Cooperative Research Centre

for National Plant Biosecurity

Final Report

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Climate Change and Pest Risk Analysis

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1. Project Overview

1.1 Project Aim

To develop a template that will incorporate climate change into pest risk analysis (PRA) of emergency pests and pathogens of quarantine concern to Australia.

1.2 Project Rationale and Background

Projected future climates will influence the entry, establishment and spread of pests, weeds and pathogens (hereto referred to as pests) which will necessitate adaptation of current biosecurity practices such as preparedness, prevention and containment and affect biosecurity policies, trade and market access.

The CRC project 10071 'The effects of climate change on plant biosecurity' increased our understanding of the effects of climate change on plant pests and diseases. We propose to build on this CRC investment by enhancing the impact of the completed project with a focus on federal biosecurity policy. At the completion of this project, the quadrilateral biosecurity network (QUADs), representing four member countries (USA, Canada, Australia and New Zealand), requested the development of a template for incorporating climate change projections into Pest Risk Analyses. This template would assist in determining the probability of entry, establishment and spread under changed climate conditions. Determining the effect of climate change on pest risk analyses could lead to re-prioritization of pest threats and implementation of new management options, directing scarce resources where they are most required.

The Australian quarantine system and biosecurity PRA procedure is underpinned by international standards and agreements set out by the World Trade Organization (WTO) for the application of sanitary and phytosanitary measures (the SPS agreement; WTO, 1995) and for plant pests, various guidelines and standards developed by the International Plant Protection Convention (IPPC). A biosecurity risk analysis procedure was developed by Biosecurity Australia to prevent or control entry and establishment of pests that could threaten humans, animals, plants, the environment and our agricultural activities (Biosecurity Australia, 2003). Requirements for PRA are detailed in International Standards for Phytosanitary Measures (ISPM) No. 2. 'Framework for Pest Risk Analysis' (FAO, 2011) and ISPM No. 11. 'Pest risk analysis for quarantine pests including analysis of environmental risk and living modified organisms' (FAO, 2006).

Pest risk analysis involves three stages: initiation (identifying pests and pathways of quarantine concern); pest risk assessment (pest categorisation, assessment of probability of entry, establishment and spread, assessment of consequences) and pest risk management (managing risk and identifying appropriate management options) (FAO, 2011). Assessment and quantification of these variables will determine management options for the likely incursion of an emergency pest or pathogen.

Given we have gained considerable understanding of pest and pathogen behaviour in response to a changing climate, the logical next step is to incorporate our knowledge into biosecurity instruments such as PRAs. A previous attempt to illustrate the potential impact of climate change on the pest risk analysis process summarised the possible scenarios for the pest risk assessment phase (Fig. 1). A template incorporating detailed potential risks to the PRA process would assist in determining the role of climate change in an assessment of pest risk analysis of all stages. Assessing risk in light of climate change may lead to new directions in biosecurity management, such as re prioritization of threats and changes to contingency and management planning, in order to direct scarce resources where they are most required.

Despite the growing awareness that climate change will affect the status of pest, pathogen and weed species incorporating climate change into a pest risk analysis is a contentious issue.

Proponents for a more inclusive process argue an urgent need to assess the vulnerability of agriculture to climate change changes given the critical role of agriculture in food production and food security (Ziska et al., 2011). Further the design and implementation of invasive species policy should not only be more accessible to policy makers (Leung et al., 2005) but address the potential consequences for climate change. According to (Pyke et al., 2008) climate change policy should include (i) characterization of interactions between climate change and invasive species; (ii) identification of areas where climate change policies could negatively affect invasive species management and (iii) identification of the areas where policies could benefit from synergies between climate change and invasive species management.

Proponents against an inclusive process argue that pest risk assessments are ‘sufficiently robust’ without including climate change implications (EFSA, 2007) although they acknowledge that circumstances may change with future increases in global trade and changes to global weather patterns.

Certainly, one of the arguments against the inclusion of climate change is that there is too much uncertainty in bioclimatic predictive models in part due to lack of informative biological data on pest species (EFSA, 2007). Further, the variety of models available for use will give a range of possible futures that can only increase uncertainty (Mearns and Nychka, 2007). A controversial method used to decrease uncertainty is the use of numerous climate models, predictor variables and projections where conclusions are based from the greatest number of models that provide consensus (Bradley et al., 2010).

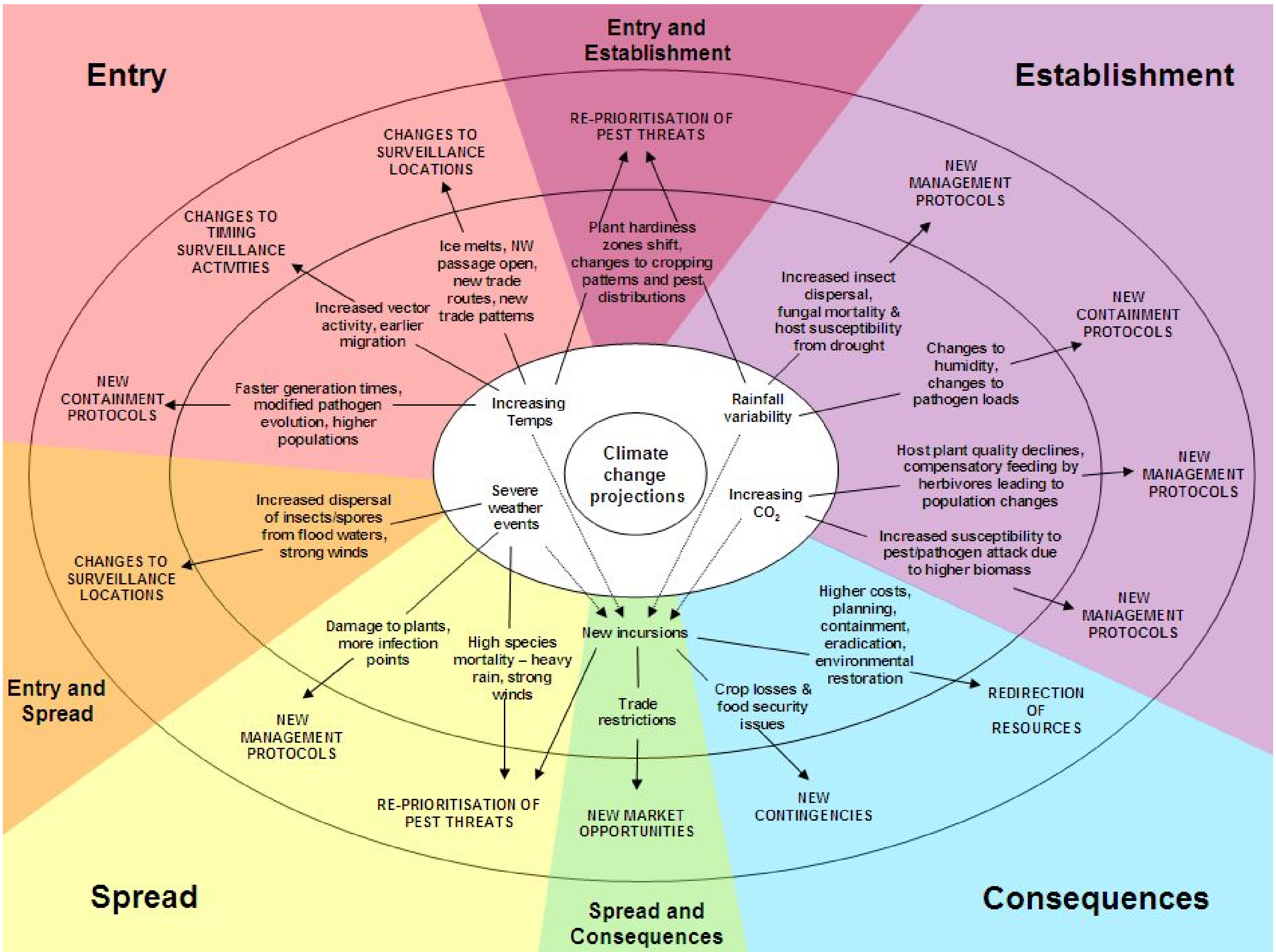
A number of challenges have been identified with respect to predictive modeling. The first is a question of spatial scale. Global climate models used for prediction need to be downscaled to national or regional levels. Not only may this take up too much time and resources, especially for issues requiring quick answers (Seem, 2004), but in some cases the spatial resolution will be insufficient to account for changes at the local and micro-climate level that may be significant for the survival of a species (EFSA, 2007).

Accompanying this is the issue of temporal scale. Climate change models are usually based on 30 year average (Hellmann et al., 2008) whereas PRAs generally have a more immediate focus. EFSA (2007) noted there is no specific time frame for the validity of PRAs in Europe as they are updated as and when new information becomes available. Further, baseline current climate data is based on 30 year averages (generally 1960-1990) but this may skew future predictions as it is not representative of current conditions (Magarey et al., 2008). Climate change parameters used must be satisfactory to each participating member. As such decisions must be made on which global climate models are appropriate for use and which, if any, IPCC projections should be used to determine the extent of potential future impacts.

Any changes to the PRA process must satisfy the basic principles of the World Trade Organization and the SPS agreement (WTO, 1995). Members must base their phytosanitary measures on international standards, guidelines or recommendations (harmonization) and must accept phytosanitary measures of other members as equivalent when trading in the same product (equivalence). Phytosanitary measures must be cost-effective and feasible, no additional measures should be imposed if existing measures are deemed effective and measures should not be more trade restrictive than necessary (‘principle of minimal impact’).

The SPS Agreement requires that measures be based on sufficient scientific evidence and that risk assessment should not be arbitrary, unjustified or concealed as a trade barrier. Unfortunately, the definition of 'sufficient' is not clear yet some measure of scientific robustness is required to meet these requirements. This may therefore be support for considering PRA's on a case-by-case basis where the decision to incorporate climate change into a PRA is based on feasibility, availability of resources and the quality of scientific evidence available. This project is contributing to meeting the SPS agreement requirements by providing a logical and transparent process through which to consider possible amendments to a PRA by including climate change.

Fig. 1. Summary of the potential impact of climate change on the pest risk assessment phase of the pest risk analysis process with potential implications for biosecurity.



2 Research Strategy

2.1 Research Questions

How might climate change impacts alter the outcome of pest risk analyses of emergency pests and pathogens?

What elements should be included in a template that incorporates climate change into pest risk analyses?

2.2 Research Strategy (detailed)

- Review and document the scientific literature on the potential impact of climate change on a pest or pathogens ability to enter, establish and spread in new areas for each stage of the PRA process, and what this may mean for pest risk management.
- Consult with BA to determine suitable elements for inclusion into PRA.
- Develop a prototype PRA template incorporating climate change into the PRA process.
- Circulate the template to Quadrilateral Biosecurity Working Group (QUADS) members for further development and refinement.
- Present the template to BA for comments and contributions to facilitate the use of the template with existing or new PRA's.

3. Incorporating climate Change into pest risk analysis

Climate change is likely to alter the risks associated with the biosecurity of Australian agriculture particularly with how pests and diseases may respond to a changing climate (Aurambout et al., 2006). Extensive research undertaken about the behaviour of pests, pathogens and host plants in future climates have determined some trends and likely outcomes in a future climate – see reviews on plants by (Thuiller et al., 2007; Walther, 2003); on herbivores (Bale, 2002; Cao and Klijn, 2006; Coviella and Trumble, 1999); pathogens (Chakraborty et al., 2008; Harvell et al., 2002) (Scherm and Coakley, 2003) and ecosystems (Thuiller et al., 2007; Hellmann et al., 2008; Root et al., 2003; Ziska et al., 2011). However, detailed analyses on individual pests are lacking and tend to be spatially and temporally variable over the vast Australian landscape.

The following is an attempt to determine generic climate change issues for each pest risk analysis stage and assess if and how they can be factored into the PRA process.

3.1 PRA Stage 1: Initiation

Initiation is the generic identification of organisms and pathways that should be considered for pest risk assessment. The PRA process may be triggered by a number of factors referred to as 'initiation points' (FAO, 2011), such as identification of a new pathway, identification of a new pest or review of phytosanitary measures due to new regulations. Each initiation point may need to be considered or re-considered in the light of climate change. The aim of the initiation process is to identify pests and pathways of concern and define the PRA area (usually Australia). Taxa determined not to be pests need no further assessment, while others are identified as candidates for further research and proceed to stage 2 of the PRA process.

3.2 PRA Stage 2: Risk assessment

The pest risk assessment process can be characterised by the following steps: 1) pest categorisation; 2) assessment of the probability of entry, establishment and spread; 3) assessment of the potential economic consequences.

3.2.1 Pest Categorisation

Pest categorisation is the process of determining whether the pest has the characteristics of a quarantine pest (FAO, 2011). Factors to consider are the identity of the pest, its presence or absence in the PRA area, the regulatory status of the pest, the potential for establishment and spread and potential for economic consequences (FAO, 2006). At present, no consideration is given as to whether pest status may change under a future climate.

The identity of the pest should be clearly defined as a taxonomic unit where differences in host range, virulence and vector relationships are considered different enough to pose a potential phytosanitary threat. A level below that of species may need to be adopted in certain cases, some of which may be triggered by climate change factors.

Presence or absence in the PRA should be definitively determined and if the pest is present but not widely distributed, it should be under official control or expected to be under official control in the near future. Consideration should be given to whether this status would change in future climates. For example, in Australia, the population genetics of southern populations of the vinegar fly (*Drosophilia melanogaster*) indicate a genetic adaptation to a warmer drier climate which equates to a 4°C latitude shift (Umina et al., 2005).

The potential for establishment and spread in the PRA area can be determined though assessment of the similarity of ecological and climatic conditions in the source and PRA area, the presence of hosts, alternate hosts, vectors and alternate vectors. Adaptive characteristics as a result of a changing environment also need factoring in at this stage.

Finally, clear indications of the potential for unacceptable economic, environmental and social impact should be assessed. At this stage detailed analysis is not required if it is widely agreed that the consequences will be unacceptable if a pest is introduced. Consideration of future climate should also be a factor here.

If it is determined that that pest has the potential to be quarantine pest or there is insufficient information to base a conclusion, pest risk assessment should continue to the next stage.

3.2.2 Probability of Entry

The probability of a pest entering a country depends on the abundance and frequency of the pest along the potential pathways from the exporting region and the frequency and quantity of pests associated with them. Documented pathways need to be considered and potential new pathways assessed.

The likelihood of new pathways is enhanced by the climate change prediction of changed weather patterns and more frequent extreme weather events. Pathways of natural dispersal will be disrupted by extreme weather events such as cyclones where long distance dispersal can occur. For example, the arrival of the English grain aphid (*Sitobian miscanthi*) in New Zealand is thought to have been derived from Australia (Close and Tomlinson, 1975). Cereal aphids have also been associated with low-level jet streams in the US (Kieckhefer et al., 1974; Wallin and Loonan, 1971). Increased wind and driving rains may result in the new incursions in previously unaffected sites particularly of splash-dispersed pathogens (Anderson et al., 2004; Rosenzweig et al., 2001). One such example is citrus canker which spread over vast areas of the Florida citrus industry as a result of Cyclone Wilma and led to the destruction of one third of all Floridian citrus orchards (Gottwald et al., 2007).

Increased temperatures may also modify dispersal patterns by disrupting thermal thresholds for development and flight. Earlier, and possibly prolonged, migration is seen in aphids and moths as a result of higher temperatures (Woