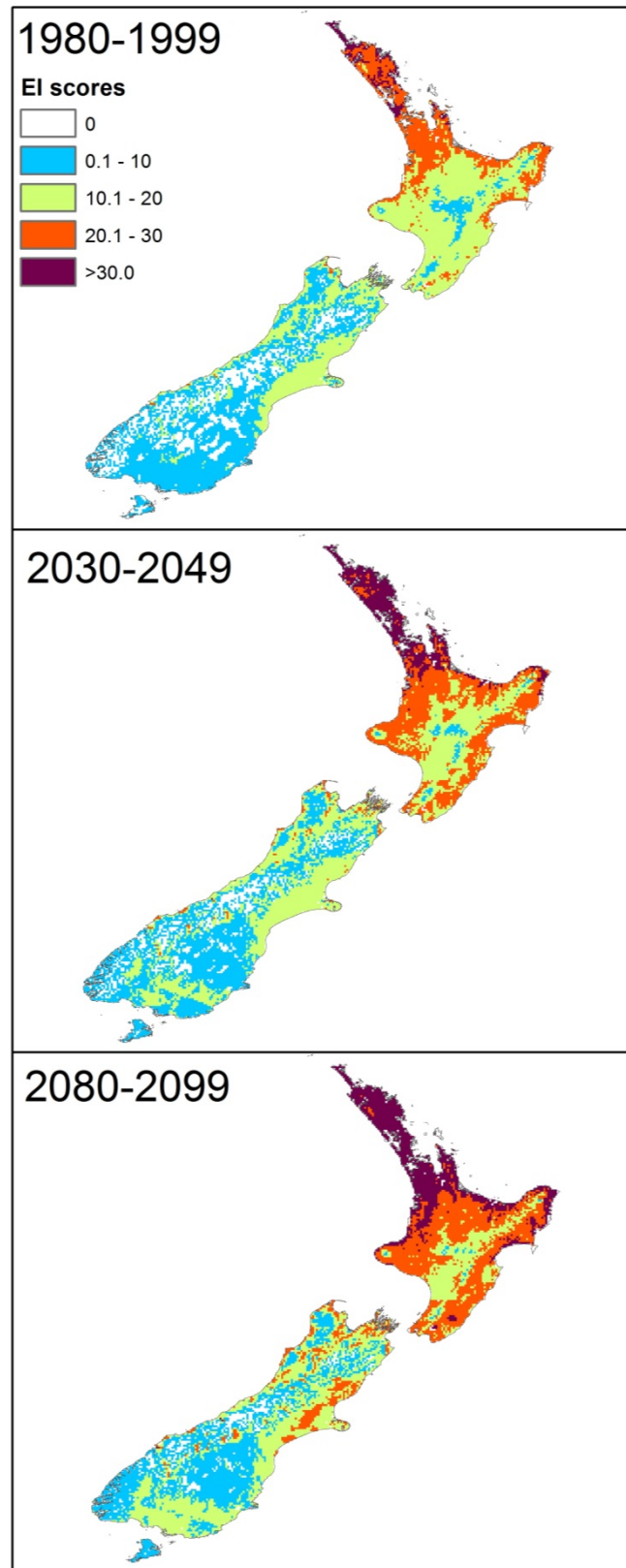**Figure 12.19.** Ecoclimatic Index scores for *Harmonia axyridis* for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.

**Figure 12.20.** Ecoclimatic Index scores for Red imported fire ant, *Solenopsis invicta*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.

Figure 12.21. Ecoclimatic Index scores for Beet armyworm, *Spodoptera exigua*, for three periods 1980-1999, 2030-2049 and 2080-2099. The climate data are for the A1B scenario and the CM2.1-GFDL GCM.

