The Current and Future Potential Distribution of Guava Rust, *Puccinia psidii* in New Zealand

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EXECUTIVE SUMMARY

Objective

The objective of this study was to assess the potential for *Puccinia psidii* (guava rust, eucalypt rust) to establish and persist in New Zealand under current and future climate scenarios.

Key Results

The major results of the study were:
1. Under current climate conditions, *Puccina psidii* appears to be capable of establishing and persisting in all of the mid-to low-altitude areas of the North Island, and a substantial part of the more agriculturally productive areas of the South Island of New Zealand. The degree of climate suitability on the North Island appears very high.
2. Climate change will exacerbate these risks, substantially increasing the climatic suitability of New Zealand for *P. psidii*.
3. The rapid rate at which *P. psidii* invaded the State of Hawai'i suggests that it could spread rapidly throughout the Pacific islands, eventually reaching New Zealand.

Application of Results

New Zealand should consider actively monitoring high risk sites in regions that have been identified as posing a future threat of invasion by *P. psidii*. The use of trap plants as onshore and offshore sentinels is likely to provide a cost-effective means of monitoring an invasion pathway. The degree of threat supports the development of education materials as a means of increasing the surveillance effort through empowering and engaging public support and increasing its effectiveness by focusing the attention of biosecurity surveyors on this problem.

Given the high climatic suitability of New Zealand for *P. psidii,* and its demonstrated capacity for rapid spread, it would seem prudent that commercially important Myrtaceae should be protected. Where these species are grown in areas of New Zealand that are projected to be suitable for *P. psidii*, they should be profiled for susceptibility, and where possible, resistant varieties should be identified or developed. Depending upon the circumstances, these varieties could either be deployed at present, or held in a repository, ready for use should *P. psidii* be detected in New Zealand. For iconic endemic Myrtaceae, particularly those that are keystone species in their respective ecosystems, it may be especially prudent to identify resistant genotypes so that remedial action can be implemented rapidly should the need arise. As a means of defraying costs, these genotypes could be preferentially planted as amenity plants in gardens that would act as resistant reservoirs.

Further Work

Preliminary qualitative modelling work in Australia indicated that the levels of genetic resistance in populations of native Myrtaceae was likely to be a key factor in determining the short-and medium-term impacts of an invasion by *P. psidii*. Profiling the susceptibility of important New Zealand native and exotic flora may be worthwhile in terms of increasing the understanding of the threat posed by *P. psidii*.

1. Introduction

Puccinia psidii Winter (Basidiomycetes, Uredinales) (common names: guava rust, eucalyptus rust) is native to South and Central America and possibly the Caribbean (Coutinho *et al.* 1998). This highly polyphagous rust is an important pathogen of guava (*Psidium pomiferum*), eucalyptus and other Myrtaceae, including *Melaleuca* spp., *Syzygium* spp., and *Eugenia* spp. (Coutinho *et al.* 1998; Rayachhetry *et al.* 2001; Tommerup, Alfenas & Old 2003, see Appendix 1). In recent times it has been observed in Hawai'i, where it attacks the native Ohi'a (*Metrosideros polymorpha*), the introduced invasive rose apple (*Syzygium jambos*) and other plants (Killgore & Heu 2005). Of most interest to New Zealand biosecurity are the potential threats to native Myrtaceae such as the iconic Pohutukawa, *Meterosideros excelsa*, Manuka, *Leptospermum scoparium,* and Kanuka, *Kunzea ericoides* as well as the introduced *Eucalyptus* spp. that constitute a small but significant component of the New Zealand Forest Plantation Estate.

There have been at least two previous published attempts to estimate the invasive potential of *P. psidii*. Booth, Old & Jovanovic (2000) used a homoclime analysis, and focused their attention on the potential threat to Australia (Booth, Old & Jovanovic 2000); the implied threat to New Zealand from *P. psidii* was equivocal. Subsequently Magarey *et al.* (2007) used NAPPFAST to estimate the potential for *P. psidii* persistence on a global scale, but provided little detail on the threat to New Zealand under current climatic conditions.

There are a variety of methods for estimating the potential distribution of an organism in a novel environment such as on a new continent or under climate change scenarios (Kriticos & Randall 2001). CLIMEX (Sutherst *et al.* 2007b) is a popular tool for predicting the potential distribution of invasive alien species. CLIMEX has two models – Compare Locations and Match Climates. Compare Locations models have several advantages over regression-based models such as GARP and Bioclim. Being a process-based model, it simulates climate in a biologically meaningful manner. The primary information to build Compare Locations models is the known geographic distribution of the organism being modelled. In addition to geographical data, information on the ecophysiology and growth phenology of the organism may also be used to parameterise CLIMEX models. By considering such a wide variety of data sources, the resulting model can be internally *verified*. It is often possible to also use available data sources in such a manner that various parts of the model can be *validated*. The more that a model can be *validated*, the more confidence can be attached to the projections.

CLIMEX Compare Locations models have been used successfully to model the potential distribution and relative abundance of plant pathogens (Morin, Batchelor & Scott ; Brasier & Scott 1994; Lanoiselet, Cother & Ash 2002; Hoddle 2004; Yonow, Kriticos & Medd 2004; Paul *et al.* 2005; Venette & Cohen 2006; Watt *et al.* submitted). Where available information is insufficient to develop a reliable Compare Locations model, it is possible to use climate matching techniques such as the CLIMEX Match Climates model to make some estimates of the invasion potential of pathogens (Pethybridge, Nelson & Wilson 2003; Viljanen-Rollinson *et al.* 2006). Using the Match Climates model it is possible to identify sites with climates that are closely matched to sites that are known to be suitable for the pest species. This is necessarily a weaker form of model than the Compare Locations models as it suffers from the fact that the connexion between the eco-physiological requirements of the modelled organism and the climatic conditions that it can tolerate are much weaker. In addition, the pattern of dissimilarity between inhabited climates and similar climates does not vary in terms of climate suitability. If climates for sub-optimal sites are being matched, then sites that are less similar than input locations may in fact be more suitable for the organism (Csurhes & Kriticos 1994).

A recent enhancement to CLIMEX in version 3 (Sutherst *et al.* 2007b) is the Region Match function, which provides the ability to select a set of input locations, and to run the Match Climates function, comparing each station in the input set with all other climate stations being considered. The model produces the best match index value for each station when compared with all of the input locations.

Climate changes associated with global warming are altering the invasion risk profiles for many species and jurisdictions, including New Zealand (Kriticos 2006; Kriticos 2007). As climates warm, cold stress limits are relaxed and species are able to colonise areas at higher latitude and/or altitude than have generally been experienced in historical times (Sutherst *et al.* 2007a). Whilst it is possible to apply climate change scenarios to regression-based climate matching models, these techniques have generally proved unreliable, producing modelling artefacts such as range contractions instead of range shifts (e.g., Beaumont & Hughes 2002). In the late 1990s, Global Climate Model (GCM) outputs were too erratic to be suitable for use in understanding pest risks, and so sensitivity analyses were generally used to assess the likely effects of climate change (Brasier & Scott 1994; Kriticos *et al.* 2003a; Kriticos *et al.* 2003b). The science of modelling global climates has now matured to the point where GCM projections are fairly stable, and they can be used within bioclimatic models with a moderate degree of certainty (Kriticos, Alexander & Kolomeitz 2006; Stephens, Kriticos & Leriche 2007; Leriche *et al.* 2007).

The invasion of Hawai'i by *P. psidii* presents opportunities to study in greater detail the geographic and climatic limitations of *P. psidii* establishment and spread. This is valuable information for those jurisdictions that may be at risk of invasion by *P. psidii*. Hawai'i has extremely steep climatic gradients, covering an extremely wide range of climatic conditions within a very limited area. It also has some very susceptible hosts that are widespread. Despite being present in Hawai'i for a relatively short period of time, it is likely that *P. psidii* has had the opportunity to spread to all suitable climates available within the area. Of particular relevance to New Zealand biosecurity are the highest location records on the island of Hawai'i, as these could indicate the cold tolerance limits for *P. psidii*. The challenge in making use of this information is that Hawai'i has relatively few climate stations. The most critical variables here are the temperature variables. Fortunately, these behave fairly predictably with respect to altitude, so it is possible to use splining techniques to accurately interpolate climate averages.

In this report, we applied several modelling techniques to estimate the climatic suitability of New Zealand for *P. psidii* under a range of climate scenarios. Three approaches were used: CLIMEX Compare Locations and Match Regions (Sutherst *et al.* 2007b), and NAPPFAST (Magarey *et al.* 2007).

2.   Materials and Methods

2.1.   BASE CLIMATE DATA

The primary base climatology used in this project is the 0.5 degree climate normals for 1971-2000. We chose to use this data as it possibly matches more closely the present distribution of *P. psidii*, better satisfying the implicit assumption that the distribution of the target organism is at equilibrium with the climate used to infer its current range limits. These climate data were calculated from the gridded time series data developed by the University of East Anglia Climate Research Unit (Mitchell *et al.* 2004). The monthly values in the time series data were first averaged by month. The methods of estimating missing variables based upon the available variables for processing the CRU 1961-1990 climate normals for use in CLIMEX are the same as those described in Stephens et al. (2007). The 1961-1990 climate surface from the CRU has proven to be quite reliable, and no systematic or serious idiosyncratic errors have been noted. A comparison between the 1961-1990 and 1971-2000 datasets using the *P. psidii* model revealed no apparent systematic or serious idiosyncratic errors in the newer dataset.

The existing climate data for Hawai'i was very scant, and on these islands the climatic gradients are extremely steep for both rainfall and temperature. We attempted to supplement the available data through the US National Climatic Data Centre and the United States Geological Survey. Whilst it was possible to supplement the existing data with additional temperature, and to a lesser extent rainfall records, it was impossible to locate any additional source of data variables to gauge atmospheric wetness (e.g., absolute humidity, relative humidity, vapour pressure, or vapour pressure deficit). In an attempt to overcome this problem, a new set of surfaces were generated using New Loc Clim (Grieser2004; Gommes, Grieser & Bernardi 2004). A digital elevation model was developed from the Shuttle Radar Topography Mission (SRTM) data (Farr *et al.* 2007) by extracting values for a 0.025 degree regular grid of points within the land areas of the State of Hawai'i. This DEM was provided to New LocClim as a means of adjusting the interpolation of meteorological station data to account for topographic variation. The thin-plate spline was selected as the interpolation method as this has been used successfully in Australia and elsewhere to produce high quality climate surfaces. The resulting surfaces for Hawai'i appear to adequately represent the temperature surfaces, and the rainfall for the wetter areas. However, the representation of precipitation in the drier areas is not satisfactory when compared with the Rainfall Atlas of Hawai'i (Giambelluca *et al.* 1986), or field observations of vegetation patterns (DJK, pers. obs.).

2.2.   CLIMATE CHANGE SCENARIOS

CSIRO has also developed a series of climate change datasets for use in CLIMEX. These scenarios have been developed from Global Climate Models (GCMs) run using two standard IPCC emissions scenarios (A1B and A2) drawn from the set of standardised emissions scenarios (IPCC 2000). The GCM data employed in this project were drawn from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl *et al.* 2007). We selected three models that satisfied the following criteria: 1) they had to have available monthly means of daily minimum and maximum temperature, monthly rainfall total, and monthly surface level specific humidity for the A1B and A2 emissions scenarios, 2) had a relatively small horizontal grid spacing, and 3) they had to have a high skill score (Watterson 1996) in representing the observed climate in Australia between 1980 and 1999 (Hennessy & Colman 2007). The latter attribute is the best indication that the models are likely to perform well for New Zealand. In recognition of the

observations by Rahmstorf et al. (2007) that recent global historical temperature and emissions observations indicate that we are tracking "hot" we only include the higher emissions scenarios in this project. The three GCMs that best met the selection criteria are: CSIRO Mark 3.0 (CSIRO, Australia), NCAR – CCSM (National Centre for Atmospheric Research, USA), and MIROC -H (Centre for Climate Research, Japan). Data from these GCMs were pattern-scaled to develop individual change scenarios relative to the base climatology (Whetton *et al.* 2005). The three models also cover a range of climate sensitivity i.e., the amount of global warming for a doubling of the atmospheric CO_2 concentration compared with 1990 levels. The respective sensitivities are: CSIRO Mark 3.0 (2.11 °C), NCAR -CCSM (2.47 °C) MIROC-H (4.13 °C).

2.3. GEOGRAPHICAL DISTRIBUTION OF PUCCINA PSIDII

The historical distribution of *P. psidii* was assembled from available sources. Booth et al (2000) had reported nine point locations where *P. psidii* had been noted in South America. In the USA, Anne Marie La Rosa (USFS) provided a set of counties in Florida and California where *P. psidii* had been recorded (unpub. data). In Hawai'i, historical survey locations had been gathered by Robert Anderson, Cherisa Coles, Anne Marie La Rosa, Janice Uchida and Mee Sook Kim (University of Hawai'i, unpub. data). As part of this project, these historical data were supplemented by a roadside survey of the island of Hawai'i by Robert Anderson in May 2008 (unpub. data). The CABI Crop Protection Compendium included many country-level occurrence records. The point distribution records for *P. psidii* indicated in Magarey *et al.* (2007) represent the centroids of country level data, and not point locations as such. The resulting known distribution of *P. psidii* is given in Figure 1.
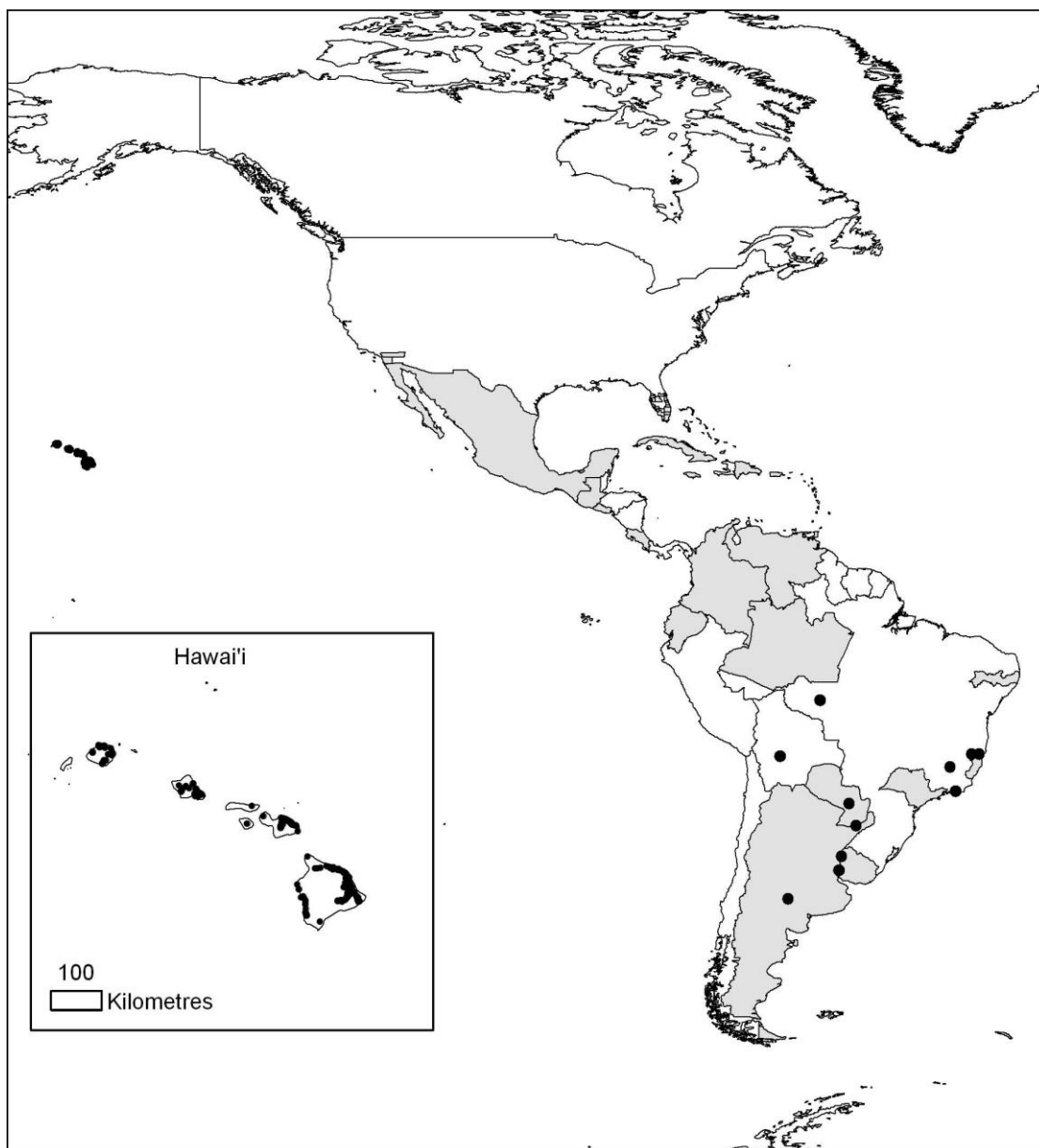
Figure 1: The known worldwide distribution of *Puccinia psidii*. The North American records are at the county level of resolution. Shaded areas indicate records where administrative regions are reported, and no more details are known. Dots represent known point locations. See text for sources of data.

2.4.   COMPARE LOCATIONS MODEL

The two main sources of information for fitting the Compare Locations model were the geographical distribution data and the ecophysiological observations of Ruiz *et al.* (1989). The stress parameters were adjusted until the Ecoclimatic Index indicated that the species could persist at all known locations. The country level data reported in the CABI Crop Protection Compendium and elsewhere were not used directly in the model fitting. These data are too coarse to guide parameter selection. The role of these records in the modelling is to provide some level of model verification where somewhere in the countries that have reliable presence records is projected to be climatically suitable. The parameters are presented in Table 1, and their derivation is discussed below.

Table 1 CLIMEX Compare Locations Model Parameters for *Puccinia psidii*.Mnemonics are taken from Sutherst et al. (2007b)

Index	Parameter	*Value*[a]
Temperature	DV0 = lower threshold	12 ºC
	DV1 = lower optimum temperature	20 ºC
	DV2 = upper optimum temperature	25 ºC
	DV3 = upper threshold	32 ºC
Moisture	SM0 = lower soil moisture threshold	0.25
	SM1 = lower optimum soil moisture	1
	SM2 = upper optimum soil moisture	1.5
	SM3 = upper soil moisture threshold	2
Cold stress	TTCS = temperature threshold THCS = stress accumulation rate	2.5 ºC -0.0045 Week$_{-1}$
Heat stress	TTHS = temperature threshold THHS = stress accumulation rate	32 ºC 0.002 Week$_{-1}$
Dry stress	SMDS = threshold soil moisture HDS = stress accumulation rate	0.2 -0.012 Week$_{-1}$
Annual Heat Sum	PDD = degree-day threshold[b]	580 ºC Days

[a] Values without units are a dimensionless index of a 100 mm single bucket soil moisture profile.
[b] Minimum annual total number of degree-days above DV0 needed for population persistence.

