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Regional climate-matching to estimate current and future sources of biosecurity threats

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Abstract Managing the threats posed by invasive alien species currently may involve a mixture of species-specific and pathway-specific policy and operational measures aimed at achieving a socially acceptable level of protection. In order to decide how to allocate scarce biosecurity resources in a manner that avoids erecting technical barriers to trade, it is necessary to undertake risk assessments for individual pests or commodity pathways. Whilst there are popular climatic niche tools available to project future pest risk in terms of a species' potential distribution, the international legal frameworks as yet have no explicit means of including future risk considerations arising from projected climate changes. Nor are there any tested and accepted tools for projecting shifts in geographic pest risk, or systematically identifying future pest risks. I use New Zealand as a case study to demonstrate a method for identifying generic geographic pest risk to a jurisdiction under historical and future climate scenarios. Under future climates, the global area from which threatening pests could originate is set to increase. Pests from some regions that presently require warmer conditions than can be found in New Zealand are likely to become a future threat. These pests will probably originate from regions presently experiencing a sub-tropical climate. As climates warm, regions that have previously been too cool to pose a pest threat will start posing a threat, particularly from rapidly dispersing ruderal species and other generalists. Taking all of the different types of threats into account, the largest increase in risk area for New Zealand appears to be in northern Europe, North America and Asia. This technique can be used to alert biosecurity pathway managers about the shifting direction from which climatically suitable biological invaders may originate, and can also be used to generate pests lists for species that are presently unsuited to the jurisdiction, but may in the future become so if global temperatures rise as expected. The results highlight the need for adaptive biosecurity systems that can recognise and assesses future risk trends, monitor these trends, and are able to respond rapidly to changing threats.

Keywords New Zealand · Biosecurity · Climate change · CLIMEX · Invasion pathways

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Introduction

The International Plant Protection Convention (IPPC) includes a set of published International Standards for Phytosanitary Measures (ISPMs). These standards address *inter alia*, how pest risks should be assessed if they are to be used to formulate policies that affect international trade. According to ISPM 11, pest risks should be assessed on a pest by pest basis. Therefore, if a jurisdiction wishes to assess and manage the biosecurity risks associated with the importation of a commodity it is necessary to first identify all of the significant pests that may be associated with that commodity and complete a Pest Risk Analysis (PRA) for each pest of concern. However, the optimal allocation of surveillance and other biosecurity resources to manage invasive species risks requires an appreciation of which pests could establish within the jurisdiction, and from where they could originate (so-called risk areas). Building up this picture from commodity-based risk assessments or surveillance data could be costly, and the full picture may start to emerge too late to be useful.

There are a number of approaches to understanding and managing the threats posed by invasive species. There have been multiple attempts to use species' traits as a basis for predicting invasion potential (Blackburn et al. 2009; Cannas et al. 2003; Pyšek et al. 2009a, b; Ruesink 2005; Simberloff 2009; Stohlgren and Schnase 2006). However, the success of these endeavours has been mixed, perhaps because the interactions between traits and environment has frequently been ignored (c.f. Thüiller et al. 2006). More recently, methods have been developed using machine learning techniques to identify invasive pest species assemblages (Worner and Gevrey 2006). This promising new analytical technique uses self organising maps to uncover invasion patterns in the CABI Crop Protection Compendium data on invasive species. The technique appears fairly robust (Paini et al. 2010), but because it is a purely descriptive model based on historical invasion patterns, it is probably of limited use for projecting pest threats under future climates.

Following the publication of the Biosecurity Strategy for New Zealand (Biosecurity Council 2003) there has been an increasing research and policy emphasis on pre-border and border biosecurity aimed at prevention or minimisation of plant pest threats. This proactive approach follows the rationale that it is better to prevent a problem than to react to it (Kriticos et al. 2005; Leung et al. 2002). It is worthwhile considering therefore where the future threats might come from, and so be aware of what future challenges New Zealand's biosecurity apparatus might face. This approach is resonating in Europe, with initiatives such as the PRATIQUE project attempting to identify emerging threat trends (https://secure.fera.defra.gov.uk/pratique/).

Climate modelling for pest risk assessment

Climate is the primary determinant of the distribution of poikilotherms and plants (Andrewartha and Birch 1954, 1984; Woodward 1987). It is therefore common to use climate-based tools to model the potential geographical range of species or other taxa (Baker et al. 2000; Guisan and Zimmermann 2000; Kriticos and Randall 2001). This species-based modelling approach has several important roles in invasion risk assessment including providing the synoptic view of an invasion, informing decision-makers of the potential area under threat from an invader (Committee on the scientific basis for predicting the invasive potential of nonindigenous plants and plant pests in the United States 2002). However, whilst it is reasonable to examine in detail the threat posed by conspicuous pests of economically important plant species, there are a myriad of potential plant biosecurity pests, and so it is also worthwhile considering biosecurity risk from a geographic perspective. Thus, for New Zealand biosecurity, we are interested in answering two distinct questions. Firstly, in the future, which pests is New Zealand going to be susceptible to, and where could they come from? Secondly, what are the future threat areas and pathways to New Zealand?

Though more reliable methods are available for analysing potential distributions of individual species, climate matching is an appropriate method when considering the potential for the establishment of all pests from a region. Peacock and Worner (2006) used the Match Climates function in CLIMEX (Sutherst and Maywald 1985; Sutherst et al. 2007) to estimate New Zealand's geographic pest risk under current climate conditions. At that time, the region matching function was not available in CLIMEX. In order to approximate the Match Index to all of New Zealand, Peacock & Worner chose to use Auckland as the

"Home" location, and employed a very low threshold Composite Match Index (CMI) of 0.5 (well below what is generally assumed to constitute a biologically meaningful match for the standard four variables of minimum and maximum temperature, annual rainfall total and rainfall pattern). Auckland is in the north of New Zealand, and so its climate is relatively warm and moist compared to most of New Zealand. By reducing the threshold CMI value so far, Peacock & Worner were effectively including climates that were much warmer than any found in New Zealand into their risk areas. At the same time, a match threshold of 0.5 for Auckland still does not include the cool wet locations on the west coast of the South Island, such as Haast and Milford Sound. An improved approach now available in CLIMEX is to sequentially compare the climates of many locations in New Zealand with the rest of the world and building a composite result set. This approach simultaneously allows the threshold climate similarity to be maintained at meaningful levels, whilst still capturing the full range of climates in New Zealand. This is the approach reported on in this paper.

Climate change and invasion risk

Global climate change is leading to increases in temperatures, particularly in the northern hemisphere, and more so for daily minimum temperatures than daily maximum temperatures (IPCC 2007b). Whilst the hydrological cycle is likely to intensify due to the increase in temperatures and concomitant increases in evapotranspiration, projections of the spatial and temporal changes in rainfall patterns are far less certain. The climate changes experienced in the twentieth century appear already to be affecting species phenological patterns, distributions and relative abundances (Parmesan et al. 2005; Parmesan et al. 1999; Walther et al. 2002; Woods et al. 2005).

Climate change is expanding niche opportunities for species from warmer climates into historically colder climates that were previously inaccessible due to cold stress or inadequate thermal accumulation. The species that are able to most rapidly expand their habitat to take initial advantage of this expanded niche are r-adapted ruderals *sensu* Grime (1979), with good dispersal capacity and few specialised habitat requirements. Conversely, the "trailing-edge" species most likely to lag behind and remain without recruitment in habitats, that on a meso-scale, are otherwise unfavourable, are Grime's k-adapted stress tolerators (Grime 1979). It is also possible that species facing local extinction due to extensive and rapid climate changes might become restricted to favourable microhabitats, such as the case of ancient hydrophilic cycads becoming restricted to a deep valley of Kings Canyon in central Australia as the climate warmed and dried.

Anthropogenic global climate change is a set of dynamic processes. Given the unprecedented rate of global climate change, it is often convenient to compare the current state of the climate with future states based on plausible future scenarios. It is also necessary to bear in mind that whilst climate will change at rates driven primarily by emissions of greenhouse gases, biogeospheric processes are likely to lag behind these changes. This is significant for managing biological incursions, since changes in species distributions are likely to lag behind their climatic potential distribution.

As the climate of New Zealand warms, we might expect that it would be susceptible to pest threats from what are presently areas that support warmer-adapted species that are presently unable to establish in the cool New Zealand climates. Therefore, to assess the present location of organisms that may pose a risk to New Zealand in the future, it is necessary to match future New Zealand climate scenarios with the 1961-1990 reference climates for the rest of the world. This procedure will highlight areas presently hosting New Zealand's future pests.

As climates change, it is likely that the potential ranges of potential New Zealand pests will shift in response to new opportunities for invasive range expansion on the one hand, and local extinction pressure due to competition and environmental stress on the other. In order to assess where these future threats might originate it is necessary to consider both the transient situation where species ranges lag well behind their envelopes, and the future equilibrium situation where species occupy their full climatic niche. In the transient dis-equilibrium situation, as climates change, species distributions are likely to lag, particularly for "slow" species (Franco and Silvertown 1996). Such species distribution inertia might also come about for instance because crop trees in New Zealand continue to be maintained in plantations outside their climatic optima due to "capital inertia" where the cost of maintaining production through additional inputs to overcome emerging climatic challenges is less than that required to translocate production infrastructure (IPCC 2007a). To project this situation we need to compare New Zealand's current (reference) climate with that of overseas locations under future climate scenarios. The pest threats from regions that are presently too cold will probably come from "fast" ruderal species *sensu* Franco and Silvertown (1996) that already pose a threat under current climatic conditions, but in the future they could invade via new ports or regions. Without a much better understanding of the process of species migration and extinction under changing climate pressure, it is impossible to gauge how long this transient pest threat might last.

Assuming that climates stabilise later this century, and further, that pest species distributions equilibrate rapidly, we could expect that New Zealand's future pest threats will mostly originate from regions with a similar climate to that of New Zealand in the future.

In this paper, the climate of New Zealand is matched to the rest of the world using CLIMEX under four scenarios to identify (1) the present pest threat areas, (2) the geographic origins of future pest threats, (3) the new geographic pest threat areas under a transient situation where productive systems are maintained despite climates becoming unsuitable and (4) the geographic pest threat areas where climate and species distributions have equilibrated under the future scenario. By identifying how the pest risk profile of New Zealand is likely to change in the future, the biosecurity system can be better equipped to face these emerging challenges.

Materials and methods

The region-matching algorithm in CLIMEX™ Version 3 (Sutherst et al. 2007) was used to match New Zealand's climate with that of the rest of the world. The mathematical derivation of the Composite Match Index is described in the Supplementary Information. The climate dataset used for this study was the University of East Anglia's Climatic Research Unit (CRU) CL1.0 1961-1990 reference climatology at a scale of 0.5° (New et al. 2002) and two climate change scenarios developed on top of the reference climatology. In the CLIMEX regional climate match schema ("Match Climates") there are two sets of locations—the *home* location set, and the *away* location set. In this case, the *home* location dataset was always the set of stations that fell inside New Zealand, and the *away* dataset was the entire set of stations in the CRU dataset, including those in New Zealand. The meteorological datasets to which these location sets are applied, and the scenarios that are applied to them can be set independently. For example, a home set could be selected from the standard world climate station dataset and the climates for each of the selected home stations could be compared with the gridded CRU dataset with a uniform 2°C increase in temperatures. In all cases, the minimum and maximum temperature, annual rainfall total and rainfall pattern were included in the CMI, and were equally weighted.

In order to represent the future climate scenarios data were taken from the Hadley mark 3 Global Climate Model (GCM), and scaled to provide estimates for thirty year means for the 2080s (centred on 2085). The Hadley model was chosen for its popularity in the global change impact assessment literature. The GCM data was sourced from the Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/~timm/grid/TYN_SC_2_0.html). This data was used to calculate the required relative humidity variables from temperature and vapour pressure data, and was transformed for use in CLIMEX. The choice of thirty year means is due to marked inter-decadal variability inherent in most GCM results, and accords with recommendations from the Intergovernmental panel on climate change (IPCC et al. 1999). Given the observations of Rahmstorf et al. (2007) that recent CO_2 emissions and global warming are tracking high in relation to the IPCC scenarios, only the climate data for the high A1 emissions scenario is considered here.

The CLIMEX region match algorithm was applied to a factorial combination of a historical climatology and a future climate scenario. For convenience, these combinations are summarised in Table 1 to identify the type of knowledge provided by each analysis. These analyses are elaborated below. Species whose geographic ranges intersect the areas with a moderate-to-high CMI value (generally values >0.7 using the standard variables) are likely to be capable of persisting in New Zealand under current climatic conditions (Worner and Gevrey 2006), hence, the threshold CMI

Table 1 Type of biosecurity threat information provided by each combination of historical and future climate scenario

		World	
		Historical	Future
Home jurisdiction (New Zealand)	Historical	Present risk *areas*	Transient geographic risk *areas*
	Future	Present *location* of future risk *species*	Future equilibrium risk *areas*

value for inclusion in the climate similarity maps was set to 0.7.

Geographic origins of present risk organisms (current climate matches)

The current high risk areas for plant pests that threaten New Zealand were identified by matching the reference climate (1961–1990 average) for New Zealand with the rest of the world using the same the reference climate. This is the baseline scenario for comparison with future scenarios.

Geographic origins of future risk organisms (future New Zealand climates and current global climate)

To assess the present locations of organisms that will likely pose a risk to New Zealand in the future, the climate scenarios for New Zealand in the future were matched with the 1961–1990 reference climates for the rest of the world. The results of this analysis indicate where presently to survey for New Zealand's future pest threats. Pests that have ranges that spatially intersect regions with a close climatic match should be considered as potential invaders.

Transient risk areas (current New Zealand climate and future global climates)

To assess the regions posing a transient risk to New Zealand in the future, the New Zealand 1961–1990 reference climate was matched with the future climate scenario.

Equilibrium risk areas (future New Zealand climates and future global climates)

To assess the future equilibrium high risk areas for plant pests of New Zealand, the future climate scenarios were used for both New Zealand and for the rest of the world.

Combined future risk areas (composite comparisons)

Due to the uncertainty in the rate of attaining equilibration in pest geographic distribution, the previous scenarios were combined to provide a combined area of pest risk threats under all scenarios. The maximum CMI value across the datasets within each emission scenario was retained.

Results

Geographic origins of present risk organisms (current climate matches)

Under current climate, the geographic origins of New Zealand's plant pests are more likely to originate from areas with a high Composite Match Index (CMI) value in Fig. 1. The closest climatic matches for New Zealand are with south-eastern Australia and western Europe, particularly the United Kingdom and Ireland.

Geographic origins of future risk organisms (future New Zealand climates and current global climate)

New Zealand's future biosecurity pest organisms are likely to originate from areas highlighted in Fig. 2a. The risk areas include locations that are presently warmer than the warmest parts of New Zealand (Fig. 2b). Under the future climate scenario presented in Fig. 2a, species whose ranges intersect the regions with a high CMI value might be capable of establishing in New Zealand in the future. In geographic terms, the increased threat areas are not dramatically increased beyond the current climate threat (Fig. 2b), though all

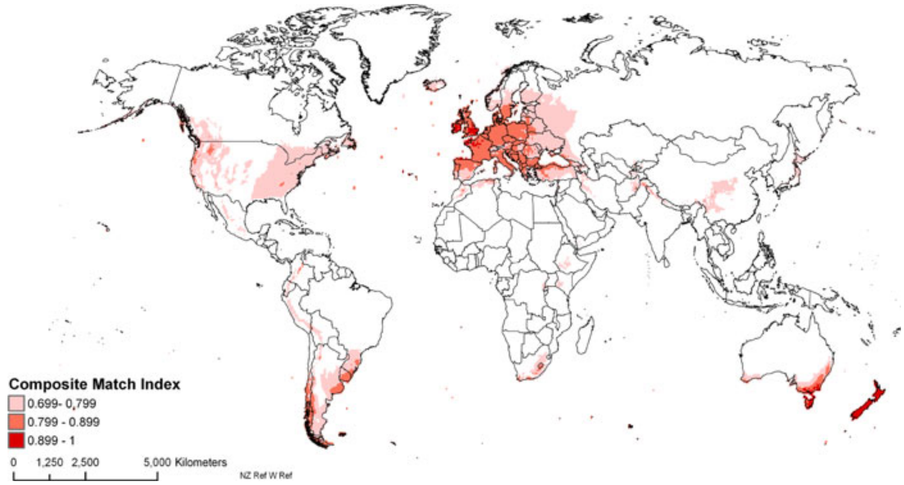

Fig. 1 Current pest threat regions for New Zealand. Climate Match between New Zealand and the rest of the world under the 1961–1990 reference climate. The results were derived using the CLIMEX Match Climates (region) algorithm

of the isolated high-altitude tropical regions appear to have increased the threat areas to include lower-lying regions, and some new countries may harbour emerging pests (e.g. Madagascar and Paraguay).

Transient risk areas (current New Zealand climate and future global climates)

The areas that are likely to pose a new, but transient threat to New Zealand are indicated in Fig. 3a. As climates change, these regions will increasingly be able to support species that are adapted to climates that are similar to New Zealand's historical climate. The large increases in areas that might pose an invasion threat are the high latitude regions including the Scandanavian countries and western Russia, parts of China and the Kamchatka Peninsula, Canada and Alaska. These areas are highlighted in Fig. 3b where the present risk areas (CMI > 0.7) are excluded.

Equilibrium risk areas (future New Zealand climates and future global climates)

The regions that are likely to pose priority biosecurity risks to New Zealand in the future, when pest species distributions have equilibrated are presented in Fig. 4a. Comparing Fig. 4a with the baseline present climate threats (Fig. 1), overall, the risk areas appear to diminish only slightly under the future climate scenario (Fig. 4b).

Combined future risk areas (composite comparisons)

The combined present and future risk areas under each of the two future climate scenarios are presented in Fig. 5. This area is significantly expanded compared with the current climate match (Fig. 6 c.f. Fig. 1).

Discussion and conclusions

The CLIMEX Region matching function was straightforward to implement, and the results could be interpreted intuitively. It is worth noting however, that similar results could probably be achieved using a variety of climate similarity tools.

New Zealand's current climate-based geographic biosecurity risk profile appears relatively limited in area (Fig. 1). Hence, it may be prudent currently to focus extra biosecurity attention on those pest dispersal pathways that originate from, or pass through these areas, particularly those with relatively high volumes of passengers and materials to New Zealand (Peacock and Worner 2006).

The analysis presented here assesses only the climatic suitability component of the geographic risk assessment. In order to gain a better appreciation of the potential threat, it is also necessary to consider other factors such as the volume of traffic to

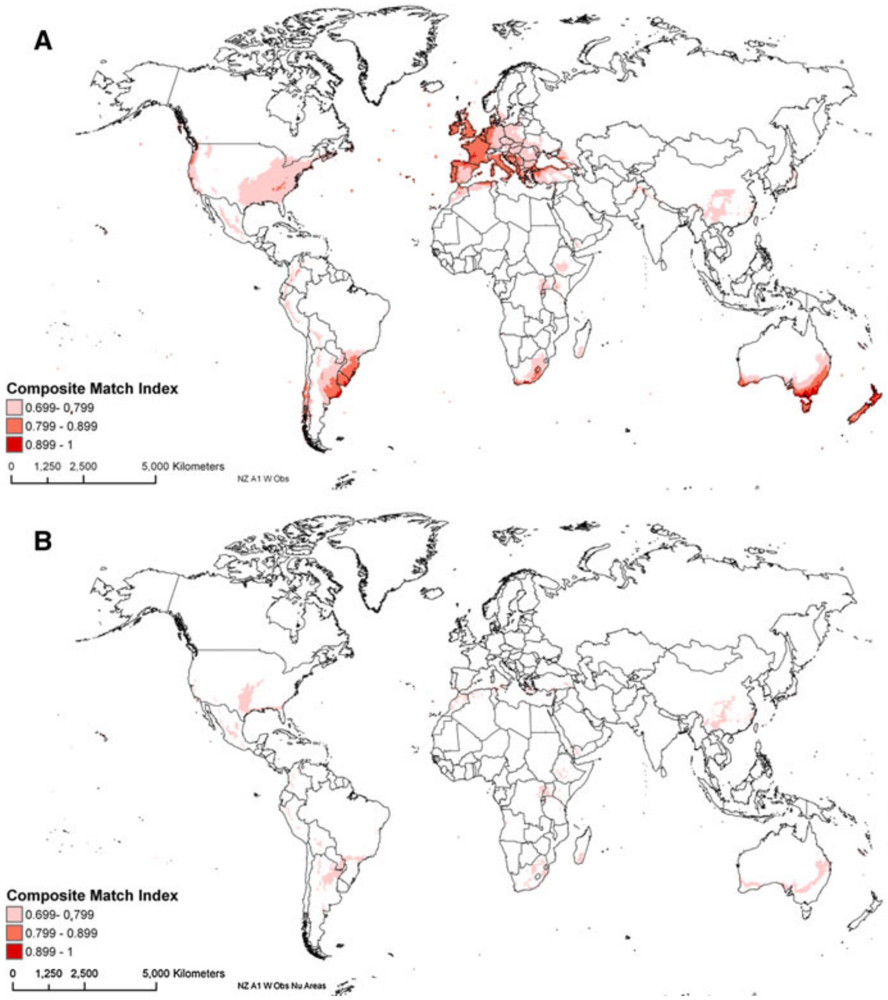

Fig. 2 The current geographic origin of pests that may pose a biosecurity threat to New Zealand in the future. **a** comparing New Zealand's climate in the 2080s under the Hadley3 GCM run with the SRES A1 scenario with the rest of the world under the reference climate (1961–1990 average), and **b** New areas containing pests that may pose a biosecurity threat to New Zealand in the future identified by areas that under current climate have a CMI $\leq$ 0.7, and under future climate have a CMI > 0.7

New Zealand from ports that service these threat areas (Richardson and Thüiller 2007) and the effectiveness of pathway risk management practices. This type of geographical network analysis could provide the basis for a rational approach to resource allocation, and also an additional tool for identifying pest organisms.

Consideration of the pests found in the future threat areas identified in Fig. 2 could reveal pest organisms hitherto considered not to be a threat to New Zealand because they were not sufficiently cold-adapted. Similarly, consideration of the transient (Fig. 3) and future equilibrium (Fig. 4) threat regions could reveal ports and pathways that could become more threatening in the future.

In considering these geographical risks, it is important to recognise also that pest organisms could still persist in areas outside of the climatically similar regions identified above, and they could arrive in New Zealand via pathways from outside of the risk regions identified above. The intention here is to indicate regions that are most likely to carry such a risk. The findings of Worner and Gevrey (2006) indicate that this approach is likely to have some merit. Whilst they did not explicitly test the association between climate and pest risk, the clustering of pest associations in their results does appear to have some climatic basis as indicated by the visual concordance between the regional clustering patterns and the climate types identified in climate type maps such as the Koppen-Geiger maps (Köppen 1936; Kottek et al. 2006).

The analyses presented here are obviously sensitive to the realised degree of global warming.

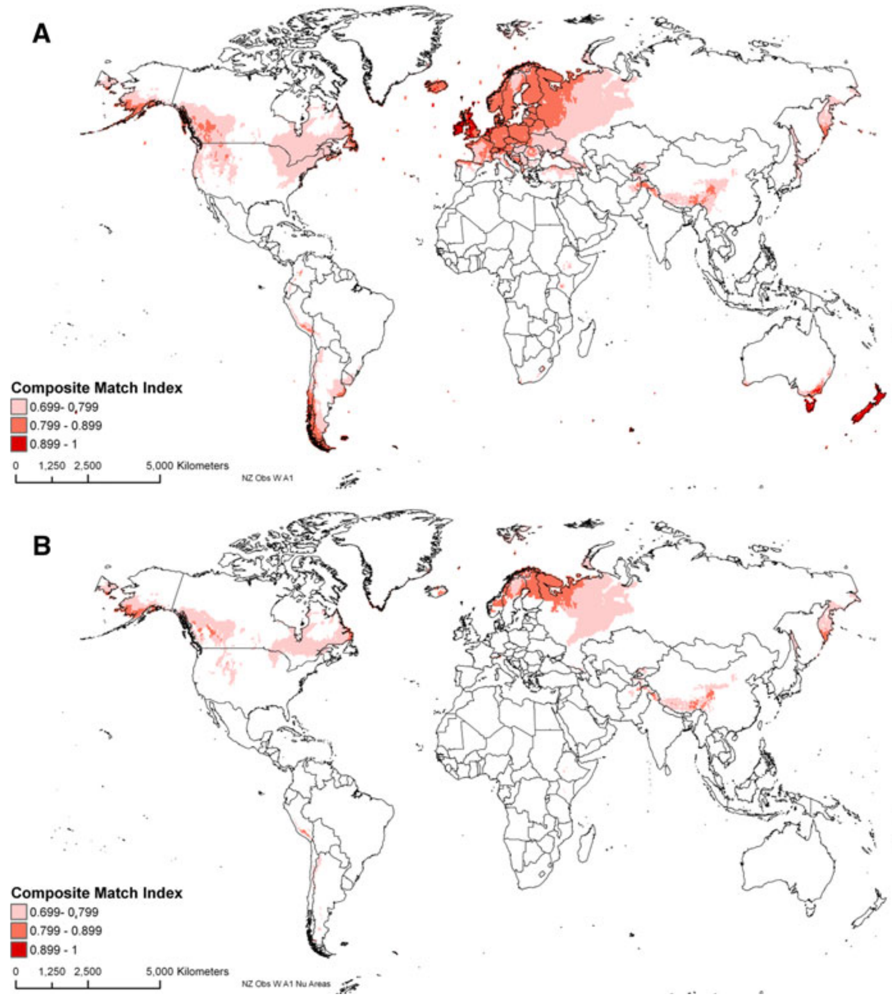

Fig. 3 **a** The transient risk areas that may pose a biosecurity threat to New Zealand in the future. Comparing New Zealand's reference climate (1961–1990 average) with the rest of the world in the 2080s under the Hadley3 GCM run with the SRES A1 scenario, and **b** the transient risk areas that may pose a biosecurity threat to New Zealand in the future, that are not included in the current risk profile (Fig. 1) identified by areas that under current climate have a CMI ≤ 0.7, and under future climate have a CMI > 0.7

Because of the severe uncertainty regarding the future greenhouse gas emissions patterns, this is the aspect of global change that is perhaps the greatest source of uncertainty in predicting global change impacts. In the absence of a clear global policy framework for responding to the challenges of climate change, it is impossible at this time to gauge which emissions scenario is more likely. Whilst the IPCC recommended treating all the emissions scenarios as being equally plausible and likely (IPCC et al. 1999), the recent analysis by Rahmstorf et al. (2007) suggests that it is more prudent to focus climate change impact and adaptation attention on only the highest emissions scenarios from the SRES offerings as used here. My intention is to demonstrate the application of the technique, rather than elaborate a complete operational analysis from the perspective of a single biosecurity agency. To operationalise this approach, it may be prudent to repeat the analysis for a number of GCM's and emissions scenarios as a means of gauging some of the uncertainty in the approach. It would be imprudent however to treat the results of this set of simulations as coming from a single distribution and taking their mathematical average. Such ensemble approaches should be treated very cautiously, as there is a natural tendency for the results to be misinterpreted as being the most likely future scenario. The correct interpretation is that the results provide a guide as to the likely range of uncertainty in the outcomes. As the century unfolds, and the historical path is characterised, uncertainty regarding the emissions scenarios will automatically reduce, but so will their forecast value for planning purposes as the time horizon shrinks in parallel.

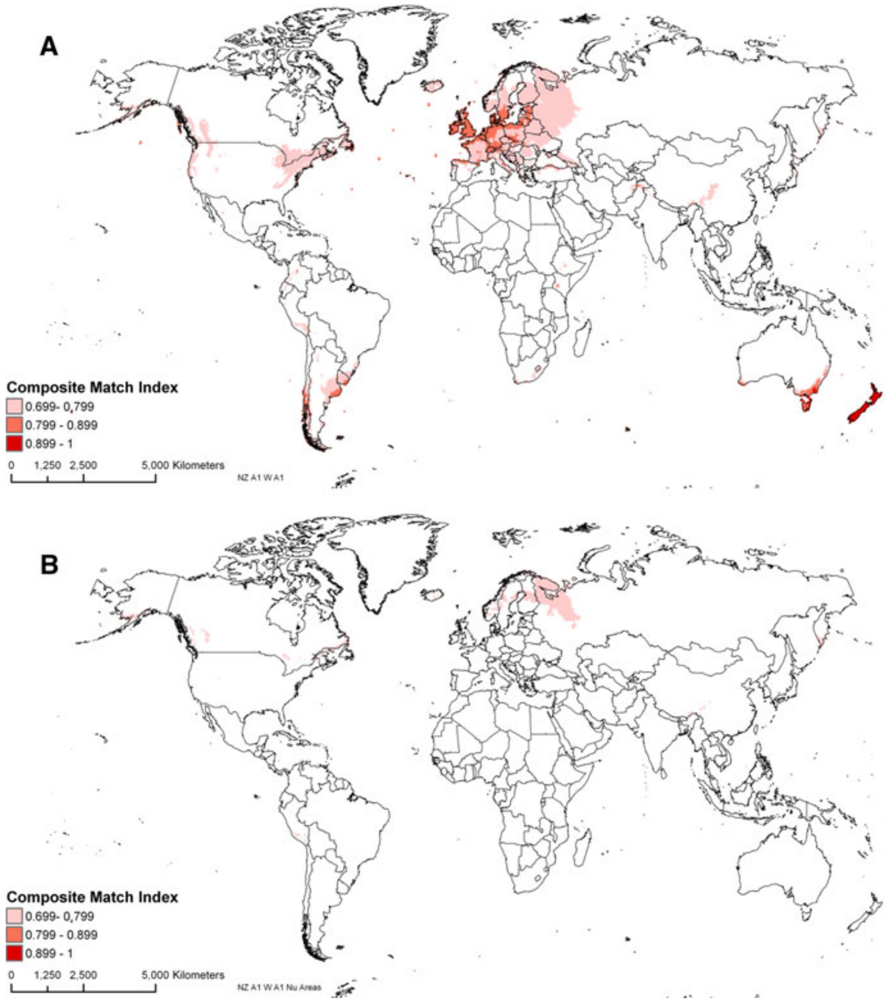

Fig. 4 The areas that may pose a biosecurity threat to New Zealand in the future, assuming that species distributions have equilibrated under a 2080's climate change scenario. **a** Derived by matching New Zealand's climate in the 2080s based on the Hadley3 GCM run with the the SRES A1 scenario to the rest of the world in the 2080s under the same scenario, and **b** To focus attention on the changes with respect to the present situation, areas that, under current climate have a CMI value greater than 0.7 are excluded

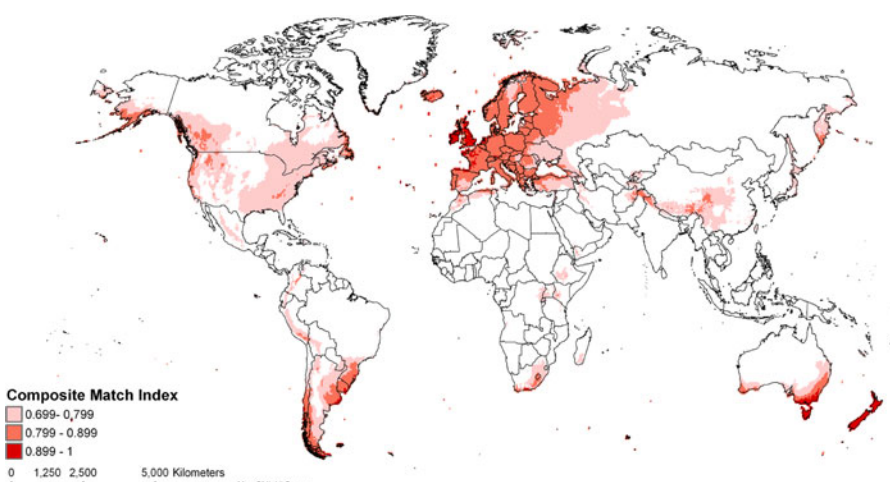

Fig. 5 The combined present and potential future pest threat regions. The maximum Composite Match Index taken across all scenarios and combinations (Figs. 1, 2, 3, 4)

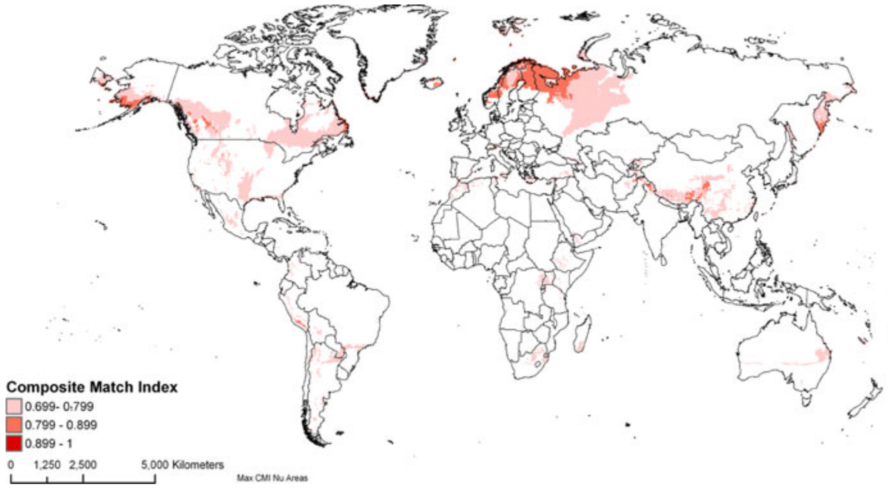

Fig. 6 The new threat regions taken from Fig. 5, but excluding those areas with a high match index (CMI > 0.7) in Fig. 1. This includes those regions that may presently harbour pests that could pose a threat to New Zealand in the future, those with a transient risk, and those that could pose a risk if the climate stabilises under the 2080s scenarios and species ranges equilibrate

Given these and other sources of uncertainty, the desirable qualities of human organisational systems that are able to adapt to the challenges posed by climate change will be *preparedness, responsiveness* and *nimbleness*. That is, a robust system would forecast potential threats and assess potential responses, ensuring that threats are appropriately monitored, and finally it would change in a timely, (preferably mildly pre-emptive) manner. In terms of pathway risk management, this could translate into devoting some resources to monitoring trade patterns from ports that service regions that sustain organisms with potential current or future threats. As changing trade patterns establish new pathways into these emerging risk areas, new risk profiles should be analysed to determine what processes should be established to ensure that the new threats are addressed appropriately. If low-cost options exist to attenuate pest threats from these regions, then implementing them early may be an appropriate "no regrets" tactic. If the future threat areas do start warming as expected, or threatening pests are intercepted from these sources, then biosecurity resources can be reallocated as appropriate toward threat mitigation and surveillance. This approach avoids the possibility of reallocating scarce resources toward the risk management of a threat that might not eventuate.

Whilst the ISPM framework does not rule out consideration of risks that may only eventuate under future climate scenarios, there appears to be nothing preventing a jurisdiction from using this information to assess risks, and to include this information in a pest risk assessment. Tools such as those presented here could inform that risk assessment procedure, providing at least an initial assessment of geographic threats. It remains to be seen however, whether a risk assessment completed on this basis would withstand a World Trade Organisation challenge.

In assessing climate change impacts it is common practice to consider the capacity of affected analytical units (e.g. industry sectors) to adapt to the challenges posed by climate changes. Many New Zealand primary production industries have shown themselves to be able to respond to emerging challenges and opportunities through rapid changes in land use. As industries adapt to the changing economic and climatic environments, it is likely that new biosecurity challenges will also emerge. If, for example, the pastoral sector chooses to adopt C_4 grasses as a means of responding to a warming climate, a new set of pests will become a significant biosecurity concern to New Zealand.

As New Zealand industries adapt, it is likely that overseas regions with a similar climate and production capacity will adopt similar responses when facing the same sorts of challenges (convergent cultural evolution). This process will ensure that at least some of the climatically similar regions are also biotically matched for some, and perhaps most agricultural pests.

The technique described here is likely to be of use for jurisdictions that encompass a relatively small climate range, as the results will allow the relevant biosecurity agency to identify relatively small pest threat regions globally, and be able to use this knowledge to focus their resources appropriately. For regions such as Australia, Europe and North America, the results are dishearteningly broad in geographic scope, suggesting that a key component of success may be for some degree of geographic compartmentalisation of their risks on a port by port basis.

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References

Andrewartha HG, Birch LC (1954) The distribution and abundance of animals. University of Chicago Press, Chicago

Andrewartha HG, Birch LC (1984) The ecological web: more on the distribution and abundance of animals. University of Chicago Press, Chicago

Baker RHA, Sansford CE, Jarvis CH, Cannon RJC, MacLeod A, Walters KFA (2000) The role of climatic mapping in predicting the potential geographical distribution of non-indigenous pests under current and future climates. Agric Ecosyst Environ 82:57–71

Biosecurity Council (2003) Tiakina Aotearoa Protect New Zealand: the biosecurity strategy for New Zealand. The Biosecurity Council, Wellington, p 63

Blackburn TM, Cassey P, Lockwood JL (2009) The role of species traits in the establishment success of exotic birds. Glob Change Biol 15:2852–2860

Cannas SA, Marco DE, Paez SA (2003) Modelling biological invasions: species traits, species interactions, and habitat heterogeneity. Math Biosci 183:93–110

IPCC, TGCIA, Carter TR, Hulme M, Lal M (1999) Guidelines on the use of scenario data for climate impact and adaptation assessment. Intergovernmental Panel on Climate Change, p 69

Committee on the scientific basis for predicting the invasive potential of nonindigenous plants and plant pests in the United States (2002) Predicting invasions of nonindigenous plants and plant pests. National Academy Press, Washington, DC, USA

Franco M, Silvertown J (1996) Lifehistory variation in plants: an exploration of the fast-slow continuum hypothesis. Philos Trans R Soc Lond B 351:1341–1348

Grime JP (1979) Primary strategies in the established phase. In: Grime JP (ed) Plant strategies and vegetation processes. Wiley, Chichester New York, pp 7–55

Guisan A, Zimmermann NE (2000) Predictive habitat distribution models in ecology. Ecol Model 135:147–186

IPCC (2007a) Climate change 2007: mitigation. Contribution of Working Group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC (2007b) Climate change 2007: The physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Köppen WP (1936) Das Geographische System der Klimate [The geographical system of the climate]. In: Köppen W, Geiger GC (eds) Handbuch der Klimatologie. Gebrüder Bornträger, Berlin, p 44

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263

Kriticos DJ, Randall RP (2001) A comparison of systems to analyse potential weed distributions. In: Groves RH, Panetta FD, Virtue JG (eds) Weed risk assessment. CSIRO Publishing, Melbourne, pp 61–79

Kriticos DJ, Phillips CB, Suckling DM (2005) Improving border biosecurity: potential economic benefits to New Zealand. N Z Plant Protect 58:1–6

Leung B, Lodge DM, Finoff D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. Proc R Soc Lond B Biol Sci 269:2407–2413

New M, Lister D, Hulme M, Makin I (2002) A high-resolution data set of surface climate over global land areas. Clim Res 21:1–25

Paini DR, Worner SP, Cook DC, De Barro PJ, Thomas MB (2010) Using a self organising map to predict invasive species: sensitivity to data errors and a comparison with expert opinion. J Appl Ecol

Parmesan C, Ryrholm N, Stefanescu C, Hill JK, Thomas CD, Descimon H, Huntley B, Kaila L, Kullberg J, Tammaru T, Tennent WJ, Thomas JA, Warren M (1999) Poleward shifts in geographical ranges of butterfly species associated with regional warming. Nature 399:579–583

Parmesan C, Gaines S, Gonzalez L, Kaufman DM, Kingsolver J, Townsend Peterson A, Sagarin R (2005) Empirical perspectives on species borders: from traditional biogeography to global change. Oikos 108:58–75

Peacock L, Worner S (2006) Using analagous climates and global insect distribution data to identify potential sources of new insect pests in New Zealand. N Z J Zool 33: 141–145

Pyšek P, Jarošik V, Pergl J, Randall R, Chytry M, Kuhn I, Tichy L, Danihelka J, Chrtek JJ, Sadlo J (2009a) The global invasion success of Central European plants is related to distribution characteristics in their native range and species traits. Divers Distrib 15:891–903

Pyšek P, Krivanek M, Jarošik V (2009b) Planting intensity, residence time, and species traits determine invasion success of alien woody species. Ecology 90:2734–2744

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, Somerville RCJ (2007) Recent climate observations compared to projections. Science 316:709

Richardson DM, Thüiller W (2007) Home away from home—objective mapping of high-risk source areas for plant introductions. Divers Distrib 13:299–312
Ruesink JL (2005) Global analysis of factors affecting the outcome of freshwater fish introductions. Conserv Biol 19:1883–1893
Simberloff D (2009) The role of propagule pressure in biological invasions. Annu Rev Ecol Evol Syst 40:81–102
Stohlgren TJ, Schnase JL (2006) Risk analysis for biological hazards: what we need to know about invasive species. Risk Anal 26:163–173
Sutherst RW, Maywald GF (1985) A computerised system for matching climates in ecology. Agric Ecosyst Environ 13:281–299
Sutherst RW, Maywald GF and Kriticos DJ (2007) CLIMEX Version 3: user's guide. Hearne Scientific Software Pty Ltd, www.Hearne.com.au
Thüiller W, Richardson DM, Rouget M, Proches S, Wilson JRU (2006) Interactions between environment, species traits, and human uses describe patterns of plant invasions. Ecology 87:1755–1769
Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee TJC, Fromentin JM, Hoegh-Guldberg O, Bairlein F (2002) Ecological responses to recent climate change. Nature 416:389–395
Woods A, Coates KD, Hamann A (2005) Is an unprecedented dothistroma needle blight epidemic related to climate change? Bioscience 55:761–769
Woodward FI (1987) Climate and plant distribution. Cambridge University Press, Cambridge, 174 pp
Worner SP, Gevrey M (2006) Modelling global insect pest species assemblages to determine risk of invasion. J Appl Ecol 43:858–867