Figure 12.22. Change in Ecoclimatic Index for Melon thrips, *Thrips palmi,* for three periods 1980-1999, 2030-2049 and 2080-2099. Climate data are for the A1B scenario and the CM2.1-GFDL GCM.
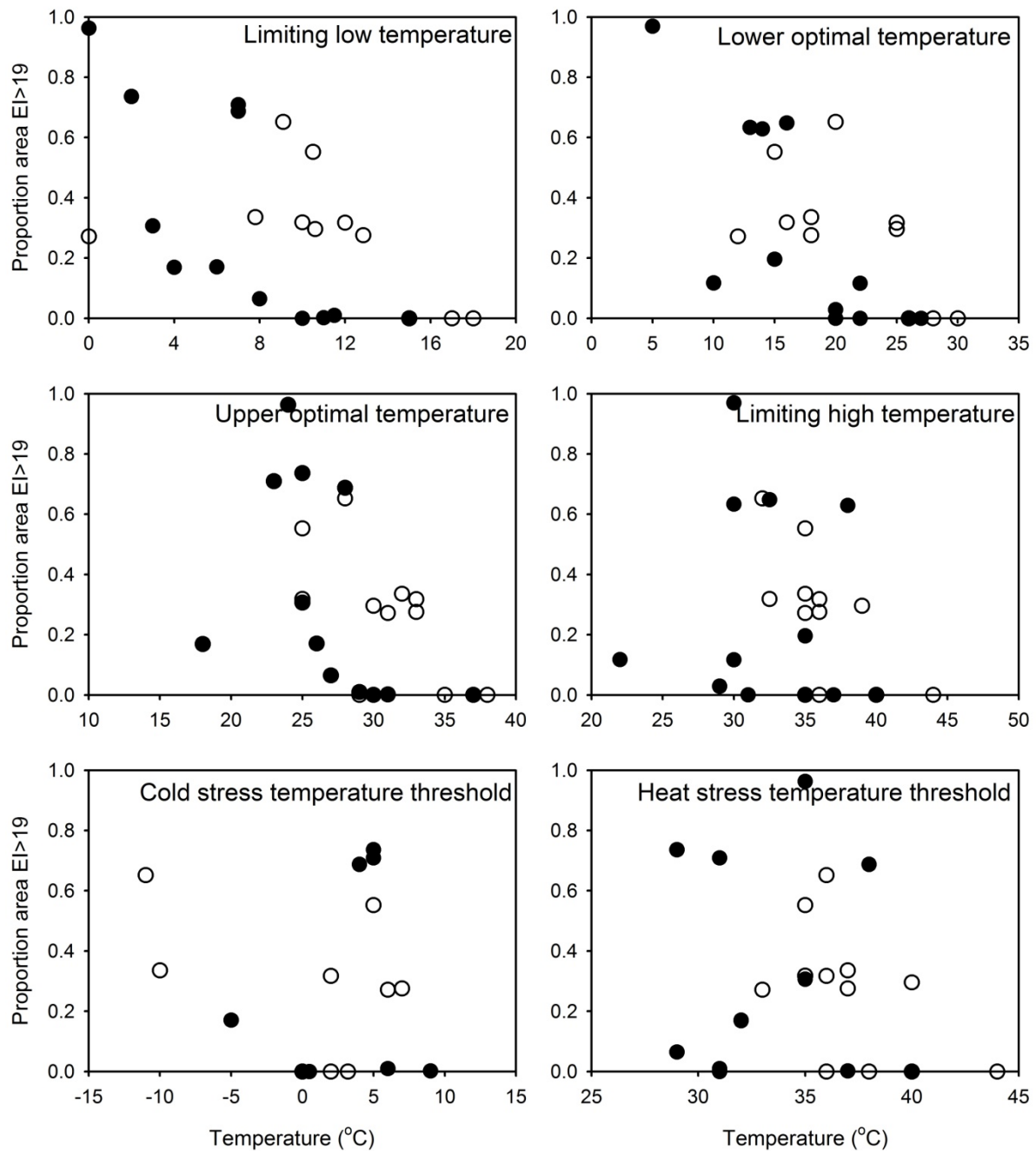
Figure 12.23. Selected temperature parameters for 24 modelled arthropod species (● present in New Zealand, ○ absent from New Zealand) and the proportion of New Zealand land mass where long-term populations persistence is likely under projected climates for 2030-2049 (as indicated by the grid cells with an Ecoclimatic index of 20 or more). Climate data set is the A1B scenario based on the gfdl_CM20 GCM.
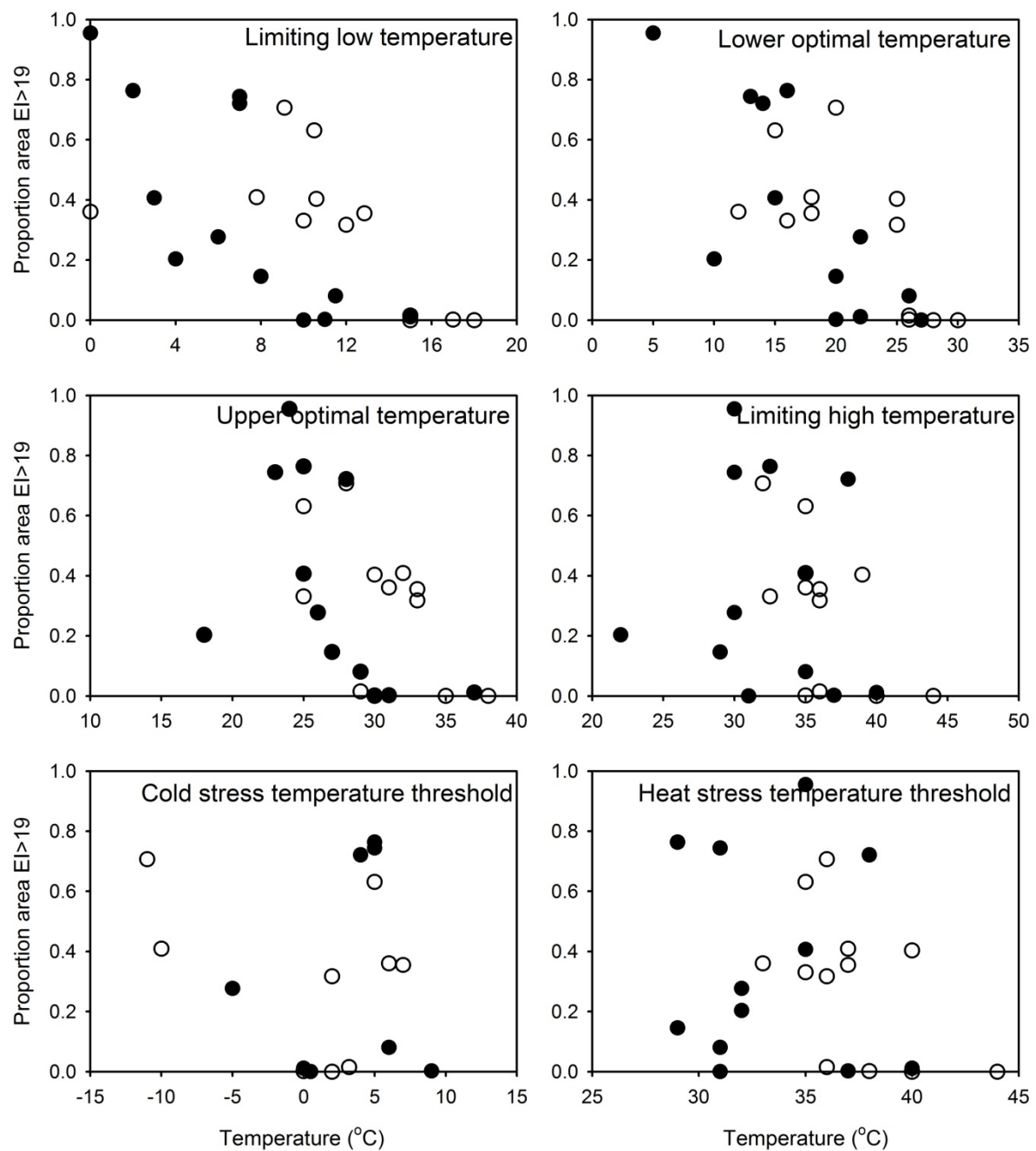
Figure 12.24. Selected temperature parameters for 24 modelled arthropod species (● present in New Zealand, ○ absent from New Zealand) and the proportion of New Zealand land mass where long-term populations persistence is likely under projected climates for 2080-2099 (as indicated by the grid cells with an Ecoclimatic index of 20 or more). Climate data set is the A1B scenario based on the gfdl_CM20 GCM.

12.5. LIST OF TAXA FOR WHICH CLIMEX MODELS ARE CURRENTLY AVAILABLE IN CLIMENZ

Species	Common name
Invertebrates	
Acantholybas brunneus	
Aedes aegypti	yellow fever mosquito
Amorbus alternatus	Eucalyptus tip wilter bug
Amorbus atomarius	
Amorbus biguttatus	
Amorbus bispinus	
Amorbus obscuricornis	
Amorbus rhombifer	Eucalyptus tip-wilter bug
Amorbus robustus	common gum-tree bug, clown bug
Amorbus rubiginosus	clown bug
Anastrepha ludens	Mexican fruit fly, Mexfly
Anastrepha obliqua	West Indian fruit fly
Anopheles arabiensis	African malaria mosquito
Anopheles gambiae s.s.	African malaria mosquito
Bactrocera correcta	guava fruit fly
Bactrocera cucumis	cucumber fly
Bactrocera cucurbitae	melon fly
Bactrocera dorsalis	oriental fruit fly
Bactrocera dorsalis	oriental fruit fly
Bactrocera jarvisi	Jarvis' fruit fly
Bactrocera latifrons	solanum fruit fly
Bactrocera musae	banana fruit fly
Bactrocera neohumeralis	lesser Queensland fruit fly
Bactrocera tryoni	Queensland fruit fly, Qfly
Bactrocera zonata	peach fruit fly
Ceratitis capitata	Mediterranean fruit fly, Medfly
Ceratitis rosa	Natal fruit fly
Cerotoma trifurcata	bean leaf beetle
Contarinia nasturtii	swede midge
Cydia pomonella	codling moth
Diaphorina citri	Asian citrus psyllid
Drosophila suzukii	spotted-wing drosophila
Epiphyas postvittana	light brown apple moth
Essigella californica	Monterey pine aphid
Frankliniella occidentalis	western flower thrips
Gelonus tasmanicus	Tasmanian leaf-footed bug
Harmonia axyridis	harlequin ladybird
Helicoverpa armigera	tomato fruitworm, corn earworm, cotton bollworm
Homalodisca coagulata	glassy-winged sharpshooter
Latrodectus hasseltii	Australian redback spider
Leptinotarsa decemlineata	Colorado potato beetle
Lymantria dispar dispar	European gypsy moth
Lymantria monacha	nun moth

Penthaleus major	blue oat mite
Plutella xylostella	diamondback moth
Rhagoletis indifferens	western cherry fruit fly
Rhagoletis pomonella	apple maggot
Rhopalosiphum padi	cereal aphid
Sirex noctilio	sirex woodwasp
Sitona lineatus	pea leaf weevil
Solenopsis invicta	red imported fire ant
Spodoptera exigua	beet armyworm
Thaumetopoea pityocampa	pine processionary moth
Thrips palmi	melon thrips
Uraba lugens	gumleaf skeletoniser

Pathogens

Guignardia citricarpa	citrus black spot
Pseudomonas syringae pv. actinidiae	bacterial canker of kiwifruit, Psa
Puccinia psidii	myrtle rust
Xylella fastidiosa	causal agent of Pierce's disease

Plants

Acacia catechu	cutch tree
Acacia cyclops	red-eyed wattle
Acacia pycnantha	golden wattle
Aeschynomene paniculata	pannicle jointvetch
Alternanthera philoxeroides	alligator weed
Arundo donax	giant cane
Asparagus aethiopicus	
Asparagus africanus	African asparagus
Asparagus asparagoides	smilax, bridal creeper
Asparagus declinatus	bridal veil
Asparagus densiflorus	plume asparagus
Asparagus officinalis	garden asparagus
Asparagus scandens	climbing asparagus fern, krulkransie
Asparagus setaceus	asparagus fern
Asparagus virgatus	African broom fern
Asystasia gangetica micrantha	Chinese violet
Baccharis halimifolia	groundsel bush
Baccharis pingraea	chilquilla
Barleria prionitis	porcupine flower
Bassia scoparia	kochia
Brillantaisia lamium	tropical giant salvia
Buddleja davidii	butterfly bush
Calluna vulgaris	heather
Cannabis sativa	marijuana, hemp, cannabis
Carduus nutans	nodding thistle
Cenchrus ciliaris	buffelgrass, African foxtail grass
Centaurea eriophora	mallee cockspur
Centaurea solstitialis	yellow star thistle
Chloris truncata	Australian windmill grass

Chromolaena odorata	Siam weed
Clematis vitalba	old man's beard
Cortaderia selloana	pampas grass
Crataegus monogyna	hawthorn
Crupina vulgaris	common cropina
Cryptostegia grandiflora	rubber vine
Cuscuta suaveolens	fringed dodder
Cynodon dactylon	Bermuda grass, couch
Cynoglossum creticum	blue hound's tongue
Cyperus teneristolon	cyperus
Cytisus multiflorus	white Spanish brrom
Cytisus scoparius	Scotch broom
Dactylis glomerata	cocksfoot
Dittrichia viscosa	false yellowhead
Eleocharis parodii	parodi spike rush
Emex australis	devil's thorn, doublegee
Emex spinosa	spiny emex
Equisetum arvense	horsetail
Eucalyptus globulus	blue gum
Froelichia floridana	snakecotton
Gmelina elliptica	badhara bush
Gunnera tinctoria	giant rhubarb
Gymnocoronis spilanthoides	Senegal tea plant
Heracleum mantegazzianum	giant hogweed
Hieracium aurantiacum	orange hawkweed
Hyparrhenia hirta	common thatching grass
Hypericum tetrapterum	square-stalked St John's wort
Jacobaea vulgaris	ragwort
Jatropha curcas	Barbados nut
Koelreuteria elegans formosana	Taiwanese rain tree
Lachenalia aloides	opal flower
Lachenalia reflexa	yellow soldier
Lagarosiphon major	oxygen weed
Lantana camara	big sage, tickberry, lantana
Lycium ferocissimum	boxthorn
Lythrum salicaria	purple loosestrife
Macfadyena unguis-cati	cat's claw creeper
Medicago sativa	lucerne, alfalfa
Melaleuca quinquenervia	paper bark tea tree
Mikania micrantha	mile-a-minute
Mimosa pigra	giant sensitive tree
Miscanthus sinensis	Chinese silver grass
Nassella charruana	lobed needle grass
Nassella hyalina	cane needle grass
Nassella neesiana	Chilean needle grass
Nassella trichotoma	serrated tussock
Nicotiana tabacum	tobacco
Oenanthe pimpinelloides	meadow parsley
Olea europaea europaea	common olive

Onopordum tauricum	Taurian thistle
Opuntia robusta	wheel cactus
Parkinsonia aculeata	parkinsonia
Parthenium hysterophorus	parthenium weed
Passiflora tripartita	banana passionfruit
Pelargonium alchemilloides	garden geranium
Pennisetum clandestinum	kikuyu
Pennisetum purpureum	elephant grass
Pereskia aculeata	leaf cactus
Phalaris aquatica	Harding grass
Phalaris arundinacea	reed canary grass
Phoenix dactylifera	date palm
Phyla canescens	lippia
Piptochaetium montevidense	Uruguay rice grass
Praxelis clematidea	praxelis
Pueraria lobata	kudzu
Ranunculus acris acris	tall buttercup
Rapistrum rugosum	giant mustard, turnipweed
Retama raetam	white weeping brrom
Rorippa sylvestris	yellow creeping cress
Rubus anglocandicans	blackberry
Saccharum officinarum	sugarcane
Senecio glastifolius	holly-leaved senecio
Senna obtusifolia	sicklepod
Setaria pumila	yellow bristle grass
Solanum elaeagnifolium	silverleaf nightshade
Solanum hoplopetalum	prickly potato weed
Sonchus oleraceus	sow thistle
Sorghum bicolor	sorghum
Sorghum halepense	Johnson grass
Stevia ovata	roundleaf candyleaf
Thunbergia laurifolia	laurel clock vine
Tipuana tipu	rosewood, tipuana tree
Tradescantia fluminensis	wandering Jew
Triadica sebifera	Chinese tallow tree
Trianoptiles solitaria	subterranean Cape sedge
Vachellia karroo	Karroo thorn
Vachellia nilotica	prickly acacia
Zantedeschia aethiopica	calla lily, arum lily

Other

Bufo marinus	cane toad

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