The Temperature Index parameters for *P. psidii* were taken from the observations by Ruiz *et al.* (1989) of the requirements for germination. Using these parameters it is apparent that the low temperature requirements for germination are not limiting the distribution of *P. psidii* because the cold stress threshold is considerably different to the minimum value for development.

The soil moisture indices were set in consideration of the distribution of the rust in Hawai'i and Argentina. The upper soil moisture values were adjusted to allow P. psidii to thrive in the extremely wet areas to the north of Hilo on the island of Hawai'i. The lower soil moisture threshold for development (DV0) was adjusted downwards to allow it to barely persist at Misiones in south western Argentina.

The minimum annual heat sum for population reproduction (580 degree days above DV0 was set to allow persistence at the highest elevation record on the island of Maui in Hawai'i.

Cold Stress was used to limit the potential range of *P. psidii* in the vicinity of the single Bolivian record. Using these parameters, the model also limits the range about 100 km south west of the westernmost location record in Argentina (Misiones), providing some additional confidence in this limit. The cold stress temperature threshold (TTCS = monthly average daily minimum of 2.5 °C) is associated with frost events (about 1 per week). This limit is probably associated with the temperature tolerances of the known hosts, rather than a direct physiological impact on *P. psidii*.

The dry stress parameters were set to barely allow persistence at the driest location on the island of O'ahu. Using these parameters, there is a considerable amount of dry stress (64) at the single high elevation location record in Bolivia (Fig 1).

On the island of Hawai'i *P. psidii* is present in all areas sampled throughout the area west of Hilo on the eastern side of the island, which, according to Giambelluca *et al.* (1986) appears to receive extremely large rainfall totals throughout the year. Accordingly, wet stress parameters were not used to limit the range of *P. psidii*.

The effect of hot-wet stress as a limit on the range extent in the Amazon basin was investigated. Using hot-wet stress to limit the distribution to the western most point location in Brazil had the undesirable effect of making Florida appear unsuitable. It also severely limited the potential range in the Amazonas province in Brazil, where the rust has been recorded, albeit imprecisely. In view of these results, it was decided to remove hot-wet stress from the model, accepting that this aspect must be treated with caution as it is possible that the model overestimates the potential for growth under very warm and wet conditions.

The Growth Index can indicate the seasons when conditions are suitable for infection and growth of the modelled organism. It can also indicate those areas where there is an opportunity for recurrent infection, but a low probability of a persistent population developing.

2.5.   CLIMEX REGION MATCHING.

This modelling used most of the input locations from known suitable locations used in developing the Compare Locations model described above. The county level datasets in the USA where *P. psidii* has been recorded were spatially intersected with a shapefile of the polygon fishnet for the stations in the CRU half-degree dataset. The counties in Florida are relatively small in area, and the climate gradients are relatively shallow. Thus, it was deemed suitable to include all climate stations that fell within the county boundaries in the set of stations used in the region matching. The two counties that have been noted with *P. psidii* in California are somewhat larger, and cover a strong rainfall gradient. Meteorological "stations" lying within the two counties in California were manually filtered to remove xeric inland sites.

The standard set of climate factors (maximum and minimum temperature, annual rainfall total and rainfall seasonality) were used in the region matching to derive the composite match index. Each climate factor was equally weighted.

In order to assess the sensitivity of the analysis to future climate scenarios, the climate change scenarios used in the Compare Locations models were also applied to the region match. In these cases, the current climates (1971-2000) at the suitable locations were compared with each of the future climate scenarios.

2.6.   NAPPFAST

NAPPFAST (Magarey *et al.* 2007) is an internet-based system for mapping the conditions necessary for plant pathogen infection. This system was used previously by Magarey *et al.* (2007) to map the suitability for infection of *P. psidii* , though not long-term persistence. This model was based on the species' requirements for infection (Magarey, Sutton & Thayer 2005), which were derived from laboratory observations by Ruiz et al. (1989). An updated version of this model (Jessica Engel, unpub. data) was run using 28 km USA National Centre for Environmental Prediction (NCEP) weather data for New Zealand. The full setup details for this model are included in Appendix 1. The Ruiz et al. (1989) model was run from 1 January to 31 December, and the accumulated infection days at each site were mapped.

3. Results

3.1. CLIMEX COMPARE LOCATIONS

The Ecoclimatic Index maps indicate that all known point locations are climatically suitable. All region records include at least some locations that are climatically suitable. Given the scant distribution records it is unsurprising that there are large areas that are projected to be suitable, but for which there are no distribution records. The cold and dry stress constraints appear to be well supported with independent point locations in North and South America and Hawai'i lying on similar limits.

Under the current climate scenario, much of the North Island and some of the South Island of New Zealand appears to be climatically suitable for *P. psidii*. The highest climatically suitable locations include those that are of particularly high horticultural value such as Northland, Bay of Plenty, Hawke's Bay and coastal parts of the Canterbury Plains (Fig 2). The Chatham Islands also appear to be climatically suitable for *P. psidii* (Fig 2). According to this model, cold stress, and an inadequate annual heat sum for development appear to limit the southern distribution of *P. psidii* in New Zealand (data not shown).
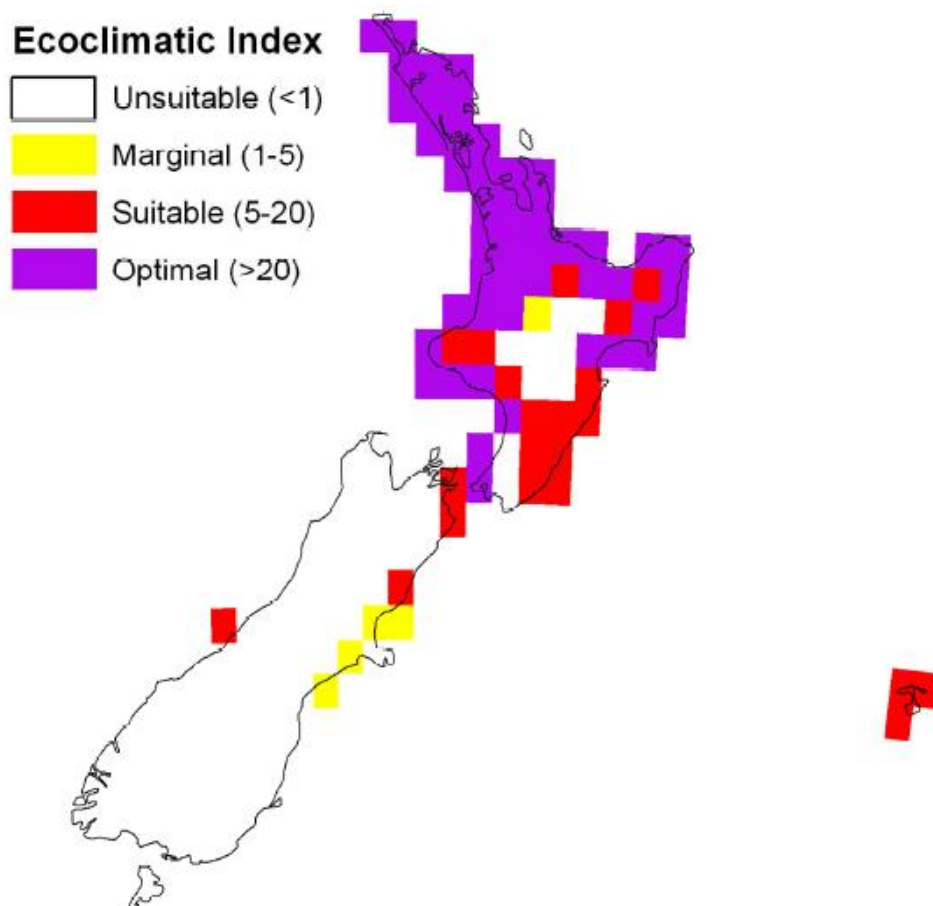

Figure 2: New Zealand showing climate suitability for *Puccina psidii* under current (1971-1990) climate averages as indicated by the CLIMEX Ecoclimatic Index. ☐ unsuitable (EI < 1); ▨ marginal (1<EI<5); ▮ suitable (5<EI<20); ▮ Optimal (EI>20)

Figure 3 indicates the seasonality of conditions suitable for population growth by
P. psidii at Auckland under current climate. This graph indicates that there is a year round
potential for population growth, though with a distinct summer bias in favourability, when
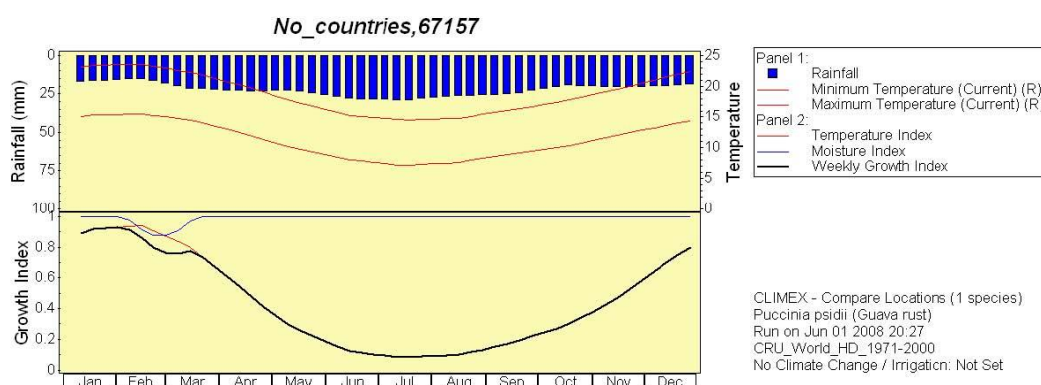conditions for germination of spores are near optimal.

Figure 3: Climate variables and Weekly Growth Index for *Puccinia psidii* at Auckland under current climate conditions (1971-2000).

The potential for *P. psidii* to infect and grow in New Zealand is indicated by the Annual
Growth Index (Fig 4). To the extent that there are areas with a positive growth index that
occur in areas depicted in Fig 2 as being unsuitable indicates that there is opportunity in these
areas for seasonal infection or germination, but there is unlikely to be suitable conditions
under current climates for persistent populations to become established. Considering that the
requirement for a minimum annual heat sum will not be met, it is likely that in these "fringe
suitability" areas that any germinating spores will not complete a lifecycle unless they are in a
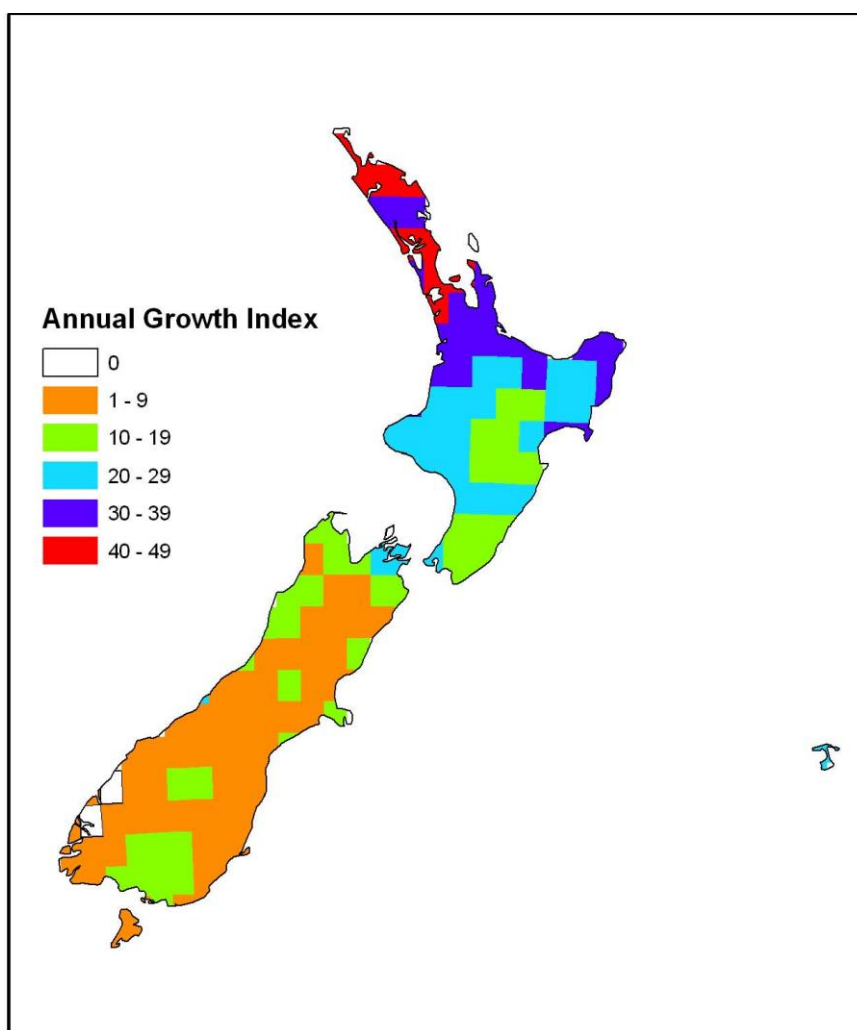favourable microsite that is considerably warmer than would be indicated by screen
temperatures.

Figure 4: New Zealand showing population growth potential for *Puccina psidii* under current (1971-1990) climate averages as indicated by the CLIMEX Annual Growth Index.

Under future climates, the projected threat to New Zealand from *P. psidii* increases somewhat under the A2 scenario for 2030, with further increases in risk under the more extreme A1B scenarios and in the later simulations for 2070 (Fig 5). Under the warmer scenarios the area of suitable habitat extends to the south eastern coastal fringe of Southland. The differences between the results from each of the GCMs reflects some of the uncertainty in future climate projections due to model formulation. The area around Mt Ruapehu remains climatically unsuitable under all scenarios examined here.

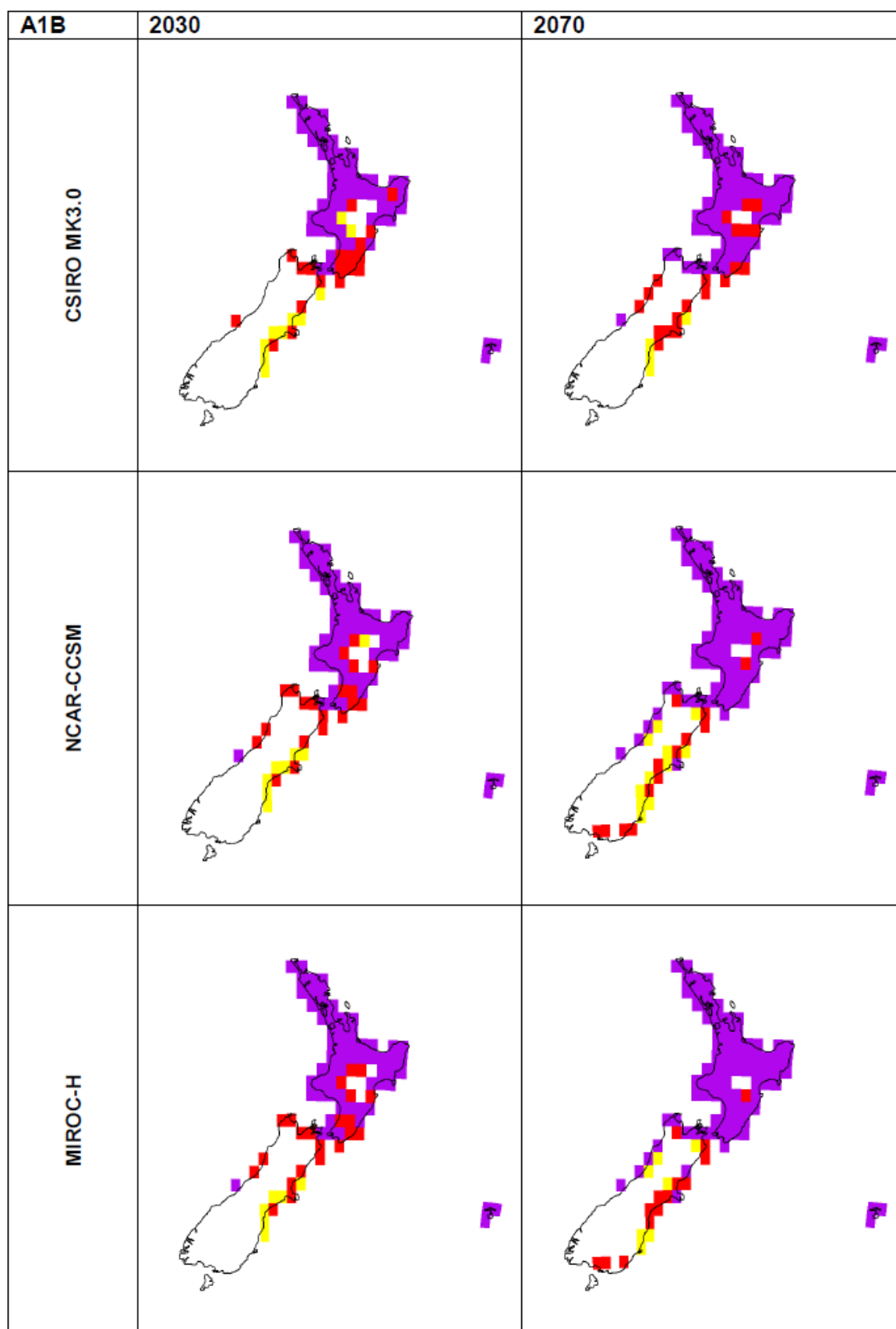| A2	2030	2070
CSIRO MK3.0		
NCAR-CCSM		
MIROC-H		
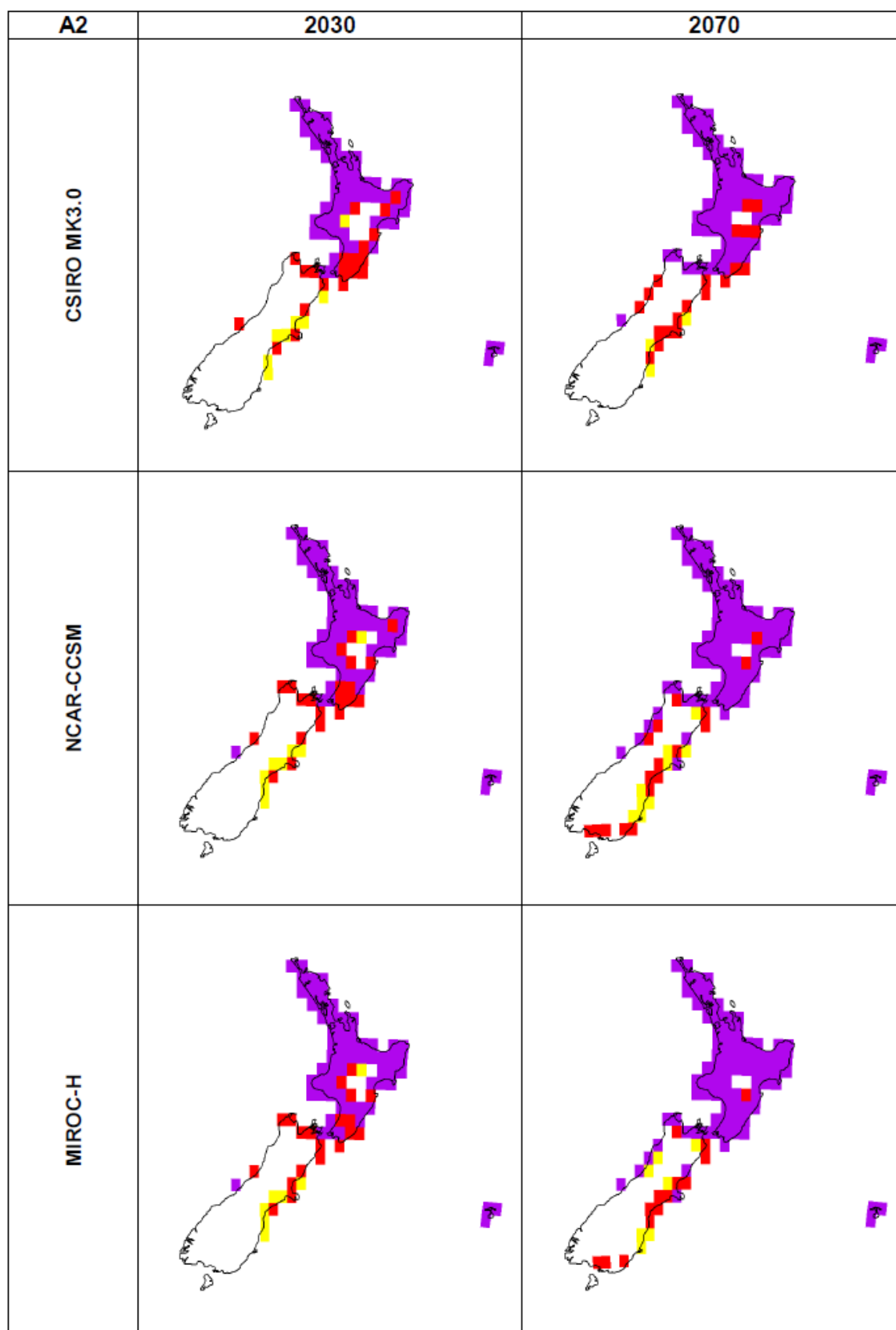
Figure 5a: New Zealand showing climate suitability for *Puccina psidii* under the A2 IPCC future climate scenario as indicated by the CLIMEX Ecoclimatic Index. ☐ unsuitable (EI < 1); ▨ marginal (1<EI<5); ■ suitable (5<EI<20); ■ Optimal (EI>20)

