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Climate change impacts on plant diseases affecting New Zealand horticulture

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Purpose and approach of the study

Plant diseases, which are a major constraint on New Zealand's horticultural production, are likely to be affected by temperature and rainfall changes resulting from global climate warming. No critical evaluation has yet been made of the impacts of climate change on horticultural plant diseases in New Zealand. This study undertook a quantitative analysis for key diseases affecting major horticultural crop sectors using disease risk models that are in use within those sectors. The purpose was to ascertain likely changes in regional disease losses and disease control requirements arising from climate change, to allow horticultural industry sectors to carry out more robust future planning.

Predicted changes in temperature and rainfall in New Zealand for the years 2040 and 2090 were reported by the Ministry for the Environment (MfE) in 2008, based on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment in 2007. These predictions were used as inputs into disease risk models for apple black spot, grapevine downy mildew, onion downy mildew and kiwifruit bacterial canker (Psa). Outputs from the models were used to interpret the likely magnitude of changes in disease risk in key regions and to estimate climate change impacts on disease losses and disease control.

Current and future climate data

Each model was adapted to run using nine-year current weather datasets that included hourly records of surface wetness, temperature and rainfall. For future weather datasets, the current weather datasets were adjusted according to predicted changes in temperature and rainfall. For some of the models the climate change rainfall adjustments were made to monthly summaries of hourly data. The models were first run with the current weather datasets, then with the future weather datasets, and the disease risk index values were compared statistically. This approach allowed both individual and combined effects of changes in temperature and rainfall on disease risk to be interpreted.

The predicted changes in temperature and rainfall used for this study were the upper and lower limit predictions from the 12 climate models used for New Zealand predictions in the 2008 MfE report. Upper and lower limits were used, rather than the more often quoted average values from these models, because, for rainfall, some climate model predictions indicated increased rainfall and some indicated decreased rainfall. Use of model averages could therefore suggest little or no change in rainfall and thereby obscure important potential outcomes predicted by some of the climate change analyses.

Each risk model was run for the seasonal period when disease develops in the crop of interest. For all diseases this was spring and summer, except for kiwifruit Psa, which was examined for four seasons.

Predicted changes in temperature and rainfall

Predicted temperature changes were relatively uniform across the regions. Lower limit temperature predictions were for a less than 1^{o}C increase. Lower limit rainfall predictions for North Island areas were a substantial decrease during spring and a lesser decrease during summer. For South Island areas, rainfall was predicted to decrease slightly in spring and summer, except for Central Otago, where a large rainfall increase was predicted in spring and a large rainfall decrease in summer.

Upper limit temperature predictions were for a 3-6^{o}C increase by 2090, depending on region and season. Rainfall predictions for North Island areas were for little change during spring but a substantial increase during summer, particularly for Gisborne and Hawke’s Bay. For South Island areas, rainfall was predicted to increase a little during spring and more during summer, except for Central Otago, where substantial rainfall increases were predicted for spring and summer.

Predicted changes in apple black spot risk

Climate change impacts on apple black spot were examined for Hawke’s Bay, Nelson and Central Otago. The greater the predicted increase in temperature, the greater was the increase in black spot risk within a given region. However, for predicted temperature changes alone, the increase in black spot risk compared with that in the current climate was statistically non-significant for all regions, even for the greatest predicted temperature increase (upper temperature limit for 2090).

Black spot incidence resulting from climate change was also predicted using a published regression equation linking infection risk, fungicide use and disease incidence. The only significant effect for temperature-alone predictions was for the 2090 upper temperature limit for Nelson, where a significant increase in black spot incidence compared with that in the current climate was predicted.

Predicted effects of rainfall changes on infection risk were more important, although not particularly great. The following scenarios did predict statistically significant changes in black spot infection risk:

- Decreased black spot risk for the Hawke's Bay drying trend for the 2090 lower limit
- Increased black spot risk for the Hawke's Bay increased summer rainfall trend for the 2090 upper limit
- Increased black spot risk for the Nelson increased rainfall trend for the 2040 and 2090 upper limits
- Increased black spot risk for the Central Otago increased rainfall trend for the 2040 and 2090 upper limits.

The current regional ranking of black spot infection risk and black spot disease incidence (Nelson>Hawke's Bay>Central Otago) would still remain under all climate change scenarios, although risk would tend to increase in each region under the upper limit predictions by 2090. Under the upper limit prediction, by 2090 Central Otago would have black spot risk similar to that in Hawke's Bay under current climatic conditions, but not as great as Nelson under current climatic conditions. The greatest increase in black spot risk would occur in Nelson for the upper limit prediction by 2090, where a 4.4% increase in infection risk would occur. However, this is likely to require only a small change to current fungicide use for black spot control, assuming fungicides are still available by 2090.

Predicted changes in grapevine downy mildew risk

Potential changes in grapevine downy mildew risk were examined for Gisborne, Hawke’s Bay, Marlborough, Canterbury and Central Otago. The analyses showed that climate change would have only a minor impact on infection risk. The magnitude of predicted changes in the number of spring and summer infection periods would not cause substantial changes in vineyard downy mildew control programmes, which currently involve preventative fungicide sprays.

The greatest potential effect was identified for Canterbury and Central Otago under the upper limit temperature plus rainfall predictions by 2090. During spring, under this scenario, the numbers of downy mildew infection periods would increase to become similar to the numbers that occur in Gisborne and Hawke's Bay under current climatic conditions. However, in

Gisborne and Hawke's Bay at the current time, downy mildew is of only sporadic importance, although regular fungicide spraying for its control does occur.

Predicted changes in onion downy mildew risk

Onion downy mildew risk was examined for Auckland and Canterbury. The risk model, DOWNCAST, which is used by horticultural consultants to monitor seasonal risk of downy mildew, was adapted to investigate effects of climate change on downy mildew risk in Auckland and Canterbury.

Onion downy mildew development is critically dependent on high relative humidity during dewy nights in spring. Because surface wetness and relative humidity were not available in climate change predictions, it was not possible to predict the effects of future climate on downy mildew risk, except in relation to temperature. No relationships between rainfall and downy mildew risk in the current weather datasets were found, so it was not possible to use future rainfall predictions to analyse changes in downy mildew risk.

For temperature alone, even the most extreme future temperature prediction (upper limit for 2090) indicated very little change in number of downy mildew sporulation-infection events per month between current and future temperatures. It was therefore concluded that, although temperature changes will have little effect on downy mildew risk, adequate analysis of future risk was not possible by the approach used in this study.

In order to investigate climate change effects on onion downy mildew risk, it would be necessary to simulate future hourly relative humidity and surface wetness data. However, it may be difficult to have confidence that such synthesised datasets would accurately represent future weather patterns.

Predicted changes in kiwifruit bacterial canker (Psa) risk

Infection risk of bacterial canker of kiwifruit, caused by *Pseudomonas syringae* pv. *actinidiae* (Psa) was assessed for the main kiwifruit growing regions of Northland, Bay of Plenty and Nelson. All months of the year were examined using a newly validated risk model for Psa. Only the Bay of Plenty is currently affected by Psa, as the disease has not yet spread to Northland or Nelson. Therefore the study’s findings in relation to Northland and Nelson are entirely theoretical.

Analysis of current climatic conditions ranked Northland>Bay of Plenty>Nelson for annual Psa infection risk. Although variation in risk among regions and months was statistically significant, the regional rankings tended to be consistent for all months of the year. The lower risk of Psa infection for Nelson, compared with Northland or Bay of Plenty, under the current climate also held true for most predictions of future climate.

The temperature increase of 4.1 to 5.8°C predicted by 2090 for the upper limit climate change prediction (assuming current rainfall) would cause a significant decrease in Psa risk for Northland and Bay of Plenty, but no change for Nelson. This temperature effect was caused by increased frequency of temperatures above the optimum for Psa infection (15°C), especially in more northern regions, leading to decreased infection risk from late spring to early autumn.

Rainfall predictions by 2090 are that the lower limit drying trend will be greatest for the northern North Island. This would cause a significant decrease in Psa infection risk for Bay of Plenty and Northland, but no significant change for Nelson. The upper limit trend for increased rainfall by 2090 gave no significant change in Psa risk compared with that in the current climate for any region. For this upper limit prediction, the combined effects of temperature and rainfall changes tended to cancel each other. Increased temperature tended to decrease risk, whereas the increased rainfall tended to increase risk.

Understanding how interactions between temperature and rainfall affect Psa damage to kiwifruit vines in different regions requires greater epidemiological knowledge than is currently available about which months are critical for infection and disease development. When such knowledge is available, more robust planning of the kiwifruit industry's strategy to cope with the impact of Psa will be possible. Better epidemiological understanding will also allow the effect of weather variability within the current climate to be understood, e.g. the degree of reduction in Psa risk resulting from a hot and dry season within a given region.

Changing weather conditions in relation to climate change, and also weather variability in the current climate, will affect kiwifruit growers' ability to manage Psa in cultivars of differing susceptibility. The cultivar 'Hort16A' is the most susceptible to Psa and deployment of any less susceptible cultivar in conjunction with regions or seasons with less favourable weather conditions, e.g. Nelson (should Psa spread there), would improve the ability of kiwifruit growers to manage the disease.

This analysis has improved our understanding of Psa infection risk in relation to climatic trends within New Zealand. Further benefits would accrue from a global climatic assessment of Psa risk in kiwifruit production areas worldwide.

Implications of climate change for horticultural disease risk

This analysis suggests relatively minor impacts on horticultural diseases as a result of the changes in climate predicted by the IPCC 2007 assessment. Only the most extreme climate change prediction (upper limit by 2090) is likely to cause a noticeable increase in risk for the diseases examined. Central Otago is likely to experience the greatest relative increase in disease risk, which, for apple black spot and grapevine downy mildew, may result in risks similar to that currently experienced in eastern North Island areas at the present time. However, such changes would have only a minor impact on disease control programmes, assuming that fungicides are still available for disease control in the future. The time frame for these changes is long in relation to the rate at which horticultural industries adapt to changing regional production and market factors, e.g. new cultivars and new production systems.

Given that future rainfall variability is expected to increase more in areas with an increase in average rainfall (more frequent extreme events), the major impact of climate change is likely to be greater fluctuation in disease from year to year, rather than increase in average disease risk in a given region. If some seasons have exceptionally wetter conditions than currently occur, increases in disease could be greater than estimated in this analysis.

The predominant cultivars for any crop that will be planted in 2090, or even 2040, cannot be identified at present. As the climate change time frame is well within the time frame for breeding new crop cultivars, if fruit crop breeders were able to focus on developing cultivars with lower disease susceptibility, rather than restricting efforts to fruit quality, the impact climate change may have on disease risk could be greatly reduced.

Introduction

Current impact of plant diseases on New Zealand horticulture

In 2011, horticultural exports were valued at NZ$3.5B, with wine (NZ$1.1B), kiwifruit (NZ$0.9B) and apples (NZ$0.4B) being the largest components (Aitken & Hewett 2011). The value of horticultural exports has approximately doubled over the last 10 years and several industry sectors are making plans for further substantial growth during the next 10-20 years.

All New Zealand's horticultural export industries suffer economic losses as a result of plant diseases. In relation to horticultural production costs, disease costs have been estimated to be NZ$35-70M per year (Plant & Food Research, unpublished). However, on-orchard costs are a very small proportion of the overall cost of diseases to New Zealand. Diseases are regionally and seasonally variable. In high disease risk years, costs arise from losses in crop yield and quality, postharvest grading and re-packing of diseased produce, losses during storage and shipping and market uncertainty costs associated with product spoilage. The use of disease control chemicals, biological disease controls and cultural crop management practices to prevent diseases typically represent 5-15% of production costs. Fungicide and bactericide chemical residues on harvested fruits and in wine create further market access risks if they exceed residue limits set by overseas governments or importing supermarkets. In some cases, overseas importers set arbitrary restrictions on agricultural chemicals without objective reference to government policies or scientific information (Kempthorne 2007). Costs associated with plant diseases are an important economic factor affecting the viability of horticultural production in New Zealand.

In New Zealand's wet maritime climate, fungal and bacterial plant pathogens are relatively more important than in many overseas temperate production areas, where continental climates often provide relatively dry growing conditions. Projected changes in New Zealand's climate as a result of global warning could either increase or decrease disease prevalence, depending on several interacting factors. Because diseases are more prevalent in high rainfall areas, understanding changes in regional and seasonal patterns of rainfall is crucial. The effect of temperature on diseases varies with specific crops and pathogens. While warmer temperatures tend to increase rates of pathogen development, hot and dry conditions tend to reduce disease prevalence. Warmer temperatures affect the seasonality of crop growth and the period when crops are susceptible to disease. Therefore, a full understanding of changes in the risk to horticulture from plant diseases as a result of climate change would require a careful analysis of interactions between weather patterns affecting plant pathogens directly and indirect effects on crop development.

Impacts of climate change on horticulture

General impacts of projected increases in global temperature on New Zealand regions have been reported by the Ministry for the Environment (MfE 2008). That assessment was based on changes predicted by the National Institute of Water and Atmosphere (NIWA Client Report WLG2007/62) for the years 2040 and 2090, using an interpretation of the 2007 Fourth Intergovernmental Panel on Climate Change (IPCC) report (Pachauri & Reisinger 2007). Current climate change methodology summarises the long-term global warming trend in terms of 20-year averages of mean global temperature from 1990 to 2040 and 2090. This trend has been regionally interpreted by "downscaling", using statistical models that provide regional spatial resolution (30 km) and seasonal time resolution (3 months).

The value of New Zealand horticulture in 50-100 years' time is difficult to ascertain. Horticulture has approximately doubled in value over the last 10 years and some industry sectors have set substantial aspirational goals out to about 2020. It is likely that the value of horticultural exports will continue to increase well beyond that, possibly reaching NZ$10B by 2040. Horticulture will continue to be of strategic importance to New Zealand, as, in addition to export revenue, it contributes to food supply and provides important economic and social diversity within regional agricultural systems.

Analysis of climate change impacts on New Zealand horticulture have not yet been carried out. Whereas for pastoral agriculture, projections of future temperature, rainfall and droughts across New Zealand regions have been interpreted for their economic impacts on dairy, sheep and beef production (MAF 2007), no similar study has been made for horticulture. Specific horticultural predictions have been made elsewhere. For example, in Australia, Landlearn (2012) reported impacts of climate change in NSW on wine grapes, including reduced grape production, earlier harvesting because of warmer temperature, temperatures becoming too warm to produce balanced wines, severe leaf and bunch stress, increased crop water needs and increased pest and disease activity.

Purpose and approach of this study

This study attempts the first quantitative analysis of the effects of climate change on plant diseases in New Zealand. It seeks to provide strategic information to horticultural industry sectors and regional councils for planning and risk mitigation. Because plant disease development is the result of interacting effects of temperature, moisture and crop growth, the impacts of climate are best determined by quantitative modelling. In this study New Zealand climate change projections were integrated with existing disease risk models, which had been validated under New Zealand conditions, and current horticultural cropping practices to predict the effects of climate change on regional and seasonal risk for selected diseases of key crops. The selected crops and diseases (pathosystems) were chosen to represent a diverse range of plant pathogens, crops and regions. The selected diseases of apples, grapes, onions and kiwifruit are ones for which existing disease risk models are available and, except for grapes, validated under New Zealand conditions. Simulations of regional disease risk were first carried out using current weather datasets. The current datasets were modified according to published climate change predictions (MfE 2008) to produce future weather datasets and the models were then rerun. The results were interpreted to identify likely impacts of climate change, for discussion with horticultural industry sectors.

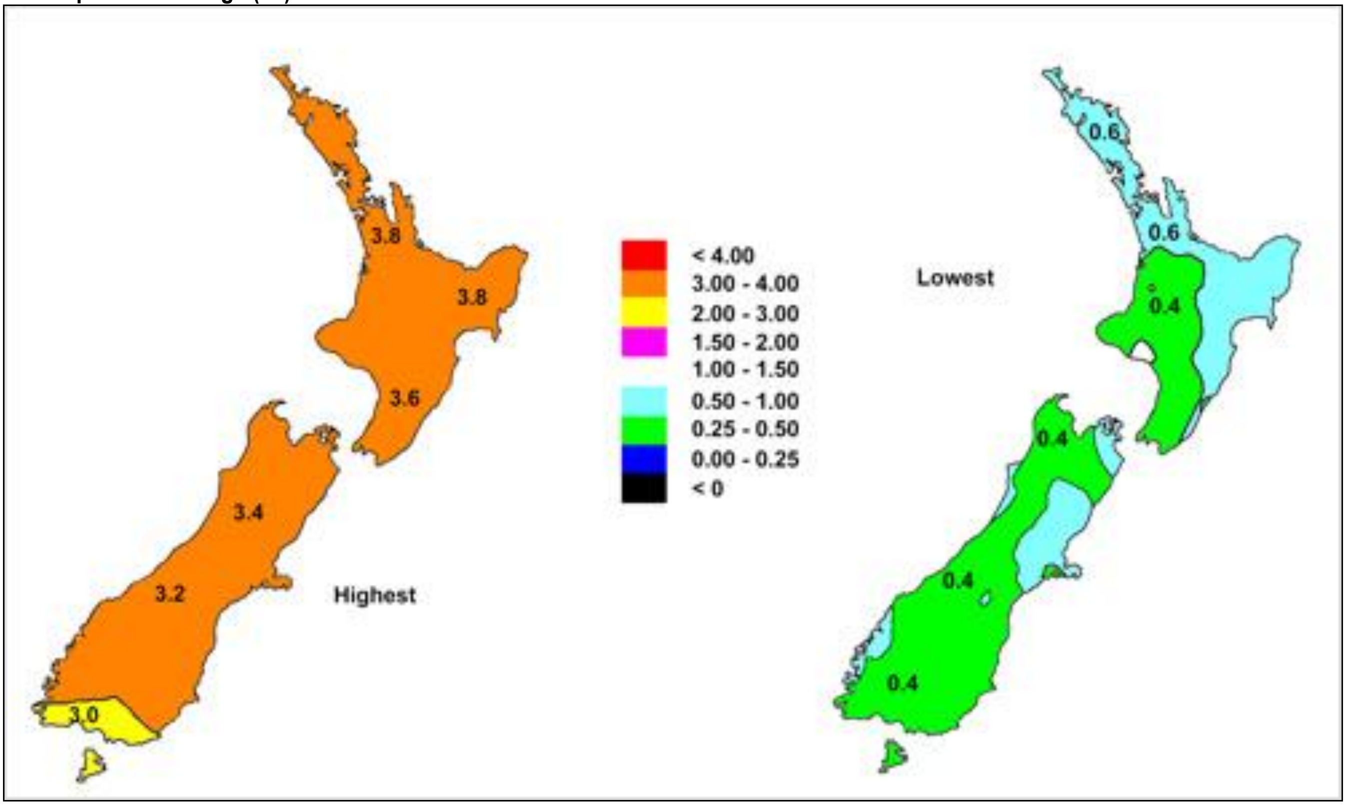
Climate change predictions for New Zealand

Global climate change projections by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report in 2007 have been interpreted for New Zealand regions by the National Institute of Water and Atmosphere (NIWA) and made available in the Ministry for the Environment report, "Climate change effects and impacts assessment" (MfE 2008). New Zealand regional projections of change in temperature and percentage change in precipitation were derived from statistical downscaling of 12 global climate change models, based mainly on the A1B emissions scenario. Different emission scenarios and different global model characteristics give a range of temperature predictions and the projections are reported as averages and upper and lower limits for the 12 models. The projections are 20-year averages for 2040 (2030-2049), which is 50 years after 1990 and for 2090 (2090-2099), which is 100 years after 1990.

It is estimated that New Zealand will experience an average 1^{o}C rise in temperature by 2040 and a 2^{o}C rise by 2090. Lower and upper limits across New Zealand from the models range from 0.2 to 2.0^{o}C by 2040 and 0.7-5.1^{o}C by 2090. There is expected to be increased frequency of westerly winds during winter and spring, bringing higher rainfall to western parts of the North and South Islands and lower rainfall to eastern and northern regions. Westerly wind frequency is expected to decrease during summer and autumn, bringing lower rainfall to the west of the North Island and higher rainfall to Gisborne and Hawke's Bay. Average predicted changes in temperature and precipitation indicate that most of New Zealand's eastern horticultural regions will become warmer and drier during the 21st century. However, considering lower and upper limit prediction of the 12 models (Figure 1), there are widely differing trends contributing to the average, particularly for precipitation (herein after referred to as rainfall). Because of the importance of rainfall to plant disease risk, this study examined lower and upper limits of the 12 models, rather than averages.

Figure 1: New Zealand annual mean temperature (A) and rainfall (B) change (1980s to 2080s), showing upper limit (left) and lower limit (right) predictions (Source: Mullan & Gentry 2009). C: Current mean annual New Zealand temperature and rainfall (Source: NIWA 2003).

A. Temperature change (°C)



B. Rainfall change (%)

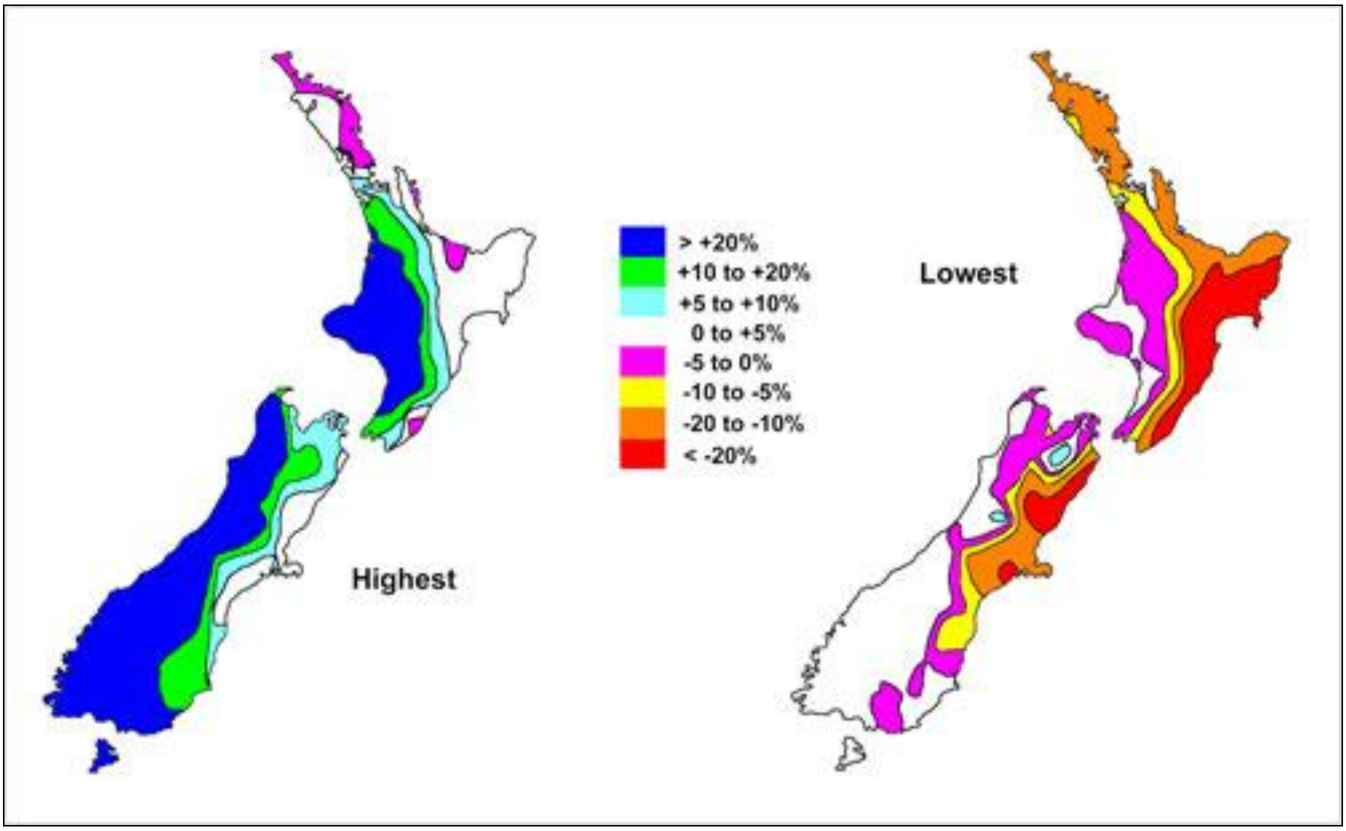
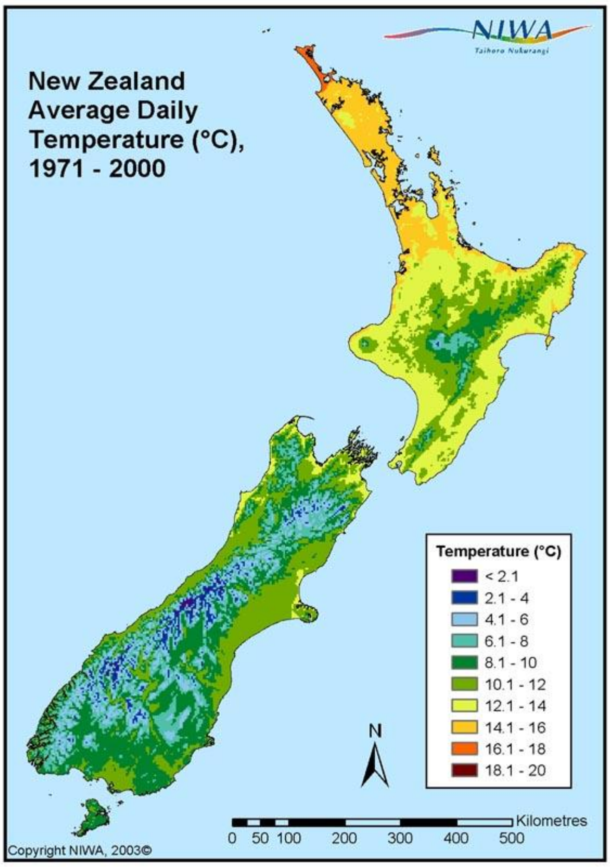
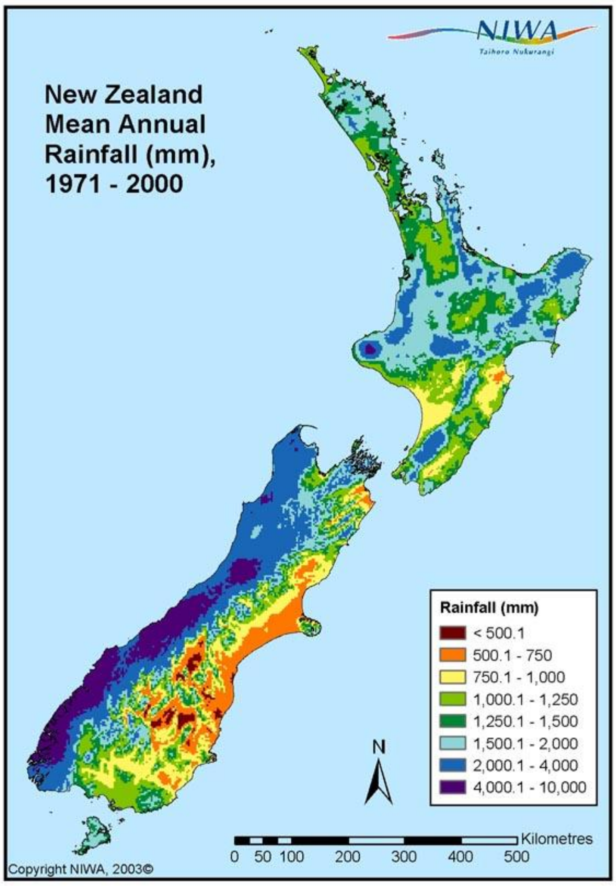


Figure 1: Continued

C. Current climate





Selected horticultural pathosystems

Apple black spot (scab) caused by *Venturia inaequalis* (Jones & Aldwinkle 1990). Apples are a major export crop for the Hawke's Bay and Nelson regions and are an important component of horticultural production in Central Otago. This study examined likely impacts of increased temperatures and drier or wetter conditions in Hawke's Bay, Nelson and Central Otago to help the apple industry to plan adaptation strategies. Such strategies could include shifting regional emphasis of apple production, greater emphasis on disease resistance in cultivar breeding programmes, non-fungicide disease control, or developing tree training systems that reduce disease risk.

Grapevine downy mildew caused by *Plasmopara viticola* (Pearson & Goheen 1988). An overseas disease risk model for downy mildew infection was used to determine whether the predicted long-term trend for drier conditions in Gisborne, Hawke's Bay and Marlborough could decrease the risk of downy mildew in wine grapes and whether wetter conditions in Central Otago could increase the risk. The aim was to assist the wine industry with decisions about selection of downy mildew-resistant varietal clones, the development of new fungicide registrations for downy mildew control, the need for fungicide resistance monitoring in *P. viticola* and the need for computer-based disease prediction systems to assist fungicide management against downy mildew.

Onion downy mildew caused by *Peronospora destructor* (Schwartz 1995). Understanding the likely impacts of climate change on downy mildew prevalence would allow the onion industry to plan future production areas and cultivar deployment to minimise reliance on fungicides. In this study, the effects of predicted changes in temperature were analysed and interpreted for downy mildew. However, a problem was encountered that prevented rainfall predictions being used for this disease. Onion downy mildew develops during spring when high relative humidity (RH) leads to overnight dew on onion leaves. Because RH and surface wetness were not available in climate change predictions, and because no relationships could be found between rainfall and downy mildew risk, it was not possible to analyse the effects of future rainfall patterns on downy mildew risk.

Kiwifruit bacterial canker (Psa) caused by *Pseudomonas syringae* pv. *actinidiae*. After this study was initiated, Psa arrived and established in New Zealand (Everett et al. 2011), with a devastating impact on the kiwifruit industry. This disease was included in the study because it is an example of a bacterial pathogen with high weather dependence, because a new disease risk model was available (Beresford et al. 2012) and because knowledge about regional and seasonal risk of Psa will be of the utmost importance for the kiwifruit industry to develop disease control strategies, if it should spread to all New Zealand's kiwifruit growing regions.

Seasonal and regional importance of the selected diseases

The regional distribution of the selected crops represents New Zealand's main horticultural production regions (Table 1).

Table 1: Regional planted crop areas (ha in 2007; Aitken & Hewett 2011) for the horticultural pathosystems for which climate change analyses were carried out in this study. National totals include production regions not shown in the table.

	Crop			
Region	**Apples**	**Wine grapes**	**Onions**	**Kiwifruit**
Northland				634
Auckland/Waikato			3,008	
Bay of Plenty				10,249
Gisborne		1,812		
Hawke's Bay	5,206	4,930		
Tasman/Nelson	2,438			614
Marlborough		17,169		
Canterbury		1683	686	
Central Otago	472	1642		
National total	**9,247**	**29,616**	**4,594**	**13,250**

The range of months in any given year when weather conditions, as depicted in the disease risk models, can affect the disease outcome, are summarised in Table 2 and explained under each disease below.

Table 2: Seasonal period over which disease risk for each of the selected pathosystems is critically influenced by weather conditions.

Pathosystem	Season	Months
Apple black spot	Spring-early summer	September-December
Grape downy mildew	Spring-mid summer	September-January
Onion downy mildew	Spring-early summer	September-December
Kiwifruit Psa	Four seasons	January-December

Importance of apple black spot

A single black spot lesion on an apple fruit renders it unsuitable for sale. The serious economic impact black spot has on the apple industry arises from the high degree of disease control required to keep 95-98% of fruit disease free. Apple growers make an average of 16 fungicide applications each season for black spot control (Beresford & Manktelow 1994), at a cost of NZ$1,000-1,500 per hectare. This represents a national cost of NZ$10-15M for imported fungicides alone and represents about 10% of overall apple production costs. The economic impacts of black spot arise from direct fruit losses, increased production costs associated with grading out diseased fruit and market access risks from fungicide residues. The development of resistance in *V. inaequalis* to fungicides (Beresford et al. 2012) is an additional risk that led to lower standards of disease control and increased risk of fungicide residues on harvested fruit.

This study focused on the apple production regions of Hawke's Bay, Nelson and Otago. Climate change predictions for spring were applied from September through November and those for summer were applied to December.

The critical risk period for black spot development is the primary infection season between apple budburst in September and mid-fruit development in December (Table 2). During this time, ascospores are released from fruiting bodies (pseudothecia) on the orchard floor (Brook 1976; MacHardy 1996). After December, ascospores become depleted and apple leaves and fruit become relatively resistant to infection. The primary infection season is when most fungicides are applied to apples and if primary infection is effectively controlled, economic losses from black spot are generally small. The two critical weather variables for black spot infection are wetness duration and temperature. Rainfall is required to release ascospores, but the amount of rainfall does not directly influence the severity of disease; rather it is the duration of leaf and fruit wetness that is important.

Importance of grapevine downy mildew

Downy mildew is the most important disease of wine grapes in some overseas wine production areas (Madden et al. 2000), where 4–8 fungicide applications per season are required for its control. *P. viticola* overwinters on the ground beneath grapevines as oospores, which develop in fallen grape leaves from the previous season. Primary infection of the new season’s leaves and fruit is by zoospores that are produced when oospores germinate and splashed up to the canopy. This can occur any time between budbreak in early spring and fruit ripening in late summer (Table 2). Overseas, oospores are the source of primary infection that causes devastating early-season downy mildew epidemics. In New Zealand, downy mildew has historically been unimportant in South Island grape-growing regions and of only sporadic importance in North Island regions. However, an increase in severity in Hawke's Bay, Gisborne and Auckland during recent wet seasons has caused concern about economic losses caused by downy mildew. In response to these increases, New Zealand Winegrowers funded a study (project NZW 11-112) to investigate the occurrence of the overwintering oospore stage of *P. viticola*, which had previously not been found in New Zealand. The presence of oospores was confirmed in vineyards in Auckland, Hawke's Bay and Marlborough (Wood et al. 2012).

If weather conditions suitable for infection occur during spring, there is greater potential for damage to the crop than if infection is initiated during summer. This study examined downy mildew infection risk in Gisborne, Hawke's Bay, Marlborough, Canterbury and Central Otago. Spring and summer seasons were examined separately. Climate change predictions for spring were applied to September, October and November and for summer to December January and February.

Downy mildew risk in these regions currently is ranked Gisborne>Hawke’s Bay> Marlborough>Canterbury>Central Otago.

Importance of onion downy mildew

Downy mildew can be responsible for large losses in onion production in some years in North Island growing areas. Losses arise when damage to foliage leads to small size and poor storage quality of onion bulbs (Chupp & Sherf 1960). Seasonal disease severity depends on weather conditions and locality. Spring conditions with anticyclonic weather patterns that result in heavy dew formation at night are particularly favourable for rapid disease development. Management of onion downy mildew in New Zealand involves applications of protective fungicides at 7 to 10-day intervals during the growing season, with additional applications of curative (systemic) fungicides when disease risk is perceived to be high (Wright 1992). Downy mildew is the reason that onions have the highest fungicide loading (kg of active ingredient/ha) for any crop in New Zealand (Wright et al. 2002, Manktelow et al. 2005).

Primary downy mildew infection of onion crops in spring arises from sporangia produced on volunteer onion plants from the previous season’s crop. Onion crops in Auckland, Waikato and Manawatu are sown in late autumn and winter and are harvested during mid-late summer. Canterbury onion crops develop a few weeks later because of cooler temperatures and are harvested between late summer and early autumn. Growers apply weekly fungicide applications against downy mildew, particularly in North Island areas, from September or October until the crop begins to senesce before harvest in December or January.

This study examined downy mildew infection risk in Auckland (Pukekohe) and Canterbury (Lincoln) over the four critical months when weather conditions affect downy mildew development (Whiteman & Beresford 1988): September, October, November and December (Table 2). Climate change predictions for spring were applied to current weather datasets from September through November and those for summer were applied in December.

Importance of kiwifruit bacterial canker (Psa)

Bacterial canker of kiwifruit, caused by the virulent strain of *Pseudomonas syringae pv. actinidiae* (Psa or Psa-V), was first recorded in the Bay of Plenty in November 2010 (Everett et al. 2011). The rapid spread of Psa and the severe damage it has caused have had a dire impact New Zealand's kiwifruit industry. Bay of Plenty is New Zealand's principal kiwifruit region (Table 1), and has been most affected by Psa. The disease has been detected in some orchards in Franklin and Waikato, but has not yet spread to Northland or Nelson.

Gold-fleshed kiwifruit ('Hort16A') has been the cultivar most severely affected by Psa. At the time Psa arrived, 'Hort16A' was the most profitable component of the industry, accounting for 21% of export volume, but 33% of value (Greer & Saunders 2012). Financial returns from 'Hort16A' were double those of the other major cultivar, 'Hayward' (MAF 2011). 'Hayward' (79% of export volume) is also affected by Psa, but appears less susceptible than 'Hort16A', as do the newer cultivars 'ZESY002' (commonly known as Gold3 or G3) and 'ZESH004' (commonly known as Green14 or G14) that are currently being evaluated. Greer & Saunders (2012) estimated that over a 15-year period, Psa will cost the New Zealand kiwifruit industry $740 to $885 million through its effect on net industry returns and delays in industry development.

Psa damage to kiwifruit vines arises from stem cankers, shoot dieback, vascular collapse, wilting and eventual vine death. Although fruit are not directly infected, damage to the vine structure from both disease and pruning of diseased material prevents development of a marketable crop. Major production losses have resulted from removal of infected vines, and even whole orchards, in the hope of slowing the spread the disease. Psa bacteria are spread by wind-blown rain, and by movement of contaminated plant debris and soil (Everett 2012). Psa also causes necrotic leaf spots, which are often the first sign that an orchard has become infected. Leaf spotting has little direct impact on the orchard, but may contribute bacterial inoculum to subsequent wood infection.

Research knowledge and disease management experience on Psa has come from New Zealand, as well as Italy and France, where the disease has caused severe damaged since about 2008. A weather-based infection risk model was developed by Plant & Food Research (Beresford et al. 2011) and has been made available within New Zealand on the Kiwifruit Vine Health website by NIWA. The model is used with weather forecast data to predict periods of low or high infection risk . This helps growers to make decisions about timing of orchard activities to minimise bacterial spread, and about the best time to apply protective chemicals to prevent infection.

Many aspects of Psa epidemiology are not yet understood. New disease symptoms develop rapidly during late winter and spring when new cankers and shoot wilting appear, but it is not known whether this infection is established during the previous cropping year, during the previous leaf fall period, during winter as a result of pruning, or whether it arises anew during late winter and spring. It is known that hot and dry summer weather slows the progress of the disease, but the degree to which drier or wetter New Zealand summers might mediate Psa development within orchards has not been quantified. It is known that the incubation period between Psa infection and appearance of disease symptoms is 1-2 weeks for leaf spots, but for woody vine tissues the incubation period is not known. Knowledge of this is crucial for understanding factors that control disease development in orchards, for predicting disease and for the effective deployment of disease control measures.

This study used the Plant & Food Research Psa risk model to examine regional infection risk in New Zealand in relation to current and future climate. Three regions were examined, Northland, Bay of Plenty and Nelson, which span the latitude range of kiwifruit growing in New Zealand. In the absence of detailed knowledge about the critical months for Psa infection, all months of the year were examined.

Influence of weather on plant diseases

The most important environmental factor affecting fungal and bacterial plant diseases is availability of free water for infection and spread of the pathogenic organisms. Most fungal pathogens require free water to infect their host plants. Rainfall is often required for dispersal of fungal spores, although some fungal spore types are wind dispersed under dry conditions. For plant pathogenic bacteria, free water is required for multiplication, infection and dispersal. Although areas with higher rainfall generally have higher disease risk, the weather variable that best represents availability of water for plant disease development is the duration of surface wetness. Wetness is the key variable in most weather-based plant disease prediction models, including those used in this study.

The powdery mildews are an important group of fungal plant pathogens with less dependence on free water for infection than other fungi, and they tend to be inhibited by heavy rainfall. Very few powdery mildew disease risk models have been developed and there is none that utilises a negative association between rainfall and disease development. Therefore examination of powdery mildew risk in relation to climate change rainfall predictions would not have been useful and powdery mildews were therefore not examined in this study.

The rainfall variable that is often highly correlated with plant disease development is rainfall frequency (e.g. number of days per month with >1 mm rainfall), rather than rainfall amount (mm). This is important in relation to climate change studies, because published climate change data (MfE 2008) are usually amount rather than frequency of rainfall. For some of the pathosystems in this study, predicted changes in rainfall amount were interpreted as changes in rainfall frequency. Although this was an approximation, it did allow useful inferences to be made about the likely effects of rainfall changes on the selected pathosystems.

Temperature affects the rate of disease development. Many fungal and bacterial pathogens have temperature optima between 15 and 20^{o}C. Below the optimum, increasing temperature increases development rate, whereas above the optimum, increasing temperature decreases development rate. In temperate climates, such as New Zealand’s, field temperatures during spring, when many crop disease epidemics begin, are most often sub-optimal. Therefore increased average temperature would tend to increase disease risk.

Developing climate change datasets

General approach

For each selected pathosystem, a weather station that recorded variables required to run the associated disease risk model was chosen at one key locality in each region. Nine-year records of archived weather data, termed **current weather datasets**, were used with the disease risk models to generate current disease risk index values. Each risk model was run for the months when weather has the greatest influence on the disease outcome of the crop (Table 2). The current weather datasets were then modified according to climate change predictions (lower and upper limits for 2040 and 2090) to generate **future weather datasets**. The models were then run to generate future disease risk index values. The current and future mean risk index values were then compared statistically using ANOVA and the nine replicate years to determine whether climate change would produce a significant change in mean disease risk, based on variability within the current weather datasets.

Availability of weather data relevant to plant diseases

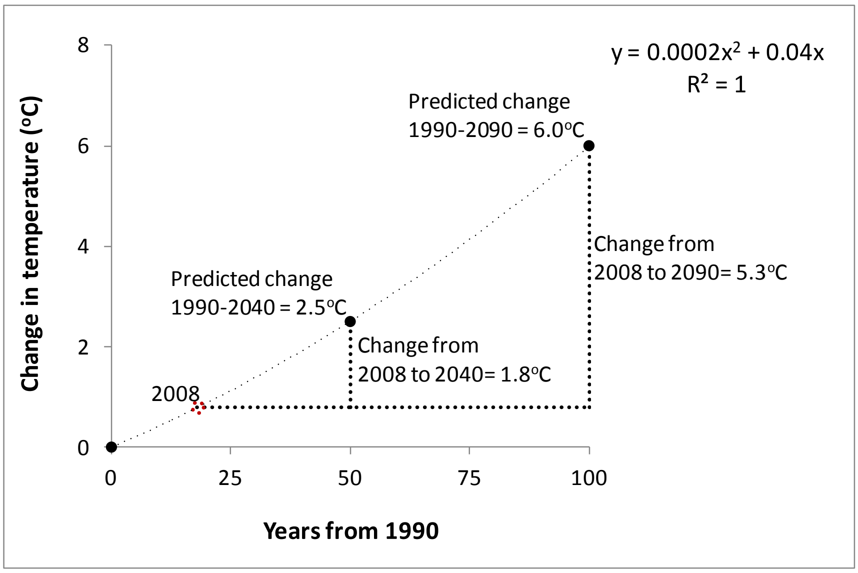
The principal variable restricting availability of suitable datasets was surface wetness. Although surface wetness can be recorded electronically (Gillespie & Kidd 1978), it is not recognised as a standard variable by the World Meteorological Organisation and has not been recorded historically at official New Zealand weather stations. An independent network of horticultural weather stations operated by Plant & Food Research and HortPlus (N.Z.) does record surface wetness for certain regional sites and those records were used for this study (Appendix 2). Surface wetness records were available for nine growing seasons (2003-2004 to 2011-2012).

The horticultural weather station network used Campbell Scientific Instruments (CSI) data loggers, with temperature monitored by Model 107 thermistor probes mounted 1.5 m above ground, in either a stacked plate thermometer screen or a Stevenson screen. Surface wetness was monitored with CSI Model 237 surface wetness sensors, 1.5 m above ground. Relative humidity was measured using either wet- and dry-bulb thermistors or a Vaisala temperature and humidity probe, also 1.5 m above ground. Rainfall was monitored using Texas instruments tipping bucket rain gauges with 0.1-mm sensitivity.

Adjusting weather datasets for climate change

The current weather datasets (2003-2012), which were 13 to 22 years after the 1990 starting point for climate change predictions, required corrections to the 1990-based 2040 and 2090 predictions to avoid over-estimating the degree of climate change and consequent disease risk. Corrections to temperature and rainfall for each region and season for lower and upper limits for 2040 and 2090 were made empirically by fitting quadratic functions to the 50- and 100-year change response and interpolating a value for 2008, which was the middle year of the current datasets (Figure 2 and Table 3). The corrected temperature or rainfall change value, rather than the value provided by MfE (2008), was used to generate future datasets. Corrected values for the predicted changes for all regions and seasons are given in Appendix 1 and are summarised for the key regions of interest in Tables 4 and 5.

A Temperature



B Precipitation

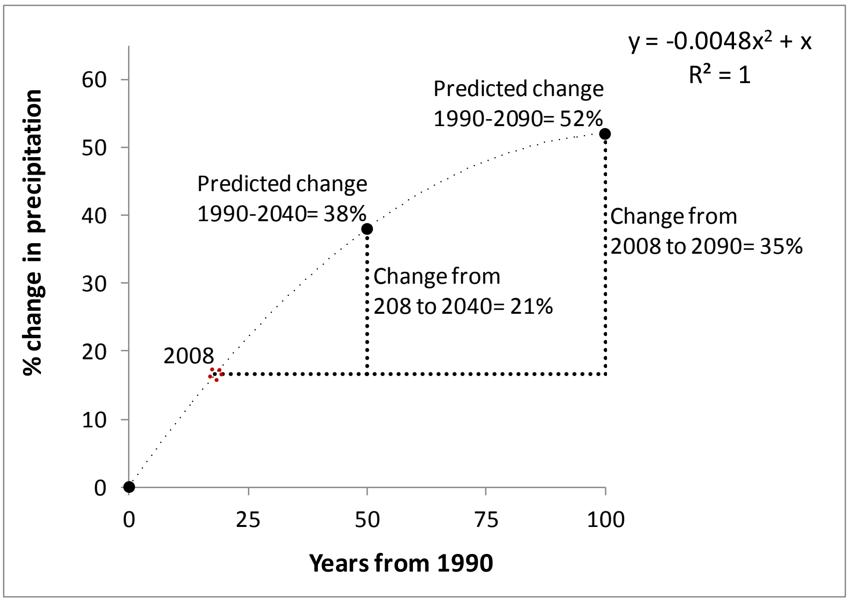


Figure 2: Method for correcting average climate change predictions to a starting date of 2008, the midpoint of the current datasets used in this study. The example shown is for Hawke's Bay, upper limit prediction for summer, showing predicted changes in temperature (A) and rainfall (B) and the correction for a starting date of 2008.

Table 3: Example of corrected temperature and rainfall changes from 2008 to 2040 and 2090. This example is for Hawke's Bay, upper limit prediction for summer. Predicted changes from 1990 (MfE 2008) are also shown for comparison. Similar corrections were calculated for all regions and seasons considered in the study (Appendix 1).

Region	Scenario	Predicted year and season		Temperature (°C) Change from 1990	Temperature (°C) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Hawke's Bay	Upper limit	2040	Summer	2.5	1.8	38	21
			Autumn	2.6	1.7	42	19
			Winter	2.2	1.2	–1	-1
			Spring	2	1.4	3	2
		2090	Summer	6	5.3	52	35
			Autumn	5.3	4.4	25	2
			Winter	5.1	4.1	–1	-1
			Spring	5.1	4.5	9	8

Table 4: Temperature change (°C) predictions (corrected for 2008) for regions and seasons of interest to this study for lower and upper limit predictions for 2040 and 2090 (derived from data in Appendix 1).

Key to temperature change colour codes					
0.0 – 0.9°C increase (yellow)	1.0 – 1.9°C increase (green)	2.0 – 2.9°C increase (light blue)	3.0 – 3.9°C increase (blue)	4.0 – 4.9°C increase (purple)	5.0 – 5.9°C increase (red)

Region		Lower limit Spring	Lower limit Summer	Upper limit Spring	Upper limit Summer
Northland	2040	0.1	0.2	1.4	1.9
	2090	0.4	0.7	4.7	5.8
Auckland	2040	0.1	0.2	1.4	1.8
	2090	0.4	0.7	4.6	5.7
Bay of Plenty	2040	0.0	0.2	1.4	1.8
	2090	0.3	0.7	4.4	5.5
Gisborne	2040	0.0	0.2	1.4	1.8
	2090	0.3	0.8	4.5	5.4
Hawke's Bay	2040	0.0	0.2	1.4	1.8
	2090	0.3	0.8	4.5	5.3
Nelson	2040	0.1	0.2	1.3	1.6
	2090	0.3	0.9	4.1	5.0
Marlborough	2040	0.1	0.2	1.3	1.4
	2090	0.3	0.9	4.3	4.9
Canterbury	2040	0.1	0.1	1.3	1.5
	2090	0.3	0.8	4.2	4.5
Central Otago	2040	0.0	0.1	1.2	1.5
	2090	0.5	0.8	3.7	3.9

Table 5: Rainfall change (%) predictions (corrected for 2008) for regions and seasons of interest to this study for lower and upper limit predictions for 2040 and 2090 (derived from data in Appendix 1).

Key to % rainfall change colour codes					
Much drier	**Slightly drier**	**Little change**	**Slightly wetter**	**Much wetter**	**Very much wetter**
20-39% decrease	10-19% decrease	0-9% decrease or increase	10-19% increase	20-39% increase	>40% increase

Region		**Lower limit**		**Upper limit**	
		Spring	**Summer**	**Spring**	**Summer**
Northland	2040	-12	-9	3	11
	2090	-27	-20	7	12
Auckland	2040	-10	-11	5	11
	2090	-25	-27	6	11
Bay of Plenty	2040	-12	-9	4	13
	2090	-26	-13	9	11
Gisborne	2040	-13	-15	2	18
	2090	-34	-27	6	26
Hawke's Bay	2040	-11	-19	2	21
	2090	-32	-32	8	35
Nelson	2040	-5	-8	6	14
	2090	-17	-7	16	17
Marlborough	2040	-4	-8	6	13
	2090	-15	-7	16	16
Canterbury	2040	-5	-9	6	12
	2090	-12	-11	22	15
Central Otago	2040	0	-10	14	12
	2090	18	-32	43	29

Temperature and rainfall adjustment to current weather datasets

To apply predicted temperature changes to future disease risk, hourly temperature values in current weather datasets were adjusted by the corrected 20-year average temperature change values for lower and upper limits for 2040 and 2090 (Table 4).

Hourly wetness data were used to calculate current disease risk indexes for each month in the current datasets. Because climate change predictions contain percentage change in rainfall amount and not surface wetness, wetness duration could not be simulated in future datasets. Simulation of effects of changes in rainfall on disease risk was done by regression analysis. Relationships were established between average disease risk per week or month and amount or frequency of rainfall for the current datasets. Predictions of future disease risk index values were then made using future rainfall predictions and the appropriate regression equation. This approach sometimes resulted in minor inconsistencies in the results if the disease risk–rainfall regression equation had a poor fit, especially if predicted disease risk was extrapolated outside the range of the rainfall variables in the current dataset.

Disease risk under current and future climate

APPLE BLACK SPOT

Black spot risk model

Seasonal risk of black spot infection is greatest during the spring ascospore release period, from September to December. Three factors that affect infection risk during this period have been modelled: 1) frequency of wet weather suitable for infection (MacHardy & Gadoury 1989; Beresford & Spink 1992), 2) seasonal availability of ascospores (Brook 1976; Gadoury & MacHardy 1982) and 3) susceptibility of apple tree leaf canopies to infection (Beresford et al. 2004). Of these three factors, the first is the most important and has been widely used in disease risk forecasting systems worldwide (MacHardy 1996).

This study used the wet weather infection risk model in use by the New Zealand apple industry since the early 1990s (Beresford & Spink 1992; Beresford et al. 2004). The model follows the widely used method of categorising infection risk according to duration of wet periods and the mean air temperature during each wet period (Table 6 and Figure 3).

Summarising black spot infection risk

Individual black spot infection periods (Marginal or greater) were calculated from hourly data in the current weather datasets and were summarised on a weekly basis as the percentage of the maximum potential infection risk per week, using the risk category numerical values in Table 6. Each hour during a wet period that exceeded the Marginal category was assigned the appropriate numerical value from 1 to 4 and the hourly numerical values were totalled for each week. Weekly black spot infection risk was expressed as a percentage of maximum potential weekly risk (risk category 4 x 24 hours x 7 days = 672). Black spot infection risk was summarised for the representative sites in the apple growing regions of Hawke's Bay (Havelock North), Nelson (Riwaka) and Central Otago (Clyde).

Table 6: Exponential functions describing number of hours of wetness duration (W) in relation to temperature (T) required to reach each of four severity categories of apple black spot infection risk (Beresford & Spink 1992).

Risk category	Wetness duration threshold (W)	Risk category numerical value
Marginal	$W = 6 + 103 * 0.735^T$ hours	1
Light	$W = 9 + 103 * 0.735^T$ hours	2
Moderate	$W = 12.4 + 137 * 0.735^T$ hours	3
Severe	$W = 19.1 + 202 * 0.735^T$ hours	4

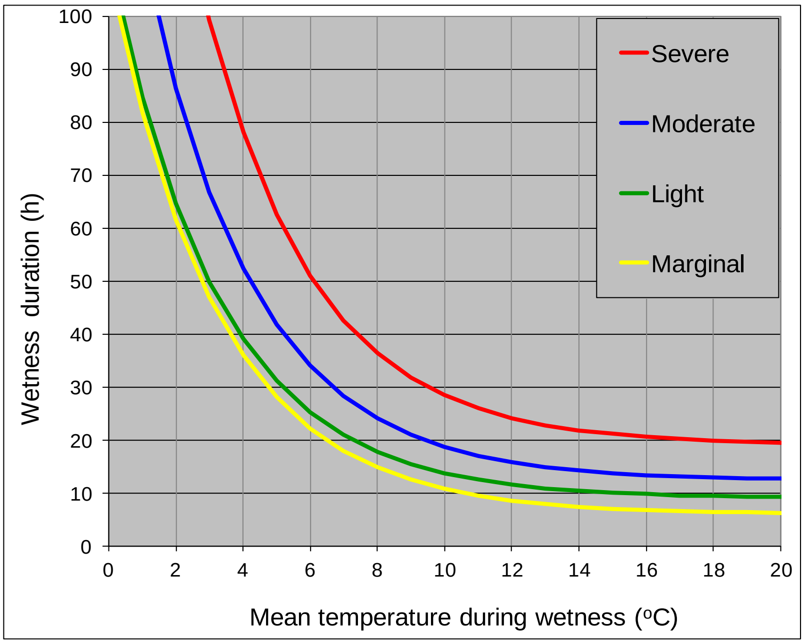


Figure 3: Thresholds for wetness duration required at different temperatures for each of four infection risk categories for apple black spot (Beresford & Spink 1992).

Rainfall adjustment to current weather datasets

In developing regression equations to link future rainfall changes to changes in black spot infection risk, poor correlations were found between rainfall amount and disease risk in the current datasets. However, significant correlations existed between weekly rainfall frequency (percentage of hours per week with rainfall) and weekly black spot infection risk (percentage of the maximum risk per week) (e.g. Figure 4). Regression equations between these variables were derived for current temperatures and lower and upper temperature limits for 2040 and 2090 for each region (Tables 7 and 8). Although the climate change predictions (Table 5) were for rainfall amount, they were assumed to represent percentage changes in rainfall frequency for this analysis.

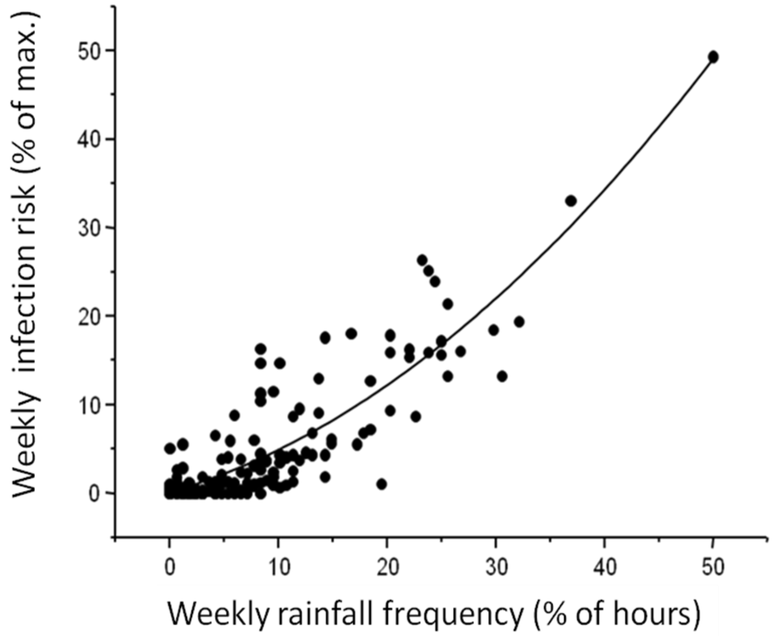


Figure. 4: Example relationship between weekly black spot infection risk (percentage of maximum risk) and weekly rainfall frequency (percentage of hours per week with ≥0.1 mm rainfall) for the Havelock North current weather dataset from 2003-2012 ($Y = 0.354X+0.0125X^2$; $R^2 = 0.84$; no intercept). Regression parameters were derived for each of three regions (Hawke's Bay, Nelson and Central Otago) for the current, 2040 and 2090 weather datasets and were used to estimate the effect of predicted future rainfall changes on black spot infection risk.

Table 7: Procedure to determine effects of predicted future rainfall on weekly percentage infection risk for apple black spot. Hourly temperature and wetness were used to determine weekly infection risk for the current and future temperature datasets. The regression between weekly infection risk and weekly rainfall frequency was used to adjust calculated infection risk for climate change rainfall predictions. This process was completed for each of three regions, Hawke's Bay, Nelson and Central Otago. The 13 scenario combinations (RH column) for each region are indicated by the following: C= current 2008-based weather data, 2040= 32 year prediction (from 2008), 2090= 82 year prediction, T= temperature, R= rainfall, L= lower limit and U= upper limit.

Dataset with hourly temperature		Current dataset with hourly wetness								Predicted % change in rainfall frequency		Scenario combination for weekly % infection risk
Current Temp.	&	Hourly wetness	→	Weekly % infection risk							→	CT-CR
				Regression								
Current Temp.	&	Hourly wetness	→	Weekly % infection risk	vs	Weekly % hours with rain	→	Regr. eqn 1	→	2040 Rainfall Lower	→	CT-2040RL
							→	Regr. eqn 1	→	2040 Rainfall Upper	→	CT-2040RU
							→	Regr. eqn 1	→	2090 Rainfall Lower	→	CT-2090RL
							→	Regr. eqn 1	→	2090 Rainfall Upper	→	CT-2090RU
2040 Temp. Lower	&	Hourly wetness	→	Weekly % infection risk	vs	Weekly % hours with rain	→	Regr. eqn 2	→	2040 Rainfall Lower	→	2040TL-2040RL
							→	Regr. eqn 2	→	2040 Rainfall Upper	→	2040TL-2040RU
2040 Temp. Upper	&	Hourly wetness	→	Weekly % infection risk	vs	Weekly % hours with rain	→	Regr. eqn 3	→	2040 Rainfall Lower	→	2040TU-2040RL
							→	Regr. eqn 3	→	2040 Rainfall Upper	→	2040TU-2040RU
2090 Temp. Lower	&	Hourly wetness	→	Weekly % infection risk	vs	Weekly % hours with rain	→	Regr. eqn 4	→	2090 Rainfall Lower	→	2090TL-2040RL
							→	Regr. eqn 4	→	2090 Rainfall Upper	→	2090TL-2040RU
2090 Temp. Upper	&	Hourly wetness	→	Weekly % infection risk	vs	Weekly % hours with rain	→	Regr. eqn 5	→	2090 Rainfall Lower	→	2090TU-2040RL
							→	Regr. eqn 5	→	2090 Rainfall Upper	→	2090TU-2040RU

Table 8: Parameters for five regression equations for each of three regions (Hawke's Bay, Nelson and Central Otago) used to determine black spot infection risk resulting from changes in rainfall resulting from climate change predictions (see Table 5 and Figure 4). Quadratic functions were used for Hawke's Bay regressions; linear functions were used for Nelson and Central Otago regressions.

Region	Temperature dataset	Regr. Eqn No.	Regression parameters X	X^2	R^2 (adj.)
Hawke's Bay	Current	1	0.354	0.0125	0.84
	2040 Lower	2	0.354	0.0125	0.84
	2040 Upper	3	0.452	0.0107	0.86
	2090 Lower	4	0.386	0.0118	0.81
	2090 Upper	5	0.0715	0.00314	0.84
Nelson	Current	1	0.74417	-	0.82
	2040 Lower	2	0.74544	-	0.82
	2040 Upper	3	0.79953	-	0.84
	2090 Lower	4	0.76329	-	0.82
	2090 Upper	5	0.88561	-	0.85
Central Otago	Current	1	0.3826	-	0.61
	2040 Lower	2	0.32558	-	0.62
	2040 Upper	3	0.3707	-	0.64
	2090 Lower	4	0.3542	-	0.63
	2090 Upper	5	0.4406	-	0.66

Predicted black spot infection risk

2040 predictions for Hawke's Bay (Havelock North)

By 2040, spring and summer temperature is expected to increase slightly (0.0 to 0.2°C) for both the lower limit and the upper limit (1.4 to 1.8°C) (Table 4). This would produce virtually no change in black spot infection risk at the lower temperature limit and a non-significant increase of 0.7% for the upper temperature limit (Figure 5).

Predicted spring and summer rainfall changes by 2040 are for a decrease of 11 to 19% at the lower limit and an increase of 2 to 21% at the upper limit (Table 5). Black spot risk would decrease (0.8%) at the lower limit and increase (0.6%) at the upper limit. Neither of these degrees of risk would be statistically significantly different from that prevailing under current weather conditions (Figure 5).

The combined effects of temperature and rainfall changes would be a decrease (0.8%) at the lower limit and an increase (1.5%) at the upper limit, neither of which would be significantly different from that prevailing under current weather conditions (Figure 5).

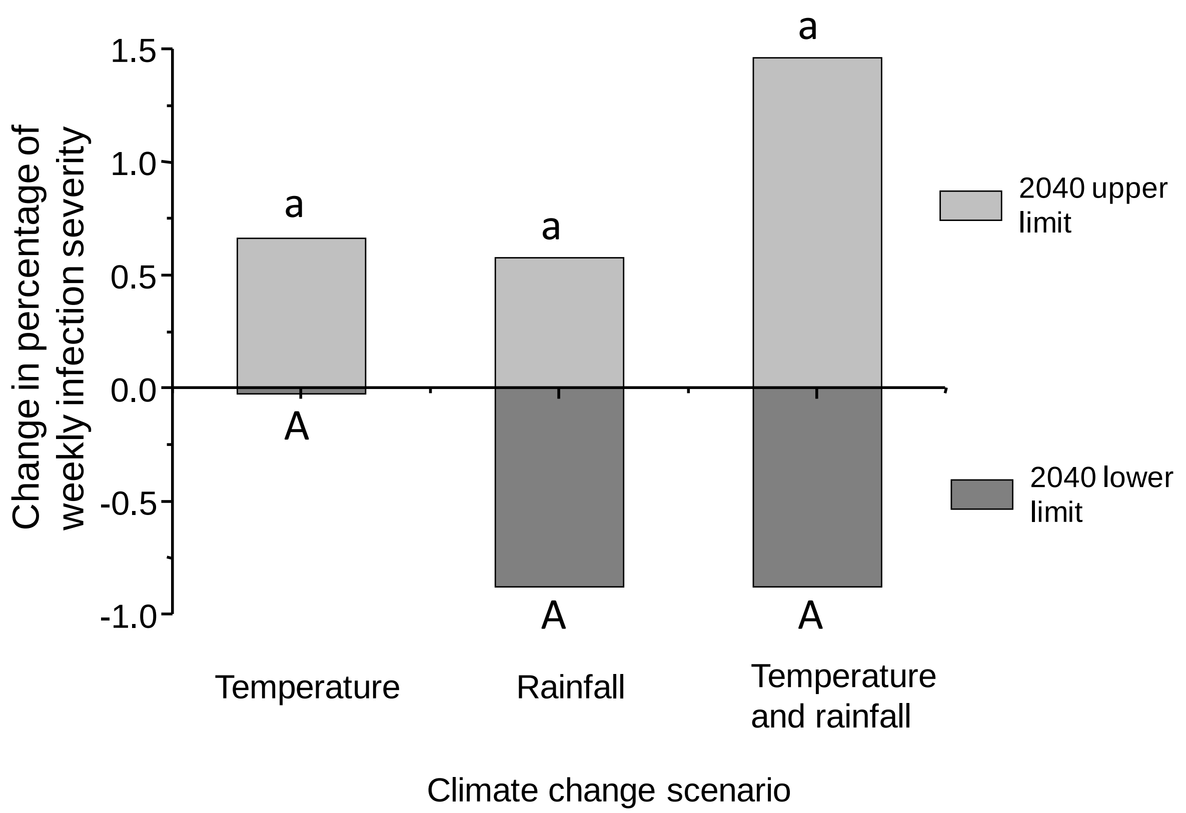


Figure 5: Havelock North, upper and lower limit changes in temperature and rainfall predicted for 2040, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset.

2090 predictions for Hawke's Bay (Havelock North)

By 2090, the spring and summer lower limit temperature prediction is for an increase of 0.3 to 0.8°C and the upper limit prediction is a more substantial 4.5 to 5.3°C increase (Table 4). Neither of these temperature effects would produce a significant change in black spot risk (Figure 6).

On the other hand, the 32% decrease in rainfall predicted under the lower limit would produce a significant decrease of 2% in risk and, for the upper limit, the 8 to 35% increase in upper limit rainfall would produce a non-significant 1.2% increase in risk (Figure 6). The combined effects of temperature and rainfall would produce a significant 2.0% decrease in risk for the lower limit and a significant 2.8% increase for the upper limit (Figure 6).

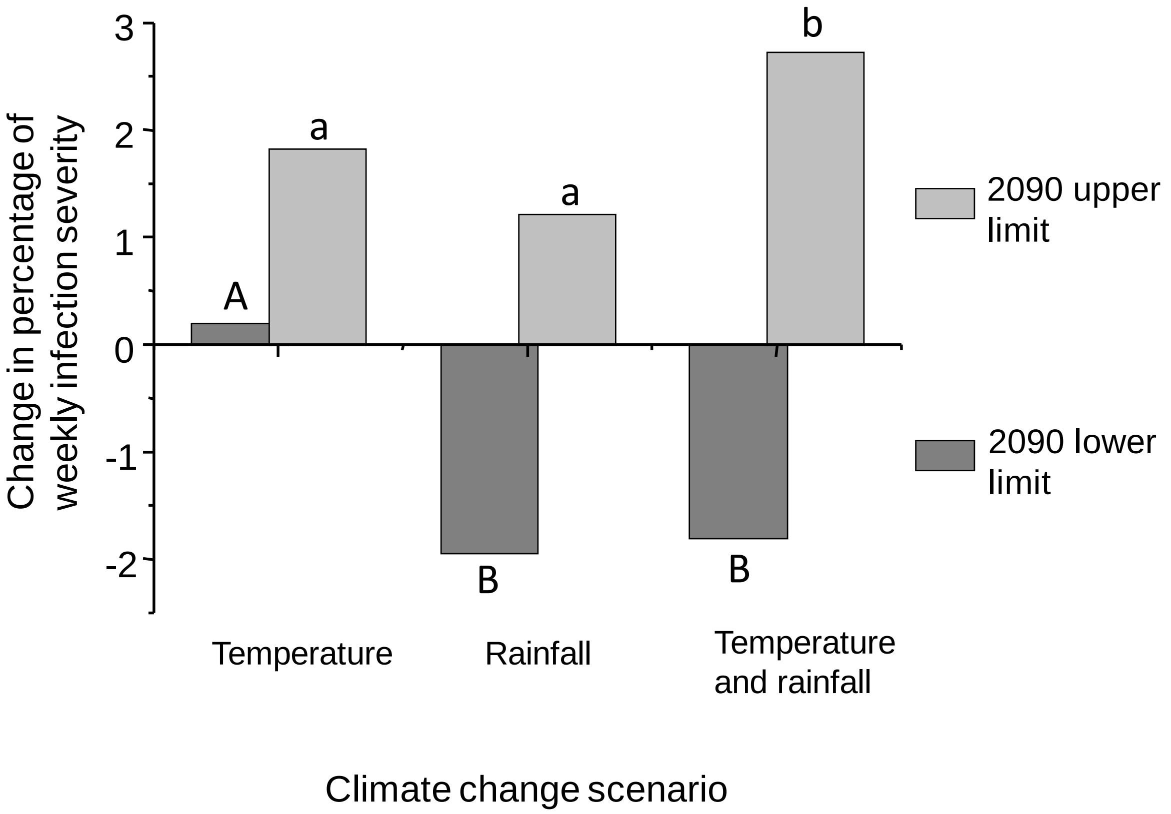


Figure 6: Havelock North, upper and lower limit changes in temperature and rainfall predicted for 2090, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset. Bars with 'B' (lower limit climate change prediction) or 'b' (upper limit climate change prediction) differ significantly (P<0.05) from the current weather dataset.

2040 predictions for Nelson (Riwaka)

By 2040 in Nelson, none of the lower or upper limit temperature increases (0.1 to 1.6^{o}C), or the lower limit rainfall decrease (5 to 8%), or the upper limit rainfall increase (6 to 14%) would cause a significant change in black spot risk compared with that prevailing under the current climate (Figure 7). The combined effect of increased temperature plus increased rainfall for the upper limit prediction would cause a significant 2.4% increase in black spot risk (Figure 7). For the combined lower limit effect, there would be no significant change in black spot risk.

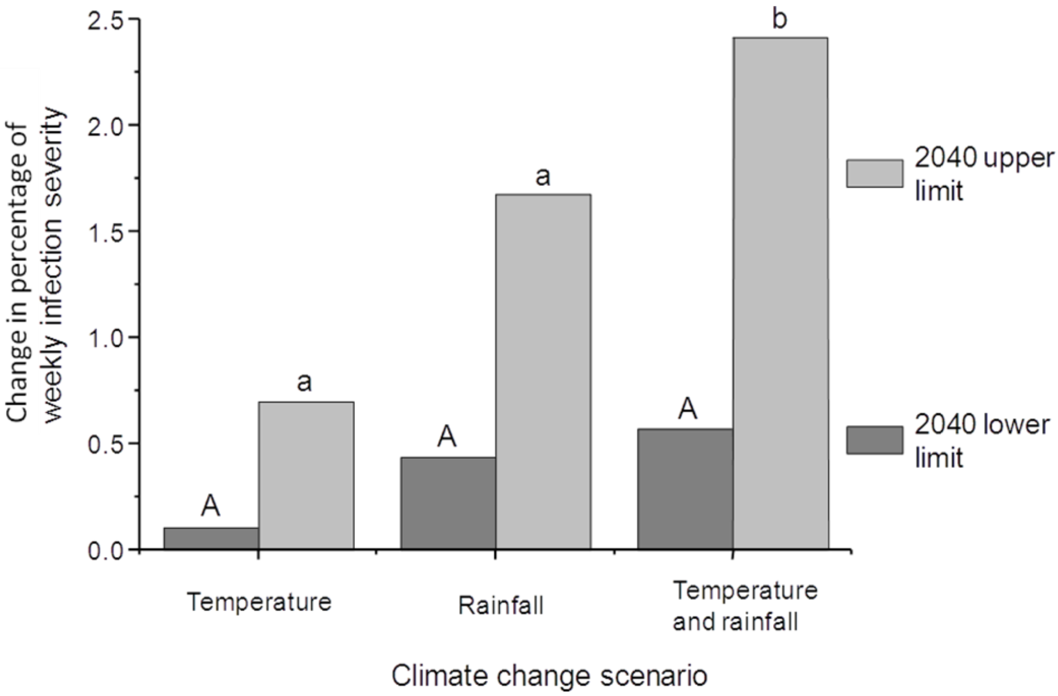


Figure 7: Nelson, upper and lower limit changes in temperature and rainfall predicted for 2040, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset. Bars with 'B' (lower limit climate change prediction) or 'b' (upper limit climate change prediction) differ significantly (P<0.05) from the current weather dataset.

2090 predictions for Nelson (Riwaka)

The 2090 predictions for Nelson were similar to those for 2040, except that the significant black spot risk increase (4.4%) predicted for the combined upper limit increases in temperature and rainfall was more pronounced than for 2040 (Figure 8).

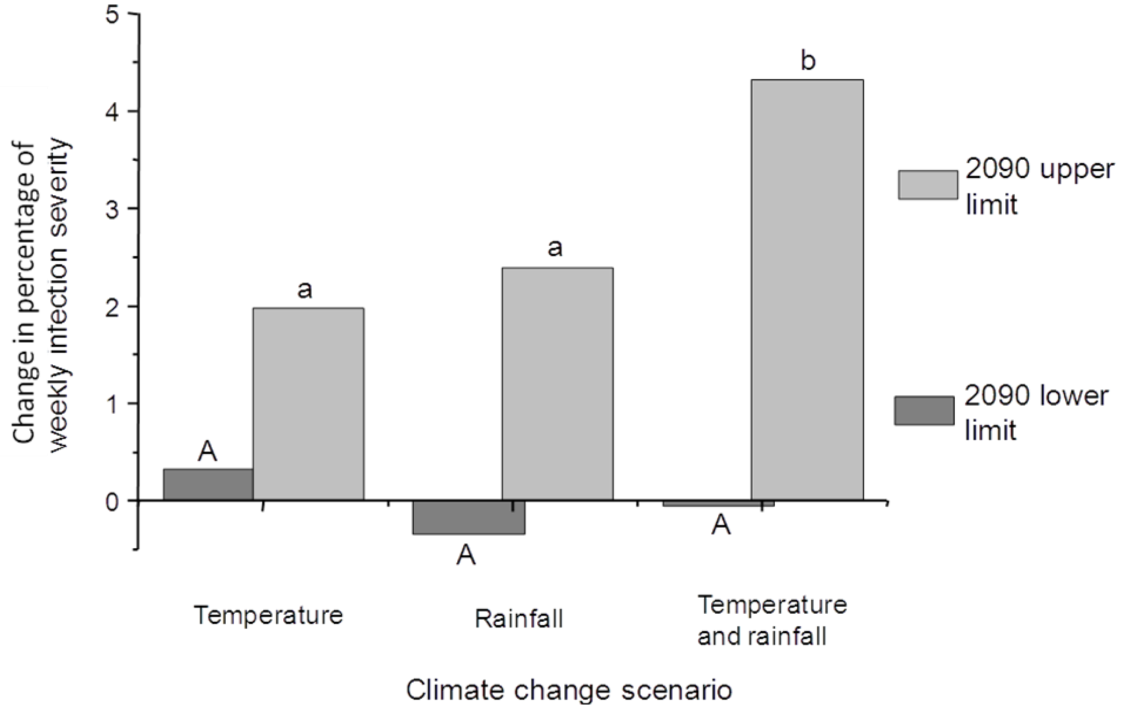


Figure 8: Nelson, upper and lower limit changes in temperature and rainfall predicted for 2090, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset. Bars with 'B' (lower limit climate change prediction) or 'b' (upper limit climate change prediction) differ significantly (P<0.05) from the current weather dataset.

2040 and 2090 predictions for Central Otago (Clyde)

The 2040 upper limit predictions for Central Otago spring and summer conditions of 14% and 12% wetter respectively would give a significant increase in black spot risk of about 0.9% for both the rainfall effect alone and the combined temperature and rainfall effect (Figure 9).

The substantial rainfall increase predicted for spring (43%) and summer (29%) by 2090 would cause a 1.5 to 2.0% increase in black spot risk for the rainfall and combined temperature and rainfall effects respectively (Figure 10).

Other Central Otago climate change predictions would not produce significant changes in black spot infection risk.

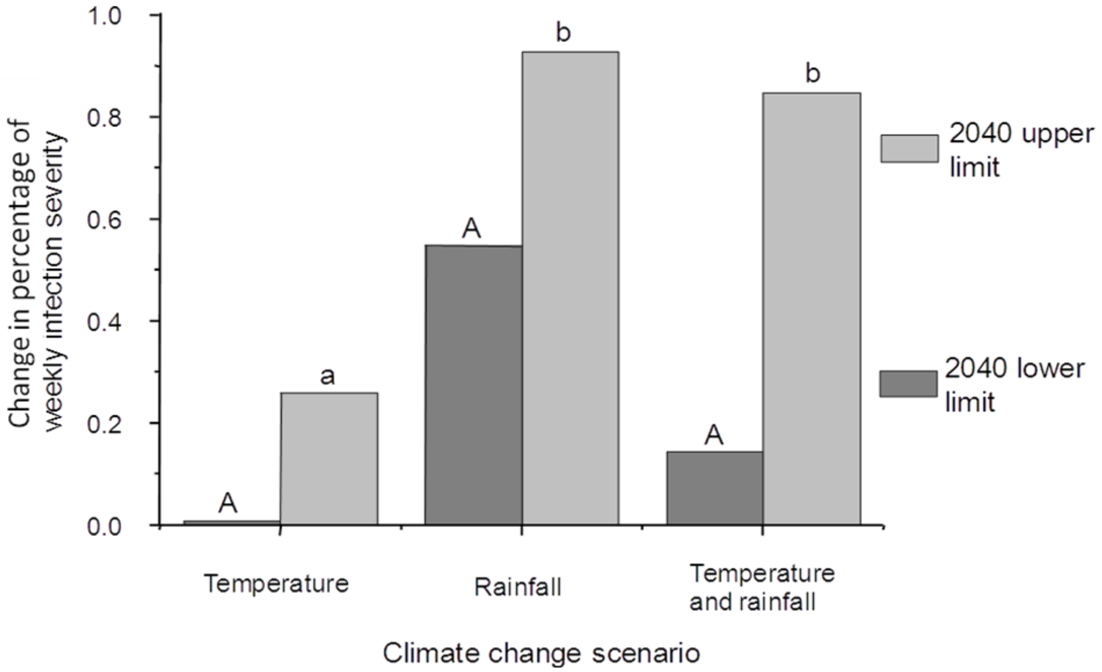


Figure 9: Central Otago, upper and lower limit changes in temperature and rainfall predicted for 2040, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset. Bars with 'B' (lower limit climate change prediction) or 'b' (upper limit climate change prediction) differ significantly (P<0.05) from the current weather dataset.

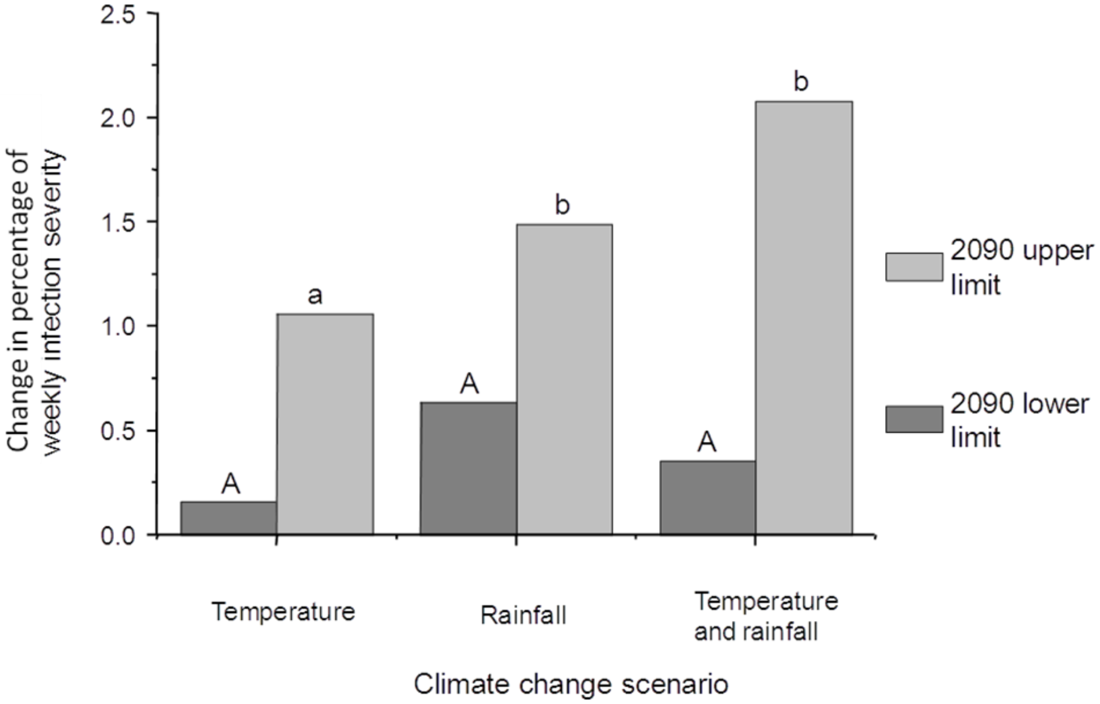


Figure 10: Central Otago, upper and lower limit changes in temperature and rainfall predicted for 2090, as percentage change in black spot risk relative to the current weather dataset. The Y-axis zero value represents the current weather dataset. Bars with 'A' (lower limit climate change prediction) or 'a' (upper limit climate change prediction) do not differ significantly (P >0.05) from the current weather dataset. Bars with 'B' (lower limit climate change prediction) or 'b' (upper limit climate change prediction) differ significantly (P<0.05) from the current weather dataset.

Effects of climate change on black spot disease incidence

Beresford and Manktelow (1994) reported a regression relationship that explained black spot incidence in orchards in terms of the total number of infection events during the primary ascospore release season and the total number of fungicide applications made to the crop. They showed that with increasing black spot incidence, the cost of production increased a result of rejected fruit and increased grading and packing costs. Black spot incidence above about 2% has an important negative impact on the economics of apple production. Using their regression equation, we calculated the black spot incidence for the current climate and for the temperature- and rainfall-adjusted projections for Hawke's Bay, Nelson and Otago to determine the relative impact climate change predictions might have on black spot incidence.

2040 predictions

The 2040 upper limit temperature plus rainfall predictions would result in significantly greater black spot incidence for Nelson but not for Hawke's Bay or Central Otago (Table 9). The Nelson result was associated with the trend for increased rainfall in both spring and summer (Table 5), and with the significant 2.4% predicted increase in black spot infection risk (Figure 7). No other climate change predictions suggested black spot incidence would differ significantly from that at the current time by 2040 (Table 9).

2090 predictions

For Hawke's Bay, Nelson and Otago, the upper limit temperature plus rainfall predictions would result in significantly greater black spot incidence (Table 9). The Nelson disease incidence (1.55%) was the greatest for any of the predictions.

None of the black spot incidence predictions from this analysis exceeded the 2% threshold above which economic losses from black spot become important. Although the absolute values of predicted incidence from this analysis may be too low, it is unlikely that the increases in black spot incidence resulting from climate change would have a noticeable effect on the frequency of fungicide applications required to control black spot in apple orchards.

Table 9: Calculated black spot disease incidence for three apple production regions under predicted changes in temperature due to climate change. Incidence was calculated using the regression equation: logit disease= 0.182 x no. infection events – 0.172 x no. fungicide applications – 5.5.4 (Beresford & Manktelow 1994), assuming 16 fungicide sprays per season were applied against black spot. Means within a row accompanied by an asterisk are significantly different (α<0.05) from those for the current climate, according to Fisher's unprotected LSD.

Apple production region	Current climate[1]	Lower T[2]	Upper T[2]	Lower R[3]	Upper R[3]	Lower T + R[4]	Upper T + R[4]
2040							
Hawke's Bay	0.21	0.21	0.28	0.14	0.26	0.14	0.37
Nelson	0.35	0.35	0.41	0.30	0.44	0.30	0.52 *
Central Otago	0.05	0.07	0.05	0.05	0.06	0.05	0.08
2090							
Hawke's Bay	0.21	0.21	0.65	0.10	0.33	0.11	1.28 *
Nelson	0.35	0.36	0.85 *	0.24	0.56	0.25	1.55 *
Central Otago	0.05	0.05	0.11	0.05	0.07	0.05	0.22 *

[1] Current climate based on a 9-year dataset of hourly recordings for the each region from 2003 to 2012.
[2] Lower and upper limit temperature change for each region (Appendix 1).
[3] Lower and upper limit rainfall change for each region calculated by adjusting the monthly number of infection periods of the temperature-corrected datasets by the predicted percentage change in rainfall for each region (Appendix 1).
[4] Lower and upper limit combined temperature plus rainfall change for each region (Appendix 1).

Overall impacts of climate change on apple black spot

Effects of temperature change on black spot infection risk and disease incidence

The greater the predicted increase in temperature, the greater was the increase in black spot risk, within a given region. Black spot infection risk increased with temperature because higher temperatures tended to increase the black spot risk category associated with a given wet period. However, for predicted temperature changes alone, the predicted increase in black spot infection risk was statistically non-significant for all regions, even for the greatest temperature increase (upper temperature limit for 2090).

For the prediction of black spot incidence using the Beresford & Manktelow (1994) regression equation, the only significant effect for temperature-alone predictions was for the 2090 upper temperature limit for Nelson, where a significant increase in black spot incidence was predicted (Table 9).

Effects of rainfall change on black spot infection risk and disease incidence

Predicted effects of rainfall changes on infection risk were more important, but also more approximate, than effects of temperature changes. They were more approximate because rainfall changes had to be inferred using a regression approach, which was sometimes based on relatively a poor regression fit (Table 8). The interaction between rainfall and temperature was even more approximate because hour-by-hour interactions between temperature and rainfall could not be simulated. However, despite these approximations, the general effects of rainfall change predictions on black spot risk could be visualised. They were not particularly great, although the following scenarios did produce statistically significant changes in black spot infection risk:

- Decreased black spot risk resulting from the Hawke's Bay drying trend for the 2090 lower limit
- Increased black spot risk resulting from the Hawke's Bay increased summer rainfall trend for the 2090 upper limit
- Increased black spot risk resulting from the Nelson increased rainfall trend for the 2040 and 2090 upper limits
- Increased black spot risk resulting from the Central Otago increased rainfall trend for the 2040 and 2090 upper limits.

Regional impacts of black spot

These analyses indicate that the current regional ranking of black spot infection risk and black spot disease incidence (Nelson>Hawke's Bay>Central Otago) would still remain under all climate change scenarios, although risk would tend to increase in each region under the upper limit predictions by 2090. Under the upper limit prediction, by 2090 Central Otago would have black spot risk similar to that in Hawke's Bay under current climatic conditions, but not as great as Nelson under current climatic conditions. The greatest increase in black spot risk would occur in Nelson for the upper limit prediction by 2090, where a 4.4% increase in infection risk would occur. However, this is likely to require only a small change to current fungicide use for black spot control, assuming fungicides are still available by 2090.

GRAPEVINE DOWNY MILDEW

Downy mildew disease risk model

The weather conditions for oospore dispersal, germination and zoospore infection are wet soil and temperature above 10°C (Ash 2000). Weather criteria identifying infection risk periods are: rainfall of at least 10 mm and temperature ≥ 10^{o}C over a 24-hour period. Grape leaves must also remain wet overnight with an accumulated temperature ≥ 45^{o}C hours (Ash 2000). Table 10 shows how these criteria were adapted for this study.

Table 10: Grapevine downy mildew risk criteria for predicting primary oospore infection by *Plasmopara viticola*. Risk of disease development is high when conditions for both spore dispersal and infection occur frequently during spring and early- to mid-summer.

Disease development process	Meteorological criteria	
Spore dispersal		24-hour accumulated rainfall ≥10 mm between 0000-2300 the previous day
	and	Mean hourly temperature ≥ 10oC between 0000-2300 the previous day
	AND	
Infection of leaves and fruit by spores		Overnight surface wetness between 2000 and 1200 on the current day
	and	Summed hourly temperature ≥ 45oC hours between 2000 and 1200 on the current day

The wetness component for infection (45^{o}C h of wetness following oospore dispersal and germination) was assumed to have been fulfilled any time that a grape canopy received greater than 10mm of rainfall in 24 hours. Disease risk criteria for secondary infection by sporangia (Ash 2000) exist but because the available weather datasets could not provide relative humidity (RH) data that were accurate in the 95-100% RH range, they could not be used in this study. Grape downy mildew infection risk was evaluated using primary infection criteria with hourly temperature and rainfall data.

Temperature and rainfall adjustment for future climate datasets

Corrected temperature change values for upper and lower limit predictions (Table 11) were applied to hourly values in the current weather datasets to generate future weather datasets. Rainfall in the current weather datasets was also adjusted by applying the corrected percentage change in rainfall amount (Table 11) to the hourly rainfall data, for hours with greater than zero rainfall. Although this did not directly alter the number of days with some rainfall, it did affect the frequency of infection periods by changing the number of days that exceeded 10 mm of rainfall (Table 10).

Predicted grape downy mildew risk

Downy mildew risk analyses were done for five grape growing regions, Gisborne, Hawke's Bay, Marlborough, Canterbury and Central Otago. Only spring (September to November) and summer (December to February) were examined each year because these were the months relevant to downy mildew development in New Zealand vineyards.

Predicted climatic trends

For temperature across all the regions, the lower limit prediction for spring and summer was a negligible 0.0 to 0.2°C warming by 2040 and 0.3 to 0.8°C warming by 2090 (Table 11). The upper limit prediction was a 1.2 to 1.8°C warming by 2040 and a substantial 3.7 to 5.4°C warming by 2090 (Table 11).

For rainfall during spring and summer, the lower limit prediction was for decreasing rainfall through 2040 to 2090, with the decrease most pronounced in North Island regions (Gisborne and Hawke's Bay). Central Otago was predicted to show an 18% spring rainfall increase by 2090, although summer would be 32% drier (Table 11). For the upper limit prediction, rainfall was predicted to increase during spring and summer through 2040 to 2090, with the most pronounced spring increase in South Island regions (16-43%) (Table 11).

Table 11: Spring and summer temperature and rainfall change predictions (Appendix 1) for five New Zealand grape production regions analysed for changes in grapevine downy mildew risk due to climate change. Lower and upper limit climate predictions from 12 models are shown.

Key to temperature change colour codes					
0.0 – 0.9°C increase	1.0 – 1.9°C increase	2.0 – 2.9°C increase	3.0 – 3.9°C increase	4.0 – 4.9°C increase	5.0 – 5.9°C increase

	Temp. change (°C)				Rainfall change (%)			
	Lower		Upper		Lower		Upper	
	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer
2040								
Gisborne	0.0	0.2	1.4	1.8	-13	-15	2	18
Hawke's Bay	0.0	0.2	1.4	1.8	-11	-19	2	21
Marlborough	0.1	0.2	1.3	1.4	-4	-8	6	13
Canterbury	0.1	0.1	1.3	1.5	-5	-9	6	12
Central Otago	0.0	0.1	1.2	1.5	0	-10	14	12
2090								
Gisborne	0.3	0.8	4.5	5.4	-34	-27	6	26
Hawke's Bay	0.3	0.8	4.5	5.3	-32	-32	8	35
Marlborough	0.3	0.9	4.3	4.9	-15	-7	16	16
Canterbury	0.3	0.8	4.2	4.5	-12	-11	22	15
Central Otago	0.5	0.8	3.7	3.9	18	-32	43	29

Key to % rainfall change colour codes					
Much drier	Slightly drier	Little change	Slightly wetter	Much wetter	Very much wetter
20-39% decrease	10-19% decrease	0-9% decrease or increase	10-19% increase	20-39% increase	>40% increase

Current grapevine downy mildew risk

Regional variation in grapevine downy mildew risk under current climatic conditions ranked Gisborne> Hawke's Bay> Marlborough>Canterbury>Central Otago. The number of downy mildew infection periods per three-month season varied from 6.6 in Gisborne in summer to 0.8 in Central Otago in spring (Tables 12 and 13). The trend for risk to decrease from north to south reflected both decreasing temperature with increasing latitude and lower rainfall in the more southern grape-growing regions. Slightly more infection periods tended to occur in summer than in spring, except in Marlborough where risk in both these seasons was the same (Tables 12 and 13).

Spring predictions of future downy mildew risk

For spring temperature, increases due to climate change would cause small increases in numbers of downy mildew infection periods (Table 12). However, these would only be significantly greater than for the current climate in Canterbury and Central Otago for the upper limit temperature for 2090. The decrease in spring rainfall predicted for the lower limit scenario, which was most pronounced for Gisborne in 2090 (-34%, Table 11), would cause a small, non-significant decrease in infection periods (5.3 to 3.3 per three-month season) (Table 12). For the predicted spring rainfall increase for the upper limit prediction, which was greatest for Central Otago (43%, Table 11), there would be a non-significant increase in infection periods (0.8 to 1.7 per three-month season) (Table 12).

The combined effects of temperature and rainfall were variable, depending on the various climate change predictions. The only predictions that led to significant changes from risk under the current climate were an increase for Canterbury and Central Otago for the upper limit temperature plus rainfall predictions (Table 12). These increases would represent substantial percentage increases in risk and would make the number of infection periods during spring more similar to those in Gisborne or Hawke's Bay at the present time.

Table 12: Spring season mean number of downy mildew infection periods per year for five wine grape production regions under current climate and lower and upper limit predicted changes in temperature, rainfall and temperature combined with rainfall for 2040 and 2090. Current climate data are repeated under the 2040 and 2090 table headings.

Region	Current climate1	Lower T2	Upper T2	Lower R3	Upper R3	Lower T + R4	Upper T + R4
2040							
Gisborne	5.3	5.3	6.1	4.4	5.3	4.4	6.1
Hawke's Bay	2.9	2.9	3.1	2.5	2.9	2.5	3.1
Marlborough	3.5	3.5	3.8	3.4	3.5	3.3	4.3
Canterbury	1.4	1.4	1.4	1.4	2.4	1.4	2.4
Central Otago	0.8	0.8	1.4	0.8	1.2	0.8	1.9
2090							
Gisborne	5.3	5.7	6.3	3.3	5.6	3.6	6.5
Hawke's Bay	2.9	2.9	3.8	1.8	3.0	1.8	4.0
Marlborough	3.5	4.2	4.8	2.4	3.6	3.1	5.3
Canterbury	1.4	1.8	3.6*	1.4	2.5	1.8	5.1*
Central Otago	0.8	1.0	1.9*	1.2	1.7	1.4	3.6*

[1] Current climate predictions derived from nine years of weather for each region, from 2003-4 to 2011-12.
[2] Effect of temperature change on downy mildew risk for lower and upper limit scenarios.
[3] Effect of rainfall change on downy mildew risk for lower and upper limit scenarios.
[4] Effect of combined temperature plus rainfall change on downy mildew risk for lower and upper limit scenarios.
*Number of infection periods is significantly greater than for that in the current climate, according to Fisher's unprotected LSD (α= 0.05).

Summer predictions of future downy mildew risk

Predicted increases in summer temperatures due to climate change would produce very little change in numbers of downy mildew infection periods (Table 13), even for the most extreme upper limit temperature increase of 5.4°C for Gisborne by 2090 (Table 11). For the lower limit predictions for 2090, increases in temperature would be small for all regions (<0.9°C) and, together with the predicted decreases in rainfall, would give small, non-significant decreases in numbers of infection periods across the regions (Table 13). For the upper limit predictions, the greater temperature increases and the increased rainfall would give greater increases in numbers of infection periods, although none of these increases would be significantly different from those experiences under the current climate.

Table 13: Summer season mean number of downy mildew infection periods per year for five wine grape production regions under current climate and lower and upper limit predicted changes in temperature, rainfall and temperature combined with rainfall for 2040 and 2090. Current climate data are repeated under the 2040 and 2090 table headings. There were no statistical differences in number of infection periods between the current climate and any of the climate change scenarios.

Region	Current climate[1]	Lower T[2]	Upper T[2]	Lower R[3]	Upper R[3]	Lower T + R[4]	Upper T + R[4]
2040							
Gisborne	6.6	6.6	6.6	5.4	7.3	5.4	7.3
Hawke's Bay	4.6	4.6	4.6	3.8	5.7	3.8	5.7
Marlborough	3.5	3.5	3.5	3.2	4.1	3.4	4.1
Canterbury	3.5	3.5	3.6	3.3	4.1	3.3	4.3
Central Otago	3.4	3.4	3.4	2.9	3.9	2.9	3.9
2090							
Gisborne	6.6	6.6	6.6	4.5	7.7	4.5	7.7
Hawke's Bay	4.6	4.6	4.6	3	7	3	7
Marlborough	3.5	3.5	3.5	3.4	4.3	3.5	4.3
Canterbury	3.5	3.6	3.8	3.1	4.2	3.3	4.6
Central Otago	3.4	3.4	3.8	1.8	4.3	1.8	4.7

[1] Current climate predictions derived from nine years of weather for each region, from 2003-4 to 2011-12.
[2] Effect of temperature change on downy mildew risk for lower and upper limit scenarios.
[3] Effect of rainfall change on downy mildew risk for lower and upper limit scenarios.
[4] Effect of combined temperature plus rainfall change on downy mildew risk for lower and upper limit scenarios.

Overall impacts of climate change on grapevine downy mildew risk

The regional ranking of grapevine downy mildew risk in the current weather dataset for spring and summer combined was:

Gisborne> Hawke's Bay>Marlborough>Canterbury>Otago (Table 14).

Hawke's Bay and Marlborough were surprisingly similar because of the chance occurrence of several years with relatively many infection periods in Marlborough and relatively few in Hawke's Bay. Similar ranking was found for all climate change scenarios, except in relation to the lower limit rainfall prediction, where the greater drying trend for Hawke's Bay gave relatively lower risk there. Central Otago showed a very large percentage increase in downy mildew risk because of the increased rainfall associated with the upper limit prediction (Table 14). However, the number of infection periods for Central Otago was still fewer than for the current climate in Gisborne.

Table 14: Averaged spring and summer season mean number of downy mildew infection periods per year for five wine grape production regions under current climate and lower and upper limit predicted changes in temperature, rainfall and temperature combined with rainfall for 2040 and 2090. Current climate data are repeated under the 2040 and 2090 table headings.

		Climate change scenario							
Region	Current climate[1]	Lower T[2]	Upper T[2]	Lower R[3]	Upper R[3]	Lower T + R[4]	*Lower T+R % change*	Upper T + R[4]	*Upper T+R % change*
2040									
Gisborne	6.0	6.0	6.4	4.9	6.3	4.9	-18	6.7	13
Hawke's Bay	3.8	3.8	3.9	3.2	4.3	3.2	-16	4.4	15
Marlborough	3.5	3.5	3.7	3.3	3.8	3.4	-4	4.2	20
Canterbury	2.5	2.5	2.5	2.4	3.3	2.4	-3	3.4	47
Central Otago	2.1	2.1	2.4	1.9	2.6	1.9	-7	2.9	76
2090									
Gisborne	6.0	6.2	6.5	3.9	6.7	4.1	-32	7.1	20
Hawke's Bay	3.8	3.8	4.2	2.4	5.0	2.4	-36	5.5	45
Marlborough	3.5	3.9	4.2	2.9	4.0	3.3	-6	4.8	37
Canterbury	2.5	2.7	3.7	2.3	3.4	2.6	11	4.9	148
Central Otago	2.1	2.2	2.9	1.5	3.0	1.6	14	4.2	194

[1] Current climate predictions derived from nine years of weather for each region, from 2003-4 to 2011-12.
[2] Effect of temperature change on downy mildew risk for lower and upper limit scenarios.
[3] Effect of rainfall change on downy mildew risk for lower and upper limit scenarios.
[4] Effect of combined temperature plus rainfall change on downy mildew risk for lower and upper limit scenarios.

The greatest potential effect of climate change was identified for Canterbury and Central Otago for the upper limit prediction, which suggested a statistically significant increase in risk during spring by 2090 (Table 12). Under that scenario, number of downy mildew infection periods would become similar to the numbers that occur in Gisborne and Hawke's Bay under current climatic conditions. In Gisborne and Hawke's Bay at the current time, downy mildew causes damage to grape crops only sporadically.

This analysis suggests there would only be a minor impact of climate change on grapevine downy mildew risk in New Zealand. The magnitude of predicted changes in the number of spring and summer infection periods would not cause substantial changes in vineyard disease control programmes, which currently involve preventative fungicide sprays.

ONION DOWNY MILDEW

Onion downy mildew risk model

Relationships between weather and onion downy mildew development are well documented (Howard et al. 1994; Mukerji 1975; Schwartz 1995). Several models have been proposed for predicting sporangia production (sporulation) and infection, based on criteria originally determined by Hildebrand & Sutton (1984). A disease risk prediction model, DOWNCAST, was developed by Jesperson & Sutton (1987). This model has been adapted for New Zealand conditions (Whiteman & Beresford 1998) and was validated under field conditions in Franklin district (Wright 2002, Chynoweth et al. 2004). It was implemented to help onion growers use fungicides more efficiently through a MPI Sustainable Farming Fund project (project no. 04/110). The key meteorological criteria required to run this model are relative humidity, surface wetness duration, rainfall and air temperature (Table 14).

Table 14: Weather criteria for the modified DOWNCAST model used to predict onion downy mildew risk in New Zealand (Whiteman & Beresford 1998). Risk of disease development is high when conditions for both sporulation and infection (sporulation-infection events) occur frequently during spring and early summer.

Disease development process	Meteorological criteria	
Sporulation (production of sporangia)		Mean temperature between 0800 and 2000 h during the previous day ≤ 24°C
	and	Mean hourly temperature at night (2000-0500 h) 4- 24°C
	and	< 0.2 mm rain between 0100 and 0500 h
	and	Relative humidity (RH) >95% continuously between 0100 and 0500 h
	AND	
Infection of leaves by sporangia	either	Leaf surface wetness between 0500 and 0800 h immediately following the sporulation event
	or	Leaf surface remains wet for 3 hours between 1900 and 2400 h on the evening following the sporulation event
	or	Leaf surface remains wet for 3 hours between 1900 and 2400 h the second evening following the sporulation event

Predicted onion downy mildew risk

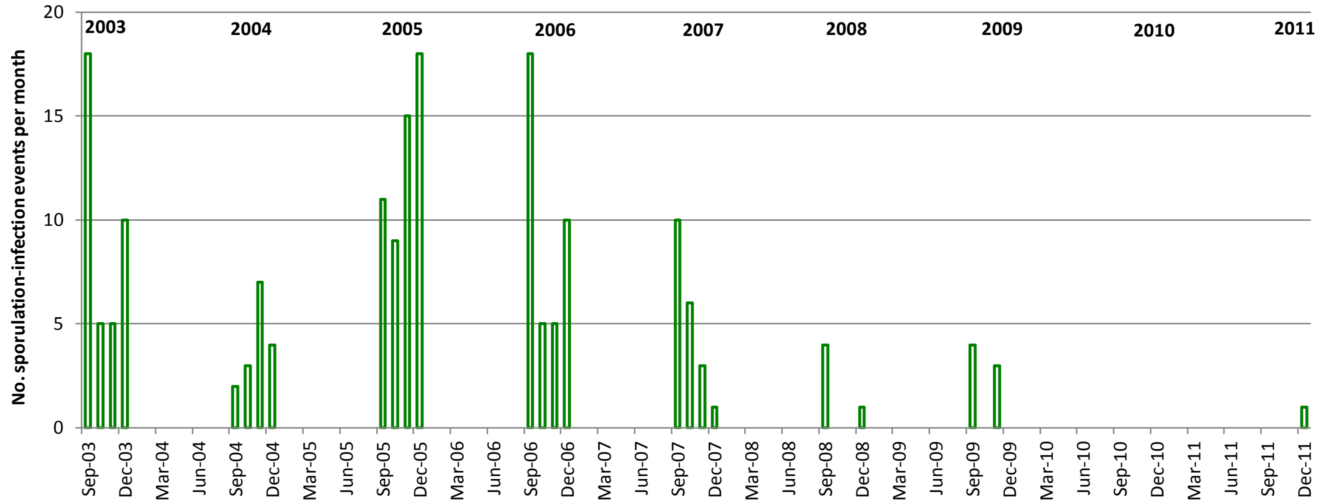
Downy mildew risk was analysed for weather datasets from Auckland/Waikato (Pukekohe) and Canterbury (Lincoln) (Appendix 2). These stations were the only ones in New Zealand onion-growing regions with continuous surface wetness records suitable for the DOWNCAST model. Surface wetness data were not available in Manawatu, so downy mildew risk in that region could not be analysed. Nine years of weather data (2003 to 2011) from Pukekohe and Lincoln were used as the current weather datasets.

Current onion downy mildew risk in Auckland (Pukekohe)

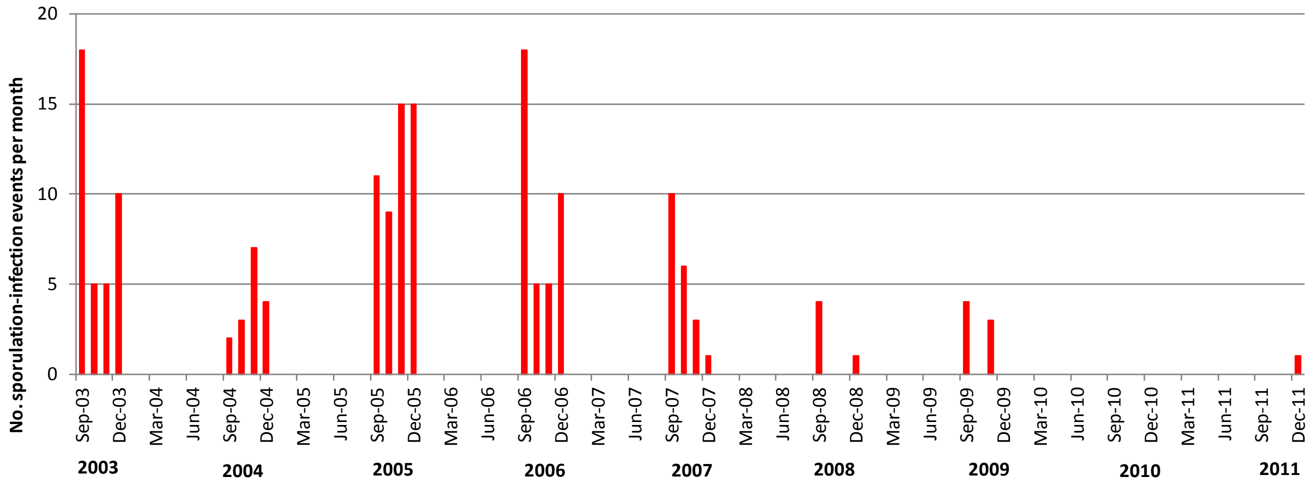
Downy mildew risk for the Pukekohe current weather dataset (Figure 11) appeared to show higher risk in 2003, 2005 and 2006 than in later years. However, this was found to be an artefact caused by errors in the RH readings. The decrease in downy mildew risk in the later years occurred because the RH sensor was recalibrated around 2007. There appeared to have been a gradual increase in RH between 2004 and 2006 followed by a decrease after 2006 (Figure 12).

The DOWNCAST model relies critically on RH >95% in the early hours of the morning (0100-0500) to identify dewy conditions suitable for *P. destructor* sporangial production (Table 14). The apparent seasonal variation in downy mildew risk at Pukekohe resulted mostly from changes in RH sensor calibration, which could not be corrected retrospectively. Therefore the analysis of inter-seasonal risk of downy mildew using the current weather dataset from Pukekohe was not accurate.

Effect of future temperature change on onion downy mildew risk in Auckland
Despite the RH calibration problem at Pukekohe, it was possible to examine the effect of future temperature change on downy mildew risk. This showed that even for the most extreme temperature prediction (upper limit by 2090), there was no overall change in predicted risk compared with the risk under the current weather (Figure 11).



9-year averages for no. spor-inf. events					
	Sep	Oct	Nov	Dec	Mean
No events/month	7.4	3.1	4.2	5.0	4.9
No. months	9	9	9	9	36



9-year averages for no. spor-inf. events					
	Sep	Oct	Nov	Dec	Mean
No events/month	7.4	3.1	4.2	4.7	4.9
No. months	9	9	9	9	36

Figure 11: Pukekohe, current weather dataset (green) and upper temperature limit for 2090 (red): Output from the DOWNCAST model showing mean number of number of onion downy mildew sporulation-infection events per month for nine years.

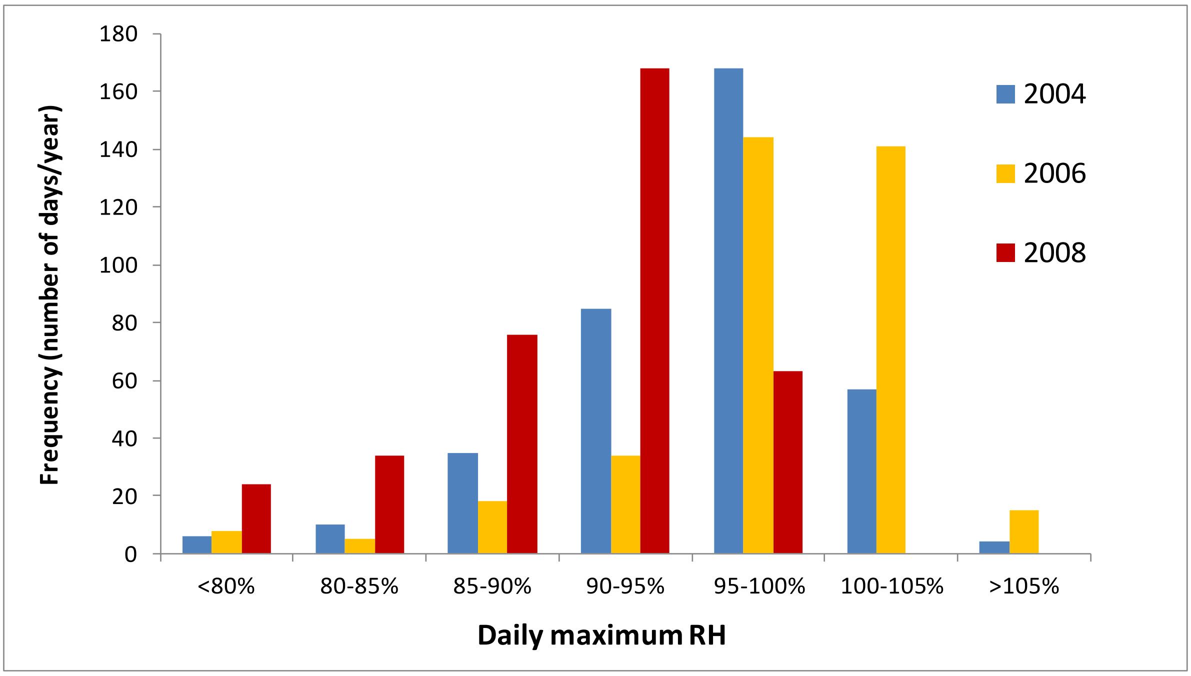


Figure 12: Frequency of daily maximum relative humidity (RH) in the current dataset at Pukekohe for 2004, 2006 and 2008. This shows how drift in the RH sensor between 2004 and 2006 gave increasing frequency of days with maximum RH greater than the theoretical maximum of 100%. The 2008 data shows the change in maximum RH distribution after re-calibration of the RH sensor. The gradual drift in sensor calibration was not able to be corrected and meant that use of the DOWNCAST model, which critically depends on accurate RH between 95-100%, to predict onion downy mildew risk at Pukekohe, was unreliable.

Effect of future rainfall change on onion downy mildew risk in Auckland

In order to examine effects of percentage rainfall change on future downy mildew risk, a regression relationship needed to be developed between monthly means of numbers of sporulation-infection events and rainfall amount or frequency. However, no significant relationships were found between any of these variables. Of four rainfall, RH and temperature variables investigated for such relationships, only hours >95% RH showed a significant relationship (Figure 13). Neither rainfall amount or rainfall frequency showed any relationship. Therefore there was no basis for predicting the effect of changes in rainfall under the climate change predictions for onion downy mildew at Pukekohe.

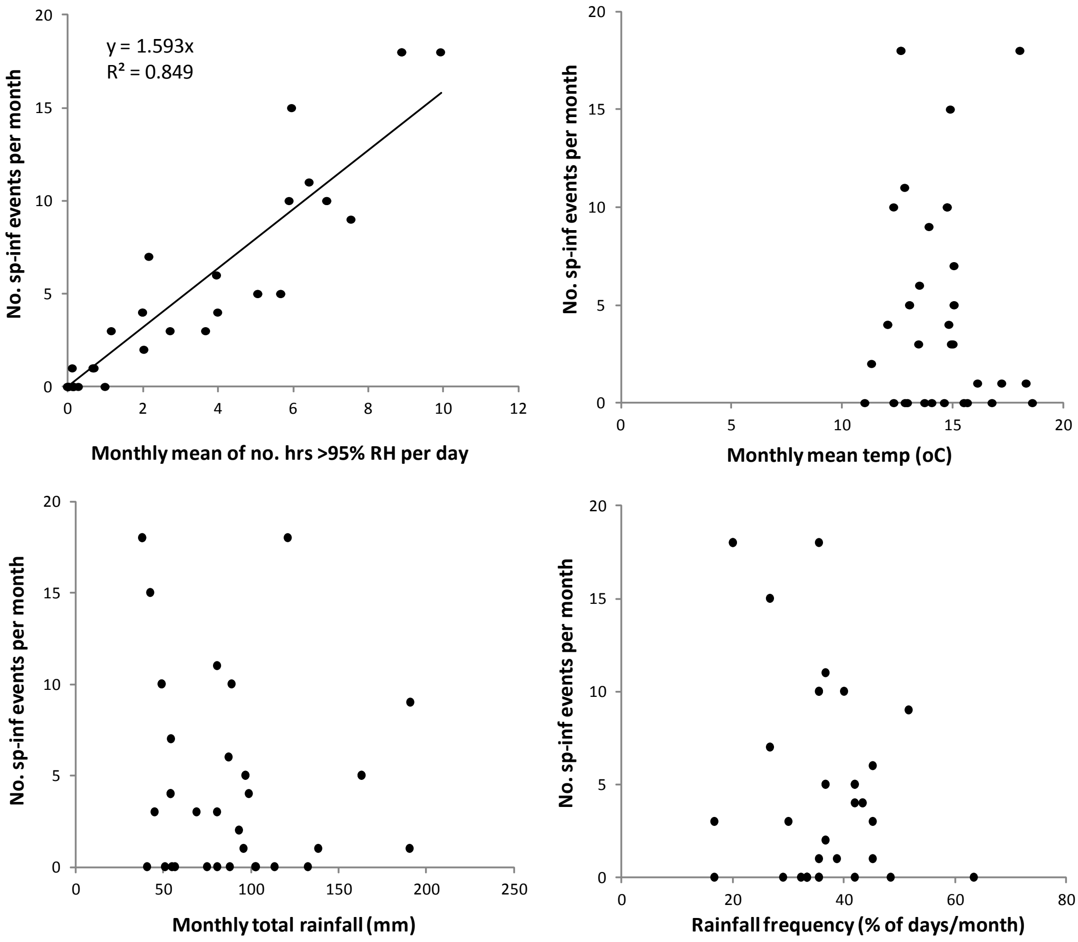
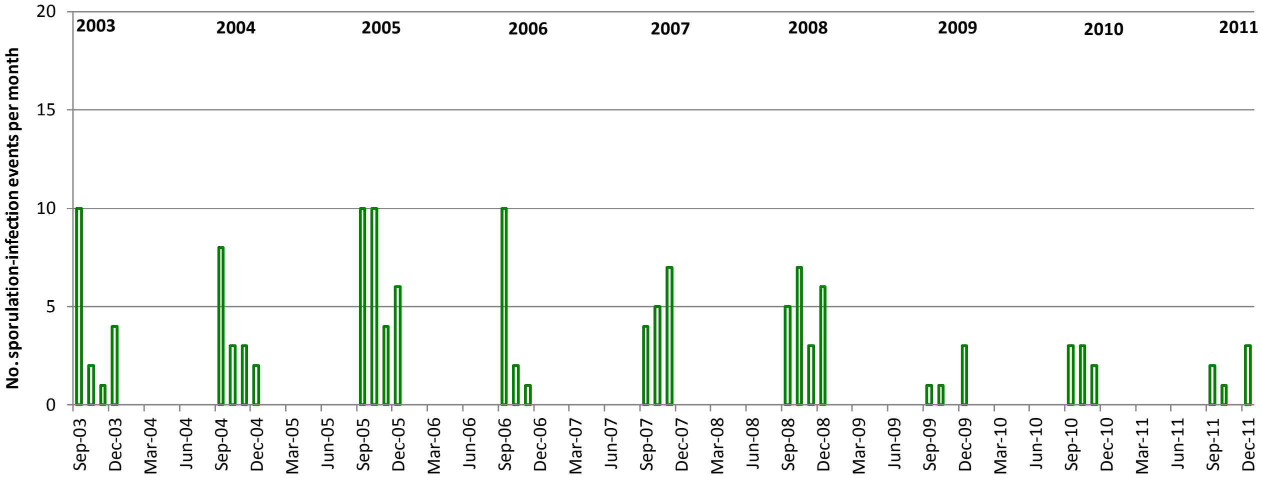


Figure 13: Pukekohe, current weather dataset: Relationships between number of onion downy mildew sporulation-infection events per month and four weather variables that were summarised monthly over nine years. Only mean number of hours >95% relative humidity (RH) per day gave a significant regression coefficient ($P<0.01$).

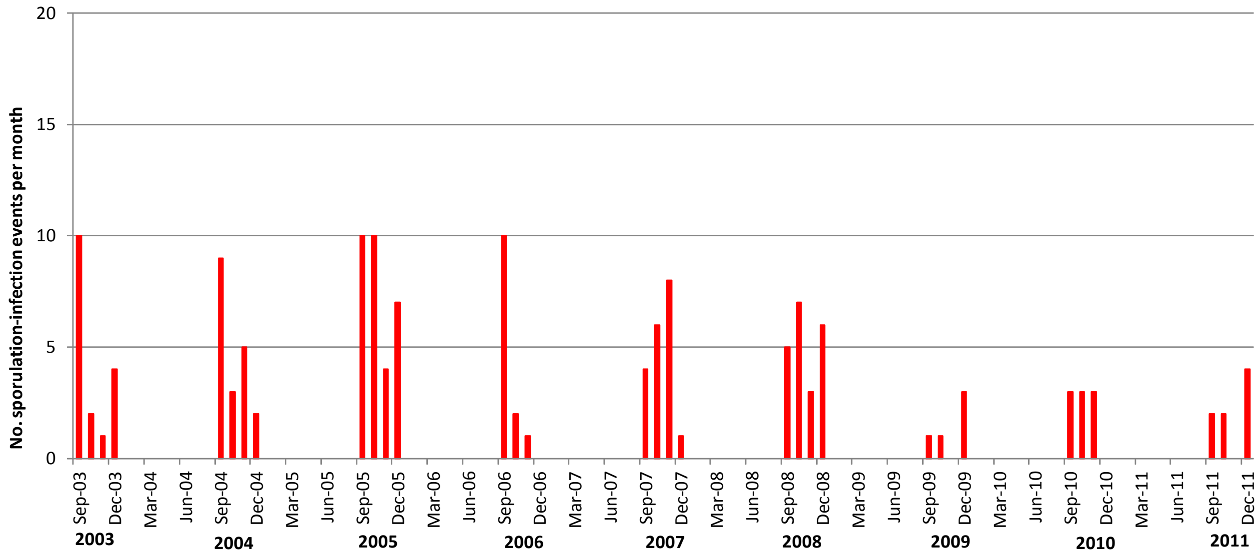
Current and future onion downy mildew risk in Canterbury (Lincoln)

RH readings at Lincoln were more reliable than at Pukekohe and could be used to summarise onion downy mildew risk for the current weather dataset and to investigate the effect of temperature changes on disease risk. For the upper limit temperature prediction for 2090, there was a small increase in number of sporulation-infection events per month between current and future temperatures (Figure 14).

Investigation of regression relationships between sporulation-infection events and rainfall in order to investigate predicted rainfall changes at Lincoln gave the same result as for Pukekohe. No relationships were found, except for hours >95% RH (Figure 15). Therefore effects of future rainfall changes on onion downy mildew risk in Canterbury could not be determined.



9-year averages for no. spor-inf. events					
	Sep	Oct	Nov	Dec	Mean
No events/month	5.9	3.8	2.3	2.7	3.7
No. months	9	9	9	9	36



9-year averages for no. spor-inf. events					
	Sep	Oct	Nov	Dec	Mean
No events/month	6.0	4.0	2.8	3.0	3.9
No. months	9	9	9	9	36

Figure 14: Lincoln, current weather dataset (green) and upper temperature limit for 2090 (red): Output from the DOWNCAST model showing mean number of number of onion downy mildew sporulation-infection events per month for nine years.

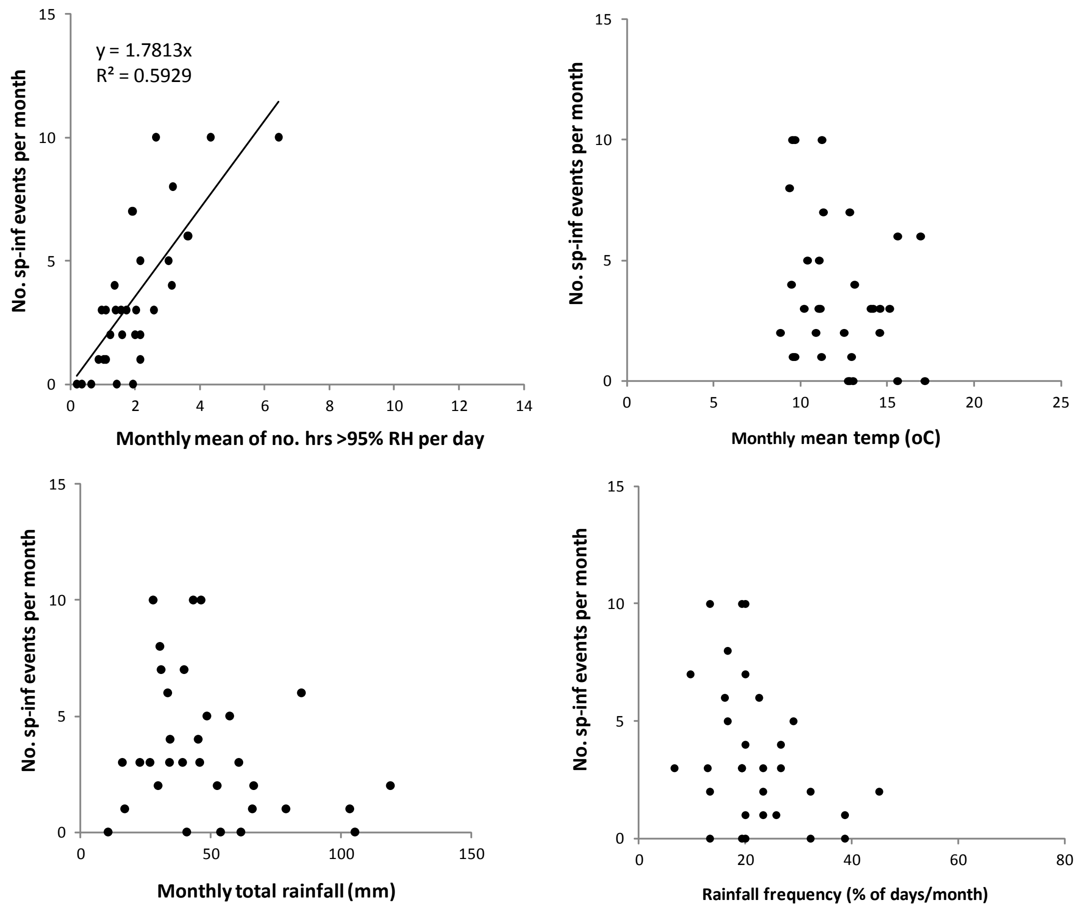


Figure 15: Lincoln, current weather dataset: Relationships between number of onion downy mildew sporulation-infection events per month and four weather variables that were summarised monthly over nine years. Only mean number of hours >95% relative humidity (RH) per day gave a significant regression coefficient ($P<0.05$).

Onion downy mildew conclusions

These analyses showed that the most extreme prediction for temperature increase (upper limit by 2090) might cause a small increase in onion downy mildew risk in Canterbury. Such an increase may require a slight future increase in use of fungicides against downy mildew, where the disease is currently a very minor problem.

Unfortunately climate change predictions for rainfall could not be analysed because no correlations were found between rainfall and downy mildew risk. This is not surprising considering that onion downy epidemics are driven by conditions of night-time dew associated with anticyclonic weather patterns. Unless future relative humidity and surface wetness data can be simulated, it will not be possible to predict the effects of climate change on downy mildew risk accurately.

The study of onion downy mildew risk was also hampered by the unreliability of RH records in the critical 95-100% RH range. At Pukekohe there was also the problem of a calibration shift in the RH sensor.

KIWIFRUIT BACTERIAL CANKER (PSA)

Psa risk model

Bacterial infection rate index (M_m)

The relationship between temperature (*T*) and rate at which Psa bacteria infect kiwifruit plants (M_m) in the presence of free water is given by the following equation (Beresford 2012):

$$M_m = -0.000003 * T^4 - 0.00011 * T^3 + 0.00201 * T^2 + 0.0541 * T + 0.247 \quad (1)$$

This relationship suggests an optimum temperature for infection of 15°C, below or above which infection declines (Figure 16). The Psa risk model calculates M_m from hourly temperature data and accumulates M_m values for hours when surface wetness is present.

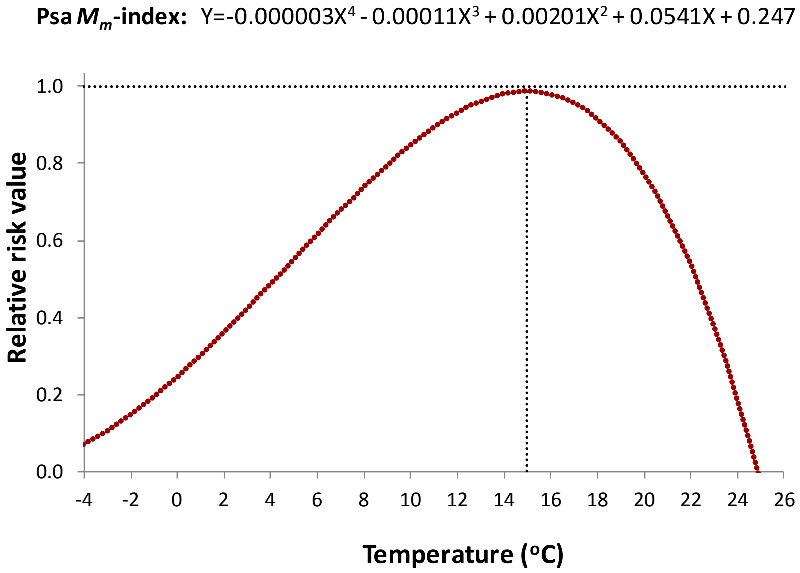


Figure 16: Influence of temperature during periods when surface wetness is present on the rate of infection of kiwifruit plants by *Pseudomonas syringae* pv. *actinidiae* (Psa).

Daily risk index (*R*)

The M_m index is used to calculate the daily risk index, *R,* which is the accumulation of M_m values over three days, e.g. the current day plus the two preceding days (72 h). *R* is the output at the end of the day (midnight), but only if total rainfall from 0100 h to midnight was >1.0 mm. The maximum possible value of *R* is 72.

Summarising Psa infection risk

Psa infection risk for the main kiwifruit growing regions of Northland, Bay of Plenty and Nelson was assessed using monthly means of daily *R*-index values. Effects of temperature changes due to climate change were examined by adjusting hourly temperatures in the current weather datasets using the seasonal temperature change predictions (Table 15) for the upper limit by 2090 (greatest predicted warming). Twelve-monthly *R*-index means were derived for each of nine years for each region. The lower limit temperature prediction was not investigated because predicted temperature change was very small and analyses for the other pathosystems in this study suggested that the associated change in Psa risk would be negligible.

Table 15: Temperature (°C) change predictions for 2040 and 2090 (corrected for 2008, Appendix 1), for three regions of interest for *Pseudomonas syringae* pv. *actinidiae* (Psa) of kiwifruit. Lower and upper limit climate predictions from 12 models are shown.

Key to temperature change colour codes					
0.0 – 0.9°C increase	1.0 – 1.9°C increase	2.0 – 2.9°C increase	3.0 – 3.9°C increase	4.0 – 4.9°C increase	5.0 – 5.9°C increase

Region		Lower limit				Upper limit			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Northland	2040	0.2	0.1	0.1	0.1	1.9	1.9	1.3	1.4
	2090	0.7	0.5	0.5	0.4	5.8	5.0	4.4	4.7
Bay of Plenty	2040	0.2	0.2	0.0	0.0	1.8	1.7	1.3	1.4
	2090	0.7	0.5	0.4	0.3	5.5	4.6	4.3	4.4
Nelson	2040	0.2	0.2	0.2	0.1	1.6	1.5	1.2	1.3
	2090	0.9	0.5	0.4	0.3	5.0	4.3	4.1	4.1

Rainfall adjustment for climate change

Effects of predicted rainfall changes on Psa infection risk were examined using regression relationships between monthly mean *R*-index and frequency of rainfall (percentage of days per month with >1 mm) for the current or temperature-adjusted datasets. Whereas there was a strong correlation in these weather datasets between rainfall frequency and *R*-index, there was a poor correlation for rainfall amount (Figure 17), which is the variable available from climate change predictions. Therefore, predicted percentage change in rainfall amount was assumed to represent percentage change in rainfall frequency for this analysis.

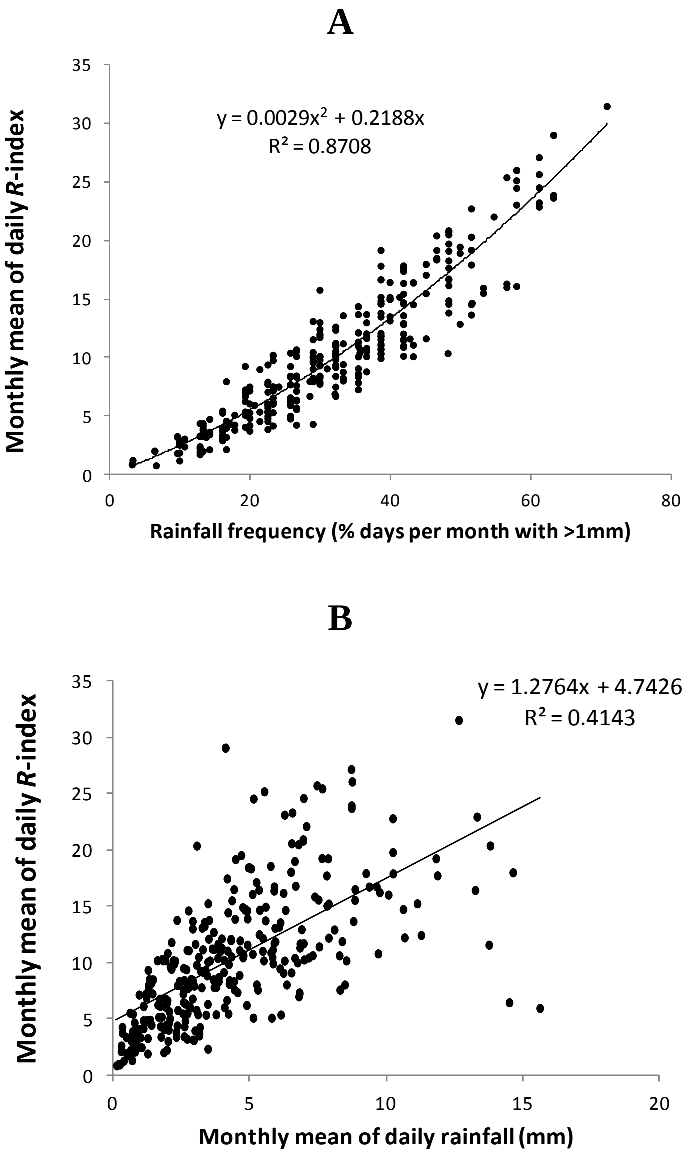


Figure 17: Relationships between monthly mean R-index and A, rainfall frequency and B, rainfall amount across three regions (Northland, Bay of Plenty and Nelson) for the current weather dataset from 2003 to 2012. The rainfall frequency regression was used to estimate effects of predicted future rainfall change on infection risk by *Pseudomonas syringae* pv. *actinidiae* (Psa).

Future rainfall change predictions (Table 16) were used with the appropriate regression equation derived from current or upper temperature limit datasets (Table 17) to predict future *R*-index values for lower and upper limit rainfall predictions for 2090. These scenarios represented the extremes in the range of climate change rainfall predictions.

Table 16: Rainfall (%) change predictions corrected for 2040 and 2090 (corrected for 2008, Appendix 1), for three regions of interest for *Pseudomonas syringae* pv. *actinidiae* (Psa) of kiwifruit. Lower and upper limit climate predictions from 12 models are shown.

Key to % rainfall change colour codes					
Much drier	Slightly drier	Little change	Slightly wetter	Much wetter	Very much wetter
20-39% decrease	10-19% decrease	0-9% decrease or increase	10-19% increase	20-39% increase	>40% increase

Region		Lower limit				Upper limit			
		Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring
Northland	2040	-9	-9	-13	-12	11	7	1	3
	2090	-20	-17	-22	-27	12	2	2	7
Bay of Plenty	2040	-9	-7	-8	-12	13	12	1	4
	2090	-13	-10	-8	-26	11	3	7	9
Nelson	2040	-8	-1	-2	-5	14	13	6	6
	2090	-7	-3	0	-17	17	12	16	16

Table 17: Regression parameters for the relationship between rainfall frequency and mean monthly *R*-index from three regions combined (Northland, Bay of Plenty and Nelson) that were used to determine *R*-index values to analyse effects of future rainfall change on infection risk by *Pseudomonas syringae* pv. *actinidiae* (Psa).

	Regression parameters		
Temperature dataset	X	X^2	R^2 (adj.)
Current	0.2188	0.0029	0.87
2090 Upper	0.1258	0.0042	0.70

Regional Psa infection risk for the current climate

Of the three regions examined, only the Bay of Plenty currently has kiwifruit orchards affected by Psa; the disease has not yet spread to Northland or Nelson. The findings about Psa infection risk in relation to Northland and Nelson are therefore entirely theoretical.

Current annual mean R-index values ranked Northland (12.2) >Bay of Plenty (10.9) >Nelson (8.1) for Psa infection risk. Analysis of variance of R-index values, using years as replicates, showed that the variation between the regions was significant (P<0.001) and that variation between months was also significant (P<0.001). However, the interaction between regional differences in risk and different months of the year was not significant (P=0.307), indicating that the regional trends tended to be consistent throughout the year (Figure 18).

Regional differences in Psa risk were heavily influenced by winter months (Figure 18), mainly because of warmer winter temperatures in the more northern regions. Nelson showed relatively low risk during summer and early autumn because of lower rainfall frequency during that time. Risks during spring, in all three regions, were quite similar. The relatively low *R*-index values in November compared with December resulted from the chance occurrence of several years with lower November and higher December rainfall frequencies.

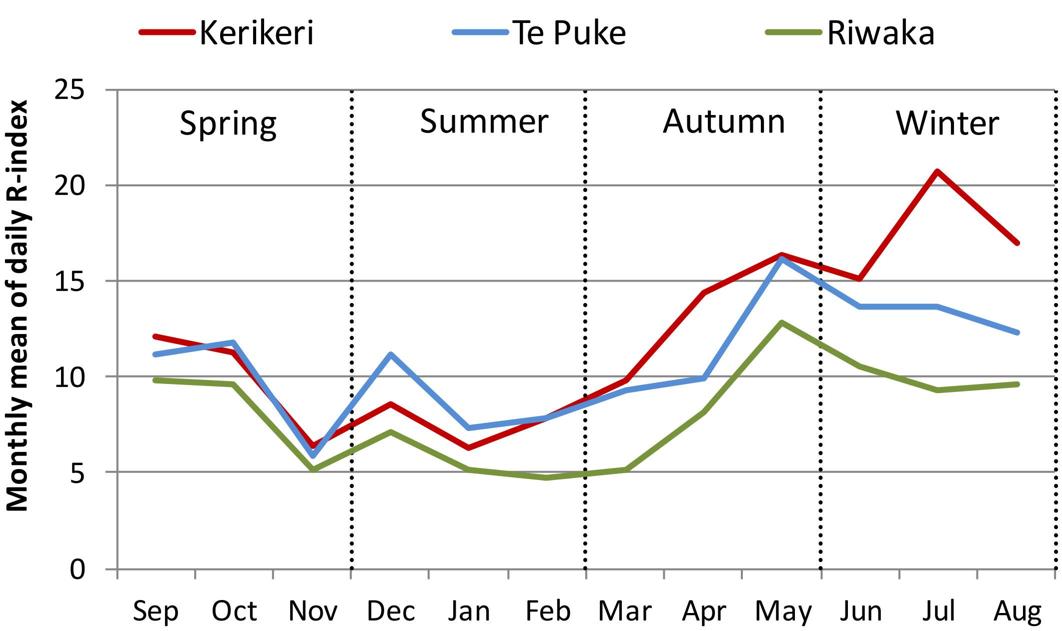


Figure 18: Current weather datasets monthly mean infection risk of *Pseudomonas syringae* pv. *actinidiae* (Psa) for three regions, Northland (Kerikeri), Bay of Plenty (Te Puke) and Nelson (Riwaka).

Effect of climate change predictions on Psa infection risk

Upper limit temperature prediction

By 2090, the upper limit temperature prediction is for an increase of 4.1 to 5.8°C (Table 15). This temperature change would cause a significant decrease in Psa risk for Northland and Bay of Plenty, but no change for Nelson (Table 18), assuming rainfall frequency were the same as at present. The reason that increased temperature would decrease disease risk is that higher summer temperature in the more northern regions would be more often above the optimum for Psa infection (15°C). This would make summer months much less favourable for disease development, even though the warmer winter temperatures would be slightly more favourable (Figure 19).

Table 18. Annual mean *R*-index values for infection risk of kiwifruit by *Pseudomonas syringae* pv. *actinidiae* (Psa) for three regions, Northland, Bay of Plenty and Nelson. The six selected scenarios were derived from the current weather dataset (T-current) and the upper temperature limit, 2090 dataset (T-upper). Rainfall effects are shown for the current dataset (R-current) and for the lower (R-lower) and upper (R-upper) limit rainfall predictions.

	Scenario					
	R-current		R-lower		R-upper	
Region	T-current	T-upper	T-current	T-upper	T-current	T-upper
Northland	12.2	9.9*	8.2*	6.8*	11.9	10.6
Bay of Plenty	10.9	9.1*	9.1*	7.6*	12.2	10.8
Nelson	8.1	8.1	8.2	6.8	10.8*	9.4

*Asterisks indicate means within a region that are significantly different from the R-current, T-current weather dataset (Fisher's unprotected LSD, α = 0.05).

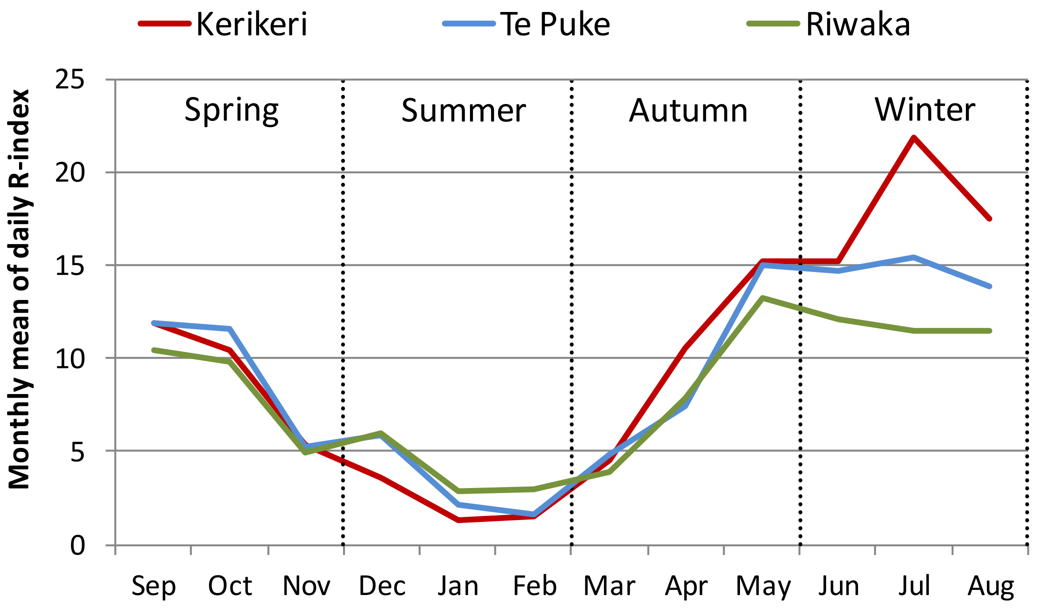


Figure 19: Rainfall (R-current), temperature (T-upper) weather datasets monthly mean infection risk of *Pseudomonas syringae* pv. *actinidiae* (Psa) for three regions, Northland (Kerikeri), Bay of Plenty (Te Puke) and Nelson (Riwaka).

Lower limit rainfall prediction

For rainfall predictions by 2090, the lower limit drying trend is greatest for the Far North (Table 16). Assuming the small temperature change for the lower limit prediction (Table 15) would produce negligible change in risk, the lower limit rainfall drying trend would cause a significant decrease in Psa infection risk for Bay of Plenty and Northland, but no significant change for Nelson (R-lower, T-current in Table 18). The substantial drying trend for the upper North Island would reduce both seasonal and regional variation in *R*-index values (Figure 20) compared with that in the current climate (Figure 18).

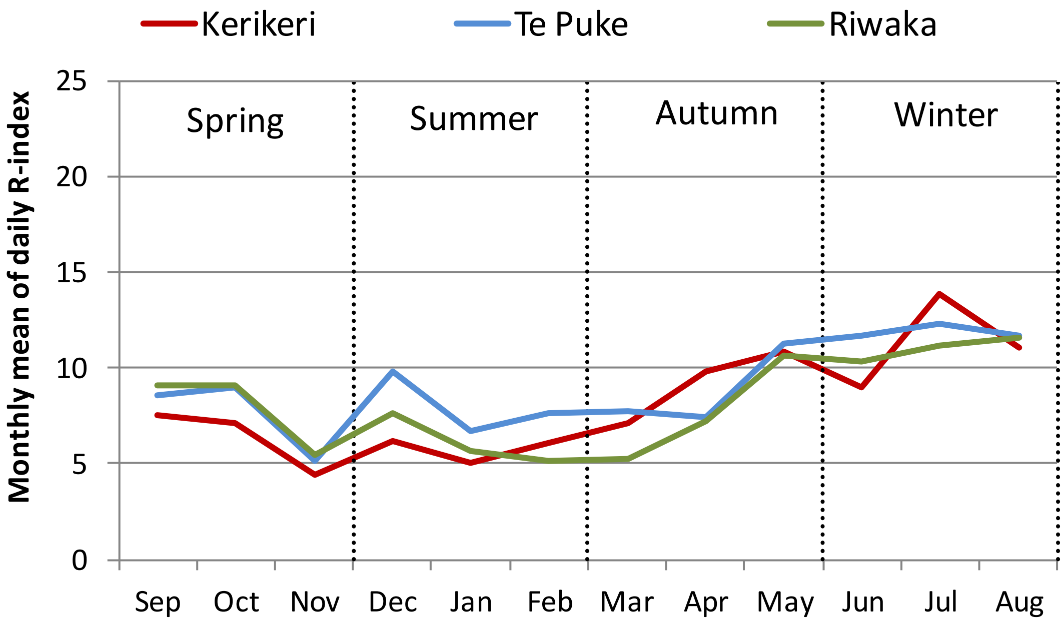


Figure 20: Rainfall (R-lower), temperature (T-current) weather datasets showing monthly mean infection risk of *Pseudomonas syringae* pv. *actinidiae* (Psa) for three regions, Northland (Kerikeri), Bay of Plenty (Te Puke) and Nelson (Riwaka).

Upper limit rainfall prediction
The trend for increasing rainfall by 2090 predicted for the upper rainfall limit was slightly greater for Nelson than for Northland or Bay of Plenty, which were more similar to one another (Table 16). The effect of these predictions on Psa risk would be for no significant change compared with that in the current climate (R-upper, T-upper in Table 18), although a tendency for slightly lower risk in Northland and Bay of Plenty and slightly greater risk in Nelson.

These predicted changes in disease risk resulted from interacting effects between seasonal changes in temperature and rainfall. In Nelson, Psa risk would increase during winter because of warmer winter temperatures and also during spring and summer because of increased rainfall (Figure 21 compared with Figure 18). However, in Northland and Bay of Plenty, risk would change little, because, although autumn risk would decrease because temperatures would be higher, it would be offset in summer by increased rainfall. The temperature and rainfall effects therefore tended to cancel each other, resulting in no significant change in overall risk and slightly lower regional and season variation than seen for the current climate (Figure 21).

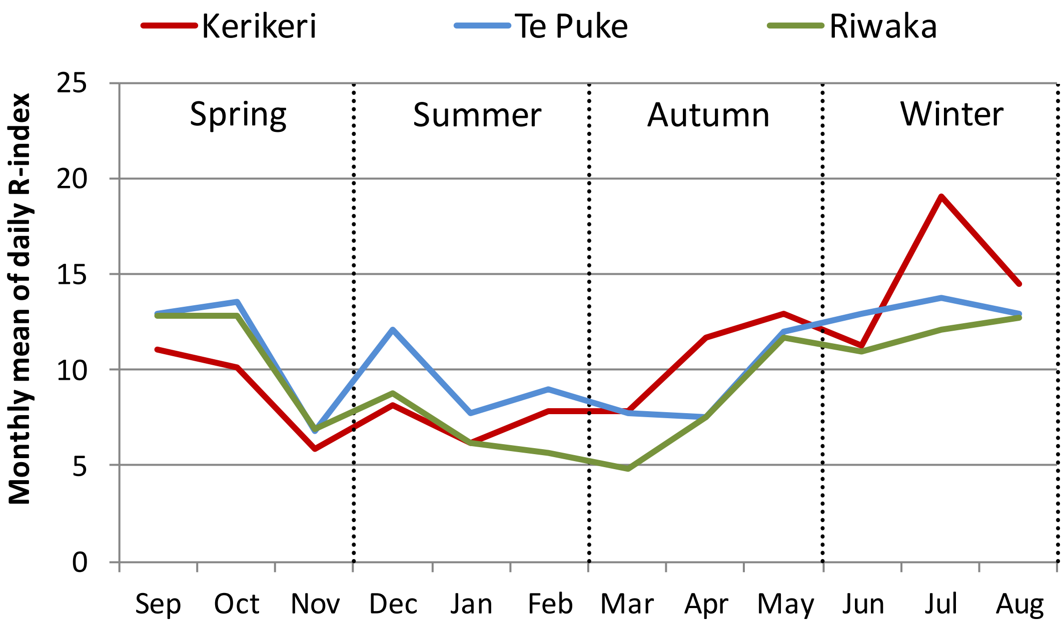


Figure 21: Rainfall (R-upper), temperature (T-upper) weather datasets showing monthly mean infection risk of *Pseudomonas syringae* pv. *actinidiae* (Psa) for three regions, Northland (Kerikeri), Bay of Plenty (Te Puke) and Nelson (Riwaka).

Overall influence of climate on the impact of Psa

Regional risk of Psa infection is lower in Nelson than in Northland or Bay of Plenty under current climatic conditions and would remain the same for most predictions of future climate. For the lower limit prediction by 2090 (similar temperature and decreased rainfall), Nelson showed negligible change in risk, whereas Northland and Bay of Plenty showed a significant decrease in risk, because of the decrease in rainfall. Despite the decreased risk in North Island regions, risk was still as high as or higher than in Nelson.

For the upper limit prediction by 2090 (increased temperature and increased rainfall), there was no significant change in overall Psa infection risk for any region because of the opposing effects from increased temperature, which decreased risk, and increased rainfall, which increased risk. For Northland and Bay of Plenty, greater climate warming would result in temperatures too high for Psa development from late spring, through summer, to early autumn. For Nelson, greater warming would result in temperatures more frequently near the optimum during all months, except in late summer and early autumn.

For the current climate, month-by month Psa risk tended to be consistent with mean annual risk for all regions. However, climate change scenarios introduced interactions between temperature and rainfall that produced different risk predictions for different seasons and regions. To resolve the effect of these interactions on Psa development in kiwifruit orchards, greater epidemiological knowledge would be required on the importance of infection during different months of the year.

General conclusions can be drawn about the impact of climate on the ability of kiwifruit growers to manage Psa in cultivars of differing susceptibility. The cultivar ‘Hort16A’ is the most susceptible to Psa damage and is the one on which the Psa risk model was developed. Use of any cultivar with lower susceptibility than ‘Hort16A’, combined with climatic conditions less favourable for Psa development, e.g. seasons that are warmer and drier than normal, or Nelson as a growing region (should Psa spread there), would improve the ability of kiwifruit growers to manage the disease.

This analysis has improved our understanding of Psa infection risk in relation to climatic trends within New Zealand. Further benefits would accrue from a global climatic assessment of Psa risk in kiwifruit production areas worldwide.

Discussion

IMPLICATIONS OF CLIMATE CHANGE FOR HORTICULTURAL DISEASE RISK

Temperature and rainfall effects on infection risk

The main features of the climate change predictions in relation to the pathosystems examined in this study were:

1. The large temperature increase for the upper limit change prediction, which was substantially greater for 2090 than for 2040
2. The drying trend for the lower limit prediction, producing a substantial decrease in rainfall for northern and eastern regions of the North Island
3. The rainfall increase for the upper limit prediction, especially for the South Island and especially in Central Otago.

These change features would affect each of the pathosystems as follows:

Apple black spot

The current regional ranking for black spot risk of Nelson>Hawke's Bay>Central Otago would remain for all future climate predictions. Greater increases in both temperature and rainfall would cause greater increases in black spot risk. For the worst case 2090 upper limit prediction, the greatest disease risk increase would occur in Nelson (4.4%) and the increase in Central Otago (2.1%) would give similar risk to that in Hawke's Bay at the current time, although not as great as in Nelson at the current time. These predicted changes in climate are unlikely to have a large impact on requirements for black spot control, assuming effective fungicides continue to be available, because frequent fungicide spraying already occurs in all regions. However, a further increase in black spot risk in Nelson would make disease control in this already difficult region even more challenging.

Grapevine downy mildew

The current regional ranking of grapevine downy mildew risk of Gisborne> Hawke's Bay>Marlborough>Canterbury>Otago varied only slightly in relation to the various climate change predictions. Greater increases in temperature and rainfall would cause greater increases in downy mildew risk. The greatest increase in risk would occur in Canterbury and Central Otago for the upper limit rainfall prediction. In these regions, the amount of fungicide spraying would have to be increased to that used in Gisborne at the present time.

Onion downy mildew

Currently, onion downy mildew risk is greater in Auckland/Waikato than in Canterbury (Whiteman & Beresford 1998). Increased temperature, even for the 2090 upper limit prediction, caused a negligible change in downy mildew risk. Effects of rainfall change could not be analysed because downy mildew risk depends on high relative humidity (RH) and no correlation with rainfall could be found. The greater risk in Auckland for the current climate is probably caused by greater RH and surface wetness duration. Definite conclusions about the effect of climate change on onion downy mildew cannot be drawn.

Kiwifruit bacterial canker (Psa)

The current regional ranking of Psa risk of Northland> Bay of Plenty>Nelson would remain under most climate change predictions. The main difference in the Psa risk response compared with the other pathosystems was that increased temperature would cause Psa risk to decrease, especially in North Island regions. This was because warmer spring and summer temperatures would often be above the optimum for infection. The lower limit predicted drying trend would decrease infection risk in all regions, particularly in Bay of Plenty and Northland. Nelson showed only very a small change in Psa infection risk for any of the climate change predictions.

Given that future rainfall variability is expected to increase more in areas with an increase in average rainfall (more frequent extreme events), the major impact of climate change is likely to be greater fluctuation in disease from year to year, rather than an important increase in average disease risk in a given region. If some seasons have exceptionally wetter conditions than currently occur, the increase in disease could be greater than estimated in this analysis.

Time frames for climate change and horticultural adaptation

The disease risk changes predicted in this study were quite small, even for the worst case upper limit climate prediction. Uncertainty in predicted rainfall, the main driver of disease risk (upper and lower limits were contradictory) would make it challenging to recommend adaptation strategies. For example, if Central Otago experienced an increase in disease risk that was significant by 2090, how should the pipfruit and wine sectors and regional council respond? Given that the effects of the predicted trend would be hardly noticeable for another 40-80 years, and that other climate change scenarios might result in contradictory predictions in relation to plant disease risk, there is little pre-emptive action that could be taken within the next 10-20 years.

The 40-80 year time frame for the predicted changes in climate to become important is long in relation to the rate at which horticultural industries have adapted in the past to changing regional production and market factors, e.g. new cultivars, new production systems and new market niches for specialist horticultural products. Unless climate change causes more catastrophic changes than those predicted in the MfE (2008) report, it seems unlikely that New Zealand horticulture will have difficulty adapting to changes in plant disease risk. Nevertheless, this analysis was worthwhile in order to examine objectively the implications of expected changes and to promote planning for the future in a general way.

The seasonal period when crop plants are susceptible to infection affects severity of disease epidemics. For example, for apple black spot, budburst date is important in determining when primary infection by *V. inaequalis* ascospores occurs. Budburst date is affected by winter chilling, which would decrease with increasing winter temperature. Therefore increase in temperature could affect disease risk in ways other than its direct effect on infection risk. Future studies of climate change impacts on plant disease risk need to consider wider aspects of horticultural production, such as the seasonality of crop growth.

The predominant cultivars for any crop that will be planted in 2090, or even 2040, cannot be identified at present. As the climate change time frame is well within the time frame for breeding new crop cultivars, if fruit crop breeders were able to focus on developing cultivars with lower disease susceptibility, rather than restricting efforts to improved fruit quality, the impact climate change may have on disease risk could be greatly reduced.

Methodology used in this study

The quantitative models used in this study provided objectivity and precision of analysis not possible from qualitative analysis. However, the weather-based disease risk models are a simplified representation of factors influencing disease development. They describe correlations between key weather variables and key pathogen process that limit disease, such as spore production, spore dispersal or infection. While these processes are important during the crop development period, other weather-dependent aspects of pathogen biology may also be important, such as effects of temperature on disease carry-over through winter. Although these were not considered in this study, they could be included in future studies.

The approach we used of simulating future climatic conditions by modifying current weather datasets had the advantage of providing variability in future weather to enable statistical comparison of disease risk between current and future climates. However, it is likely weather variability will increase in the future with global warming. For rainfall, which is particularly important for plant diseases, increased occurrence of extreme events could greatly increase disease risk in some seasons. In that way, these analyses may have underestimated increases in disease risk, particularly for the worst case of upper limit changes by 2090.

Acknowledgements

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APPENDIX 1. Corrections for 2008-based datasets

Corrected temperature and rainfall change values (20-year averages) for the lower and upper limit predictions from climate models for 2008-2040 and 2008-2090. Predicted changes from 1990 (MfE 2008) are also shown for comparison.

Northland lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Northland (Kaitaia)	Lower lim	2040	Summer	0.3	0.2	-15	-9
			Autumn	0.2	0.1	-14	-9
			Winter	0.1	0.1	-23	-13
			Spring	0.1	0.1	-18	-12
		2090	Summer	0.8	0.7	-26	-20
			Autumn	0.6	0.5	-22	-17
			Winter	0.5	0.5	-32	-22
			Spring	0.4	0.4	-33	-27

Northland upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Northland (Kaitaia)	Upper lim	2040	Summer	2.7	1.9	20	11
			Autumn	2.9	1.9	16	7
			Winter	2.4	1.3	1	1
			Spring	2.2	1.4	4	3
		2090	Summer	6.6	5.8	21	12
			Autumn	6	5.0	11	2
			Winter	5.5	4.4	2	2
			Spring	5.5	4.7	8	7

Auckland lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Auckland (Mangere)	Lower lim	2040	Summer	0.3	0.2	-17	-11
			Autumn	0.2	0.1	-14	-9
			Winter	0.2	0.1	-10	-4
			Spring	0.1	0.1	-15	-10
		2090	Summer	0.8	0.7	-33	-27
			Autumn	0.6	0.5	-21	-16
			Winter	0.5	0.4	-12	-6
			Spring	0.4	0.4	-30	-25

Auckland upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Auckland (Mangere)	Upper lim	2040	Summer	2.6	1.8	20	11
			Autumn	2.8	1.8	17	9
			Winter	2.4	1.3	5	3
			Spring	2.2	1.4	10	5
		2090	Summer	6.5	5.7	20	11
			Autumn	5.9	4.9	12	4
			Winter	5.5	4.4	9	7
			Spring	5.4	4.6	11	6

Bay of Plenty lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Bay of Ple (Tauranga)	Lower lim	2040	Summer	0.3	0.2	-16	-9
			Autumn	0.3	0.2	-12	-7
			Winter	0.1	0.0	-16	-8
			Spring	0	0.0	-18	-12
		2090	Summer	0.8	0.7	-20	-13
			Autumn	0.6	0.5	-15	-10
			Winter	0.5	0.4	-16	-8
			Spring	0.3	0.3	-32	-26

Bay of Plenty upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Bay of Ple (Tauranga)	Upper lim	2040	Summer	2.5	1.8	25	13
			Autumn	2.7	1.7	25	12
			Winter	2.2	1.3	2	1
			Spring	2.1	1.4	7	4
		2090	Summer	6.2	5.5	23	11
			Autumn	5.6	4.6	16	3
			Winter	5.2	4.3	8	7
			Spring	5.1	4.4	12	9

Hawke's Bay lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Hawke's Bay (Napier)	Lower lim	2040	Summer	0.2	0.2	-33	-19
			Autumn	0.3	0.2	-14	-8
			Winter	0.1	0.0	-1	14
			Spring	0	0.0	-17	-11
		2090	Summer	0.8	0.8	-46	-32
			Autumn	0.6	0.5	-14	-8
			Winter	0.5	0.4	-1	14
			Spring	0.3	0.3	-38	-32

Hawke's Bay upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Hawke's Bay (Napier)	Upper lim	2040	Summer	2.5	1.8	38	21
			Autumn	2.6	1.7	42	19
			Winter	2.2	1.2	-1	-1
			Spring	2	1.4	3	2
		2090	Summer	6	5.3	52	35
			Autumn	5.3	4.4	25	2
			Winter	5.1	4.1	-1	-1
			Spring	5.1	4.5	9	8

Gisborne lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Gisborne (Gisborne)	Lower lim	2040	Summer	0.2	0.2	-26	-15
			Autumn	0.3	0.2	-18	-11
			Winter	0.1	0.0	-2	13
			Spring	0	0.0	-21	-13
		2090	Summer	0.8	0.8	-38	-27
			Autumn	0.6	0.5	-25	-18
			Winter	0.5	0.4	1	16
			Spring	0.3	0.3	-42	-34

Gisborne upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Gisborne (Gisborne)	Upper lim	2040	Summer	2.6	1.8	33	18
			Autumn	2.7	1.7	46	16
			Winter	2.2	1.3	-2	-3
			Spring	2.1	1.4	3	2
		2090	Summer	6.2	5.4	41	26
			Autumn	5.6	4.6	27	-3
			Winter	5.2	4.3	1	0
			Spring	5.2	4.5	7	6

Appendix 1 cont …

Tasman-Nelson lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Tasman-N (Nelson)	Lower lim	2040	Summer	0.2	0.2	-14	-8
			Autumn	0.2	0.1	-2	-1
			Winter	0.2	0.1	-4	-2
			Spring	0.1	0.1	-8	-5
		2090	Summer	0.9	0.9	-13	-7
			Autumn	0.6	0.5	-4	-3
			Winter	0.5	0.4	-2	0
			Spring	0.3	0.3	-20	-17

Tasman-Nelson upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Tasman-N (Nelson)	Upper lim	2040	Summer	2.2	1.6	27	14
			Autumn	2.3	1.5	19	13
			Winter	2	1.2	9	6
			Spring	1.8	1.3	9	6
		2090	Summer	5.6	5.0	30	17
			Autumn	5.1	4.3	18	12
			Winter	4.9	4.1	19	16
			Spring	4.6	4.1	19	16

Marlborough lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Marlborou (Blenheim)	Lower lim	2040	Summer	0.2	0.2	-16	-8
			Autumn	0.2	0.1	-4	-2
			Winter	0.2	0.1	-10	-5
			Spring	0.1	0.1	-7	-4
		2090	Summer	0.9	0.9	-15	-7
			Autumn	0.6	0.5	-5	-3
			Winter	0.6	0.5	-14	-9
			Spring	0.3	0.3	-18	-15

Marlborough upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Marlborou (Blenheim)	Upper lim	2040	Summer	2.1	1.4	25	13
			Autumn	2.4	1.5	24	11
			Winter	2	1.2	7	3
			Spring	1.8	1.3	10	6
		2090	Summer	5.6	4.9	28	16
			Autumn	5	4.1	16	3
			Winter	5	4.2	9	5
			Spring	4.8	4.3	20	16

Canterbury lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Canterbur (Christchurch)	Lower lim	2040	Summer	0.1	0.1	-15	-9
			Autumn	0.2	0.2	-10	-4
			Winter	0.4	0.4	-30	-17
			Spring	0.2	0.1	-8	-5
		2090	Summer	0.8	0.8	-17	-11
			Autumn	0.7	0.7	-6	0
			Winter	0.8	0.8	-41	-28
			Spring	0.4	0.3	-15	-12

Canterbury upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Canterbur (Christchurch)	Upper lim	2040	Summer	2.2	1.5	22	12
			Autumn	2.2	1.5	30	11
			Winter	2	1.2	7	4
			Spring	1.8	1.3	9	6
		2090	Summer	5.2	4.5	25	15
			Autumn	4.9	4.2	20	1
			Winter	5.1	4.3	10	7
			Spring	4.7	4.2	25	22

Otago lower limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Otago (Queenstown)	Lower lim	2040	Summer	0	0.1	-16	-10
			Autumn	0.1	0.2	-15	-10
			Winter	0.3	0.3	2	1
			Spring	0	0.0	-3	0
		2090	Summer	0.7	0.8	-38	-32
			Autumn	0.8	0.9	-32	-27
			Winter	0.8	0.8	7	6
			Spring	0.5	0.5	15	18

Otago upper limit

Region	Scenario	Predicted year and season		Temperature (oC) Change from 1990	Temperature (oC) Change from 2008	Rainfall (%) Change from 1990	Rainfall (%) Change from 2008
Otago (Queenstown)	Upper lim	2040	Summer	2.4	1.5	20	12
			Autumn	1.9	1.3	23	10
			Winter	2.1	1.4	38	24
			Spring	1.8	1.2	21	14
		2090	Summer	4.8	3.9	37	29
			Autumn	4.6	4.0	20	7
			Winter	4.8	4.1	76	62
			Spring	4.3	3.7	50	43

APPENDIX 2. Locations of Plant & Food Research/HortPlus™ weather stations