Figure 5b: New Zealand showing climate suitability for *Puccina psidii* under the A1B IPCC future climate scenario as indicated by the CLIMEX Ecoclimatic Index. ☐ unsuitable (EI < 1); ☐ marginal (1<EI<5); ■ suitable (5<EI<20); ■ Optimal (EI>20).

3.2. CLIMEX MATCH REGIONS

It is unlikely that when calculated using the standard set of variables, a composite match index of less than 0.7 is biologically meaningful. In the results presented here, only values above 0.7 are presented. The CLIMEX region match under the 1971-2000 baseline climate is given in Fig 6 and 8. In Fig 6 the climate stations adjacent to the input locations have the highest similarity. This verifies that the model was set up and run correctly for this scenario. It is worth noting that there are regions within what we might presume to be the core of the native range of *P. psidii* (e.g. south-eastern Brazil) that have similarity values as low as 0.75, or even 0.7. This suggests that the climates *within* the geographic range of *P. psidii* are not well sampled by the input locations.
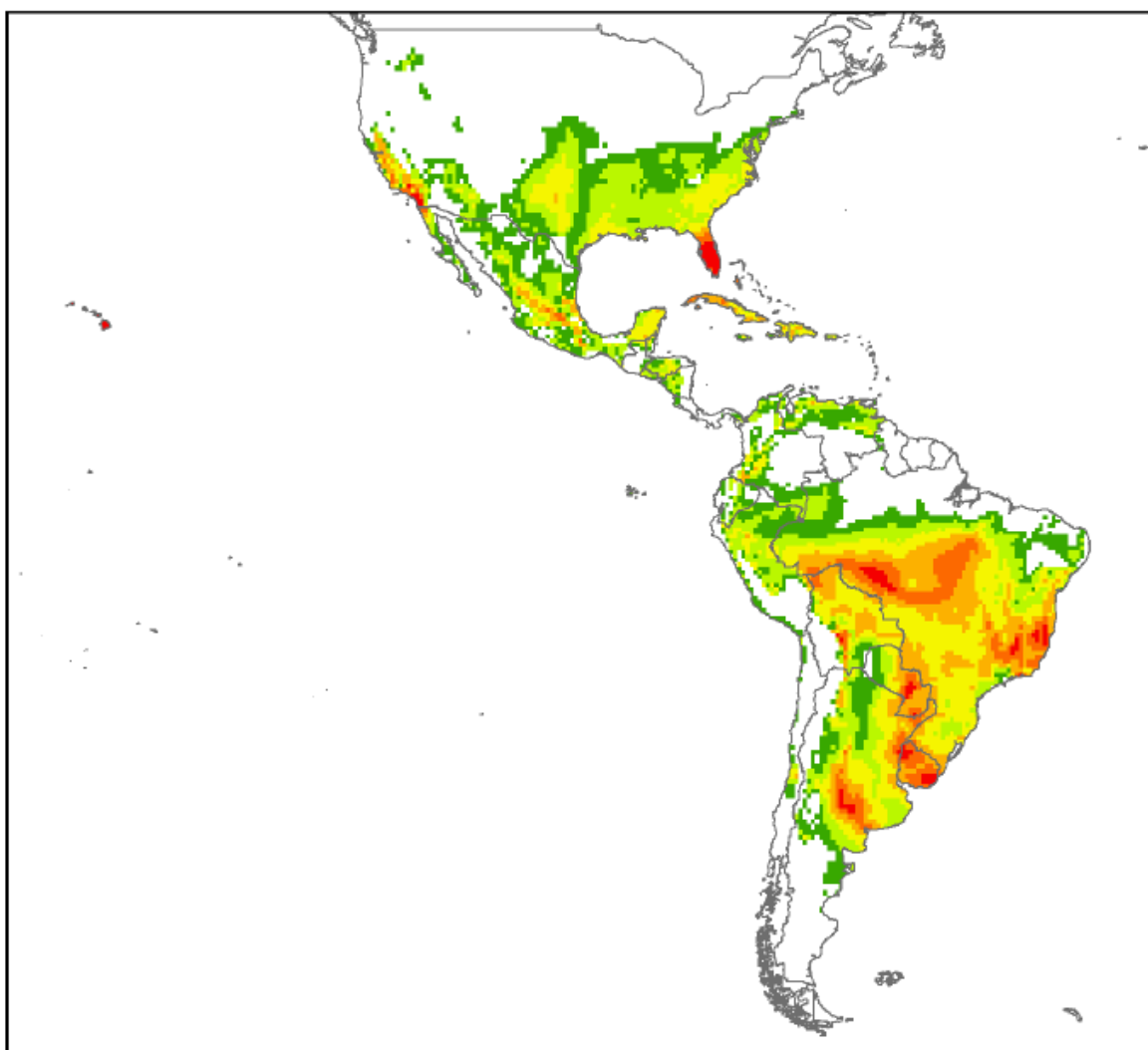

Figure 6: The Americas and Eastern Pacific showing CLIMEX composite match index for *Puccinia psidii* based on known occurrences in South America, USA counties and detailed distribution data in Hawai'i. The climate dataset used is the 1971-2000 climate normals derived from the CRU TS 2.1 dataset (Mitchell et al. 2004). ▉ 0.7<CMI<0.75; ▉ 0.75<CMI<0.8; ▉ 0.8<CMI<0.85; ▉ 0.85<CMI<0.9; ▉ 0.9<CMI<0.95; ▉ 0.95<CMI<1.0. Projection is Mercator.

In Florida and California, colder stations to the north of known suitable locations have been shown to be moderately climatically similar to known suitable locations. All of the countries and other administrative regions noted in the CABI Crop Protection Compendium and other sources (Fig 1) have some locations with a climate match greater than 0.75.

In New Zealand it is apparent that much of Northland and some parts of Hawkes Bay and Canterbury share a moderately similar climate to some locations at which *P. psidii* has been recorded (Fig 7).
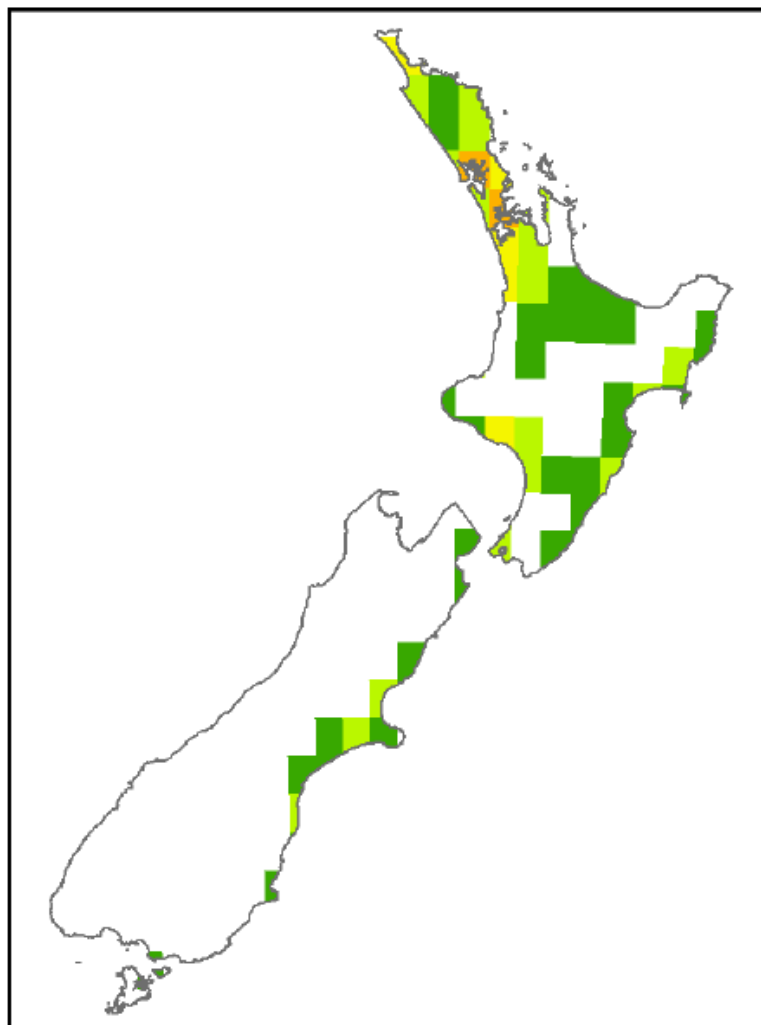

Figure 7: New Zealand, showing CLIMEX composite match index for *Puccinia psidii* based on known occurrences in South America, USA counties and detailed distribution data in Hawai'i. The climate dataset used is the 1971-2000 climate normals derived from the CRU TS 2.1 dataset (Mitchell et al. 2004). ■ 0.7<CMI<0.75; ■ 0.75<CMI<0.8; ■ 0.8<CMI<0.85; ■ 0.85<CMI<0.9; ■ 0.9<CMI<0.95; ■ 0.95<CMI<1.0. Projection is NZMG

Under future climates in New Zealand, the areas that are climatically similar to known presently invaded sites increases steadily with warmer GCMs, higher emissions scenarios and further into the future (Fig 8). The proportion of cells that fall in the moderate similarity classes (0.8 -0.9) increases in a similar manner. The greatest sensitivity in the similarity classes is to the changes in climate through time, with strong increases in the area with a similarity > 0.7, and also the proportion of moderate similarity classes. The differences in results between GCMs and the chosen emissions scenarios are relatively small.
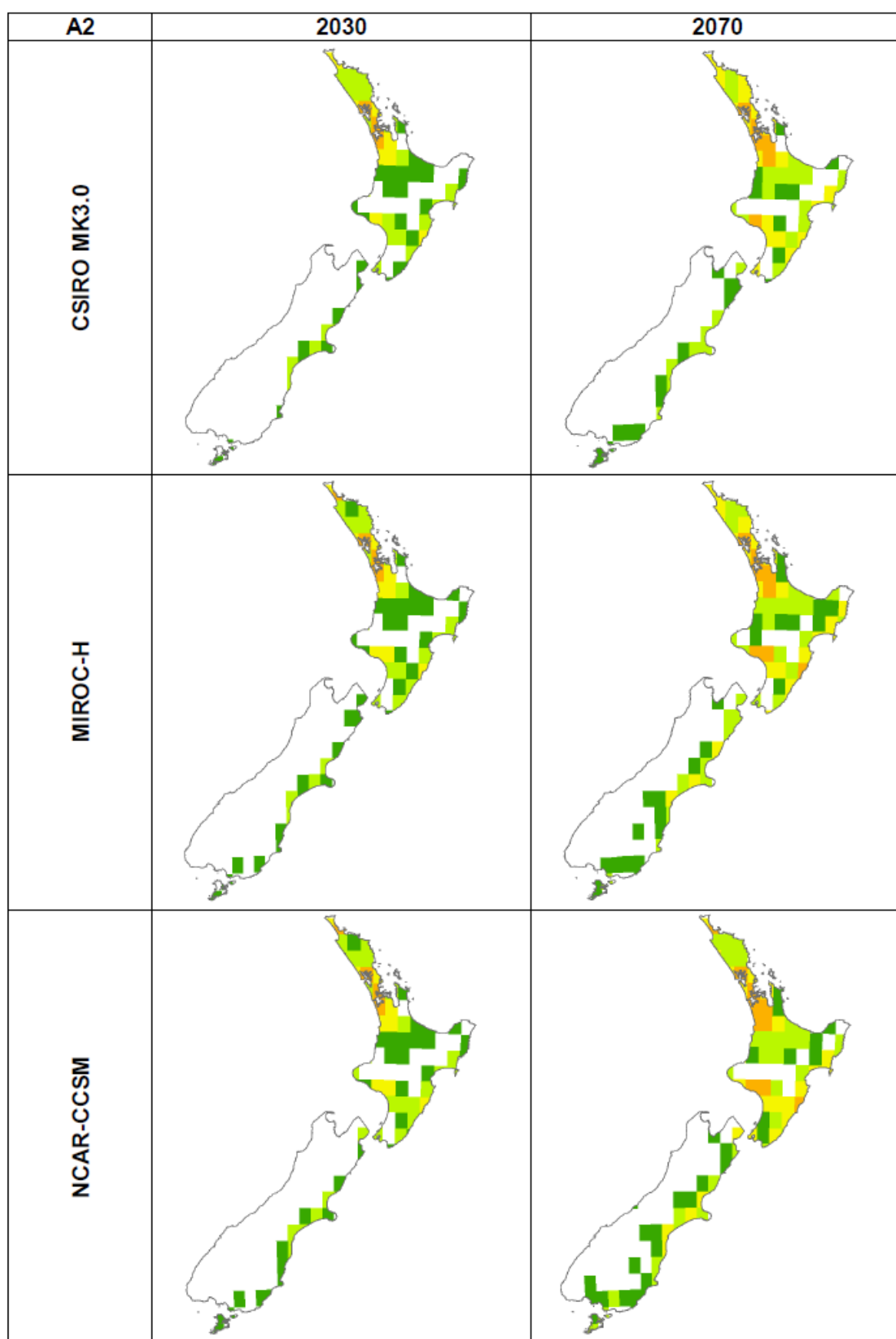
Figure 8a New Zealand, showing the CLIMEX composite match index under the A2 IPCC future climate scenario for *Puccinia psidii* based on known occurrences in South America, USA counties and detailed distribution data in Hawai'i. ■ 0.7<CMI<0.75; ■ 0.75<CMI<0.8; ■ 0.8<CMI<0.85; ■ 0.85<CMI<0.9; ■ 0.9<CMI<0.95; ■ 0.95<CMI<1.0. Projection is NZMG.
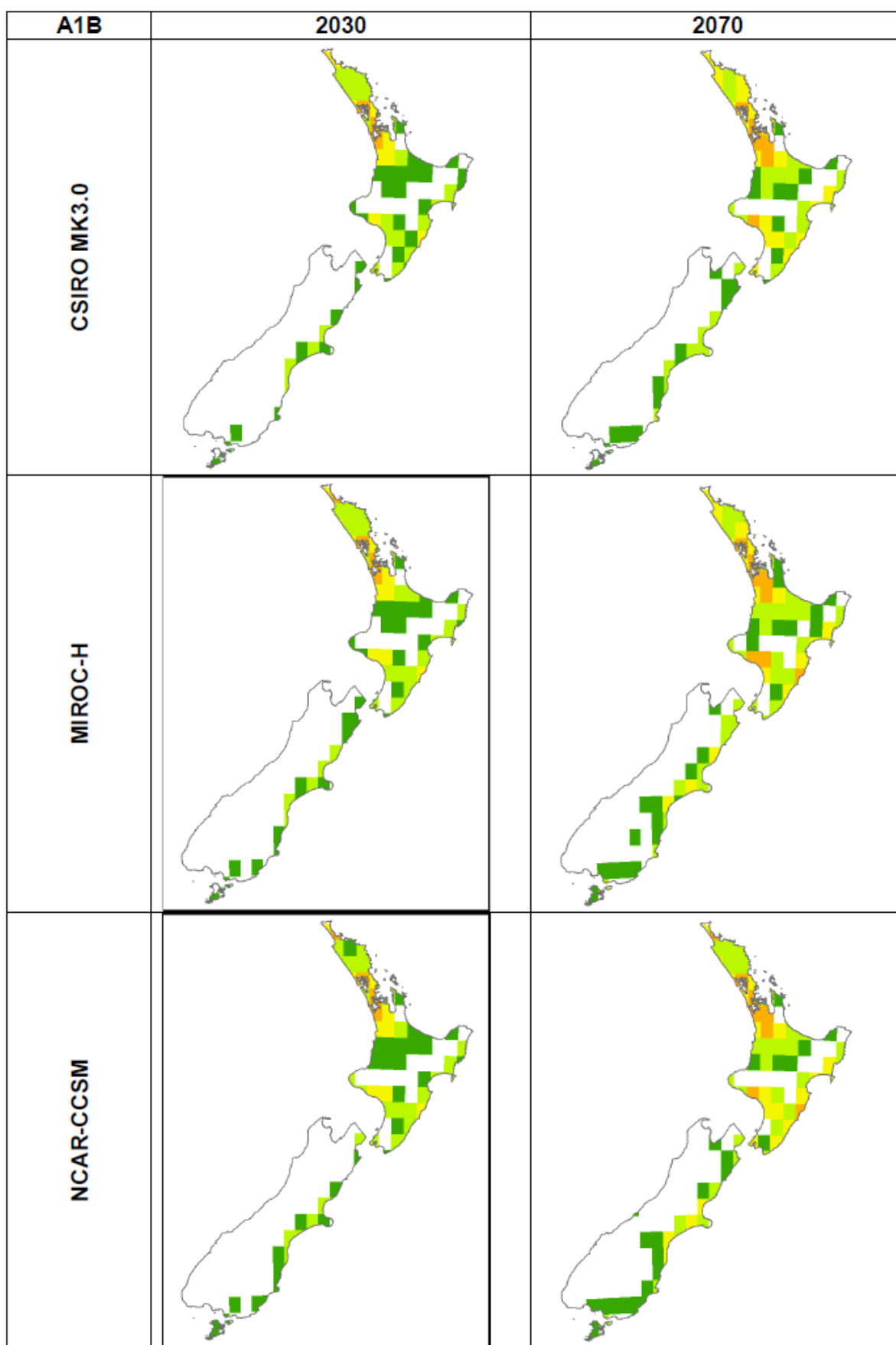
Figure 8b New Zealand, showing the CLIMEX composite match index under the A1B IPCC future climate scenario for *Puccinia psidii* based on known occurrences in South America, USA counties and detailed distribution data in Hawai'i. ■ 0.7<CMI<0.75; ■ 0.75<CMI<0.8; ■ 0.8<CMI<0.85; ■ 0.85<CMI<0.9; ■ 0.9<CMI<0.95; ■ 0.95<CMI<1.0. Projection is NZMG

3.3. NAPPFAST

The projected accumulated infection levels for *P. psidii* in New Zealand using the NAPPFAST model are mapped in Fig. 9. The predicted accumulated infection levels range from 20 to 120 days. This means that under current climatic conditions, in a given year, the conditions necessary for infection would be met on average between 20 and 120 days. However, the results are curious, indicating that the conditions in the Mackenzie Basin in Otago are better for *P. psidii* infection than Auckland, Bay of Plenty and East Cape. This result does not seem plausible for a pathogen that appears to prefer mild temperatures (optimum temperature of 21.5 °C, and minimum leaf wetness duration of 6 hours (Ruiz et al. 1989; Magarey, Sutton & Thayer 2005). These conditions are far more likely to be found in the warmer parts of New Zealand, rather than the continental conditions in Central Otago. This apparent anomaly has been drawn to the attention of relevant NAPPFAST contacts, but at the time of preparation of this report, the issue had not been resolved.
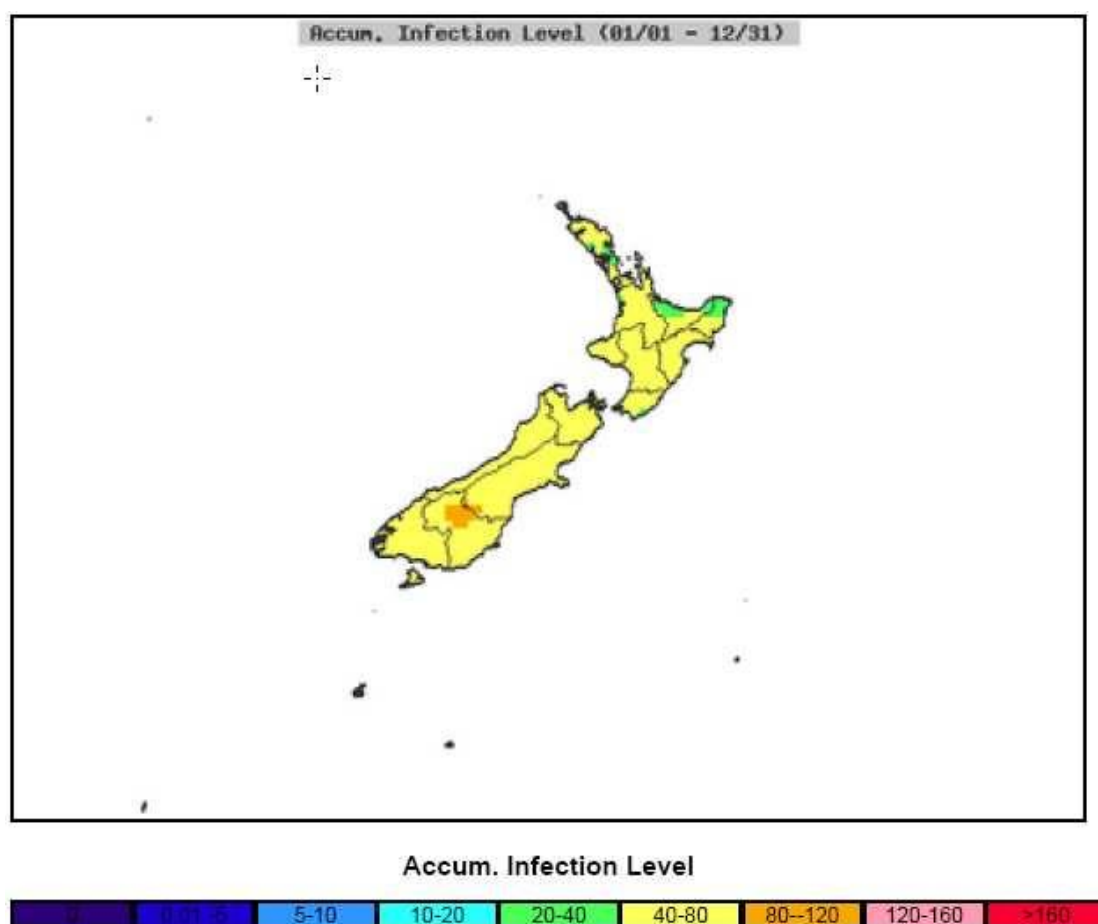

Figure 9: Accumulated infection level for *Puccina psidii* in New Zealand modelled using the parameters detailed in Appendix 1.

4.   Discussion

The Compare Locations model indicates that under current climatic conditions there is likely to be a substantial risk of establishment and persistence of *P. psidii* should it be introduced to New Zealand. The Compare Locations model has not been completely validated because there was insufficient data available to reserve some data for independent assessment of fit. However, it has been *verified*, indicating that it is consistent with all of the known distribution and development rate data. In addition, the high degree of concordance between the results for the Compare Locations and Match Regions models provides additional confidence that at least the gross features of these models are likely to be robust.

The fact that both Compare Locations and Match Regions models are projecting a high degree of climatic suitability and similarity respectively across the most productive parts of New Zealand for horticulture and silviculture should provide cause for concern by biosecurity managers. In addition, the geographic range of M. excelsa is completely within the most climatically favourable areas of New Zealand for *P. psidii*.

The uncertainty surrounding the wet and hot-wet tolerance limits for *P. psidii* do not affect the projections for climate suitability in New Zealand, but this uncertainty should be kept in mind when applying this model to other jurisdictions that experience warm and wet conditions. Should this aspect of the model become critical to some important decisions, then transect surveys using susceptible trap plants could be undertaken along critical climatic gradients (Kriticos *et al.* 2007).

The indicated southern limits of *P. psidii* in New Zealand should be considered indicative, rather than prescriptive. In the region where *P. psidii* suitability appears to peter out on the central and western part of the South Island (Fig 2), the climatic gradients are extremely steep in relation to the scale of the climate data used in this exercise. It is highly likely that there will be small areas along the north western coast of the South Island where meso-climatic conditions would favour the establishment and persistence of *P. psidii*. Whilst finer scale gridded climate datasets are available for use with CLIMEX, they have some undesirable idiosyncracies that make their use in pest risk assessment work questionable. Their apparent spatial precision belies their potential inaccuracy.

The high degree of concordance between the accumulated infection levels for P. psidii in Australia project by NAPPFAST and the results of the two CLIMEX analyses for all regions except New Zealand suggests that the model setup in NAPPFAST is probably reasonable. However, the NAPPFAST results for New Zealand appear unreliable as they stand. It is completely infeasible that given the model setup that central Otago would be the most suitable location in New Zealand for infection, and Northland and the Bay of Plenty the least suitable. It is most likely that the meteorological data in the New Zealand portion of the underlying dataset has been geographically scrambled.

As climates warm under projected climate changes, the susceptibility of New Zealand to the threat posed by *P. psidii* will increase substantially. Whilst not specifically examined in this project, the prospect of this rust island-hopping through the Pacific is significant (data not shown). Should *P. psidii* become established in Australia there is an added opportunity for it to establish in New Zealand through natural wind dispersal (Viljanen-Rollinson, Parr & Marroni 2007), as well as through passenger and freight movements. Given the rapid rate at which *P. psidii* has invaded the entire State of Hawai'i, the prospect of *P. psidii* island-hopping throughout the Pacific should be a significant concern for New Zealand Biosecurity managers. As an obvious pathway, this route should be one that should be considered for

targeted monitoring. The Forestry, rural and urban biosecurity plan for *Puccinia psidii* (Office of the Chief Plant Protection OfficerNo Date) recommends the use of trap plants as a means of regularly monitoring for the presence of *P. psidii* around high risk sites as well as during delimitation surveys following an incursion. This report recommends the use of *Syzygium jambos* as a sentinel planting as it is susceptible to most known biotypes of the rust and is susceptible at all ages. The second choice is a combination of *Kunzea baxteri* and *Callistemon citrinus*, as these are both highly or moderately susceptible (Tommerup, Alfenas & Old 2003). *Melaleuca quinquenervia* and *Pimenta dioica* were recommended as sentinels for the biotype that infects allspice in Jamaica and Florida. However, when considering the use of these plants overseas, their weed potential should be considered and managed appropriately. Both *Syzygium jambos* and *Melaleuca quinquenervia* have been identified as weeds under different circumstances.

Preliminary qualitative modelling work in Australia indicated that the levels of genetic resistance in populations of native Myrtaceae was likely to be a key factor in determining the short-and long-term impacts of an invasion by *P. psidii* (DJK, pers. obs.). The greater the proportion of plants that are resistant, the less initial impact there would likely be, and the more rapidly the resistant plant genotypes can respond to the altered selection pressure, increasing the proportion of the population that is resistant to *P. psidii*. Noting these observations, it may be worthwhile to profile the susceptibility to infection by *P. psidii* for important New Zealand native and exotic flora to better understand the threat posed by *P. psidii*, and to identify options for preparing for an incursion. If resistant varieties can be identified or developed, then depending upon the circumstances, these varieties could either be deployed at present, or held in a repository, ready for use should *P. psidii* be detected in New Zealand. For iconic endemic Myrtaceae, particularly those that are keystone species in their respective ecosystems, it may be especially prudent to identify resistant genotypes so that remedial action can be implemented rapidly should the need arise. As a means of defraying costs, these genotypes could be preferentially planted as amenity plants in gardens that would act as reservoirs of resistant varieties.

This study has clearly identified that New Zealand's climate and some of its flora is susceptible to attack by *P. psidii*. Given the large distance to the nearest presently known sources of viable spores (Hawai'i and South America), the present threat is most likely to come from mechanical transmission. Viable spores have been detected on clothing and personal effects such as cameras and spectacles after visits to severely affected plantations (Langrell *et al.* 2003). If *P. psidii* becomes established in Australia or another nearby island nation, then the risk of transmission of spores to New Zealand by air currents becomes greater (Viljanen-Rollinson & Cromey 2002), and the options for attenuating this incursion pathway are all but non-existent, and the emphasis must fall upon early detection of an incursion.

5.   Acknowledgments

6.   References

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7.   Appendices

Appendix 1 – Known hosts for *Puccinia psidii*. Source Rob Anderson (University of Hawai'i, unpub. data)

Species	Common name	Reference
Myrtaceae	... ...	
Acmena spp.	Lily-pilly	Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Angophora costata	Gum Myrtle	Tommerup, I. C., Alfenas, A. C., and K. M. Old. 2003. Guava rust in Brazil - A threat to *Eucalyptus* and other Myrtaceae. New Zealand Journal of Forestry Science 33: 420-428.
Callistemon citrinus	Red bottlebrush, Crimson bottle brush	Tommerup et al. 2003 - Guava rust in Brazil
Callistemon glaucus		Rayachhetry, M. B., Van, T. K., Cneter, T. D., and M. L. Elliott. 2001. Host range of *Puccinia psidii*, a potential biological control agent of *Melaleuca quiquenervia* in Florida. Biological Control 22: 38-45.
Campomanesia spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Eucalyptus camaldulensis	River red gum	Coutinho, T. A., et al., 1998.
Eucalyptus citriodora	Lemon-scented gum	Coutinho, T. A., Wingfield, M. J., Alfenas, A.C., Crous, P. W. 1998. Eucalyptus rust: a disease with potential for serious international implications. Plant disease 82: 819-825.
Eucalyptus cloeziana		Coutinho, T. A., et al., 1998.
*Eucalyptus dunnii**	Dunn's white gum	Inoculation by Kilgore, Uchida, (date??)
Eucalyptus globulus	Tasmanian blue gum, blue gum	Coutinho, T. A., et al., 1998.
Eucalyptus grandis	Rose gum	Coutinho, T. A., et al., 1998.
Eucalyptus maculata	Spotted Gum	Coutinho, T. A., et al., 1998.
Eucalyptus microcorys	Tallow-wood	Coutinho, T. A., et al., 1998.
Eucalyptus nitens		Coutinho, T. A., et al., 1998.
Eucalyptus paniculata	Gray ironbark	Coutinho, T. A., et al., 1998.
Eucalyptus pellita		Coutinho, T. A., et al., 1998.
Eucalyptus phaeotricha		Coutinho, T. A., et al., 1998.
Eucalyptus punctata	Grey gum	Coutinho, T. A., et al., 1998.
Eucalyptus pyrocarpa		Coutinho, T. A., et al., 1998.
Eucalyptus saligna	Sydney blue gum	Coutinho, T. A., et al., 1998.
*Eucalyptus smithii**		Inoculation by Killgore, Uchida, (date??)
Eucalyptus tereticornus	Forest red gum	Coutinho, T. A., et al., 1998.
*Eucalyptus torelliana**		Inoculation by Killgore, Uchida, (date??)
Eucalyptus urophylla		Coutinho, T. A., et al., 1998.

Species	Common name	Reference
Eucalyptus viminalis	Manna gum	Coutinho, T. A., et al., 1998.
Eugenia brasiliensis	Spanish-cherry	Rayachhetry, et al., 2001.
*Eugenia koolauensis**	Nioi	J. B. Friday. 2006. Pest and diseases update, 7/05
Eugenia paniculatum	brush cherry	J. B. Friday. 2006. Pest and diseases update, 8/06
Eugenia pyriformis var. *uvalha*		Rayachhetry, et al., 2001.
Eugenia reinwardtiana	Nioi	Rayachhetry, et al., 2001.
Eugenia uniflora	Surinam cherry	Rayachhetry, et al., 2001.
Feijoa spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Kunzea baxteri		Tommerup et al. 2003 - Guava rust in Brazil
Marlierea edulis		Rayachhetry, et al., 2001.
Melaleuca alternifolia		Tommerup et al. 2003 - Guava rust in Brazil
Melaleuca cajuputi		Tommerup et al. 2003 - Guava rust in Brazil
Melaleuca decora		Rayachhetry, et al., 2001.
Melaleuca quinquenervia	Paperbark	Rayachhetry, et al., 2001.
*Metrosideros polymorpha**	ohia-lehua	Killgore and Heu, 2005. New pest advisory 05-04 - Ohia rust. Hawai'i Dept. of Agriculture.
Myrcia sp.		Rayachhetry, et al., 2001.
Myrcianthes fragrans		Rayachhetry, et al., 2001.
Myriciaria cauliflora	Jaboticaba	Rayachhetry, et al., 2001.
Myrtus spp.	Myrtle	Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Paivaea spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Phyllocalyx spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Pimenta dioica	Allspice	MacLachlan, J. D. 1938. A rust of pimento tree in Jamaica, British West Indies. Phytopathology 28: 157-170
Pimenta racemosa	Bay-Rum Tree, Bay Tree	Rayachhetry, et al., 2001.
Pseudomyrcianthes spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Psidium guajava	Guava	Tommerup et al. 2003 - Guava rust in Brazil
Psidium guineense	Guisaro	Rayachhetry, et al., 2001.
*Rhodomyrtus tomentosa**	Downy rosemyrtle	J. B. Friday. 2006. Pest and diseases update, 8/06
Stenocalyis spp.		Australian Quarantine Inspection Service - Public Quarantine Alert PQA0452, 11/05.
Syncarpia glomulifera	Turpentine tree	Tommerup et al. 2003 - Guava rust in Brazil

Species	Common name	Reference
Syzygium cumini	Java or jambolan plum	Rayachhetry, et al., 2001.
Syzygium jambos	rose apple	Tessman, D. J., Dianese, J. C., Miranda, A. C., and L. H. R. Castro. 2001. Epidemiology of a neotropical rust (*Puccina psidii*): periodical analysis of the temporal progress in a perennial hosts (*Syzygium jambos*). Plant Pathology 50: 725-731.
Syzygium malaccense	mountain apple	Rayachhetry, et al., 2001.
Heteropyxidaceae		
Heteropyxis natalensis		Alfenas A.C., Zauza E.A.V., Wingfield M.J., Roux J., and M. Glen. 2005. *Heteropyxis natalensis*, a new host of *Puccinia psidii* rust. Australasian Plant Pathology 34: 285-286.

Appendix 2 – Model setup details for NAPPFAST *Puccinia psidii* model based on the work of Ruiz et al. (1989)

Model Setup

Begin Day (mm-dd)	01-01
End Day (mm-dd)	12-31
Infection Level Lower Limit	0
Infection Level Upper Limit	1

Degree Day Initiation

Method	Unit	Base	Max	Init	Term
Default	C				

Setup Variables

Variable	Unit	Min	Opt	Max
Air Temperature	C	1	21.5	30
Leaf Wetness	hrs	6		24
Precipitation	mm	2		

Setup Output

Name: Infection Leve ☑ Accumulate

		Low		High		Text	Color	R	G	B
1.	>		<=	0.9999	===>	No		13	0	136
2.	>	0.999	<=		===>	Yes		255	25	33

Setup Accumulated Output Variable

Name: Accum. Infect

		Low		High		Text	Color	R	G	B
1.	>		<=	0	===>	0		45	0	119
2.	>	0.001	<=	5	===>	0.01 -5		29	0	205
3.	>	5	<=	10	===>	5-10		45	150	255
4.	>	10	<=	20	===>	10-20		42	255	255
5.	>	20	<=	40	===>	20-40		74	255	91
6.	>	40	<=	80	===>	40-80		255	255	90
7.	>	80	<=	120	===>	80--120		247	168	0
8.	>	120	<=	160	===>	120-160		255	154	180

9.	>	160	<=		===>	>160			250	0	48

Display Name

Model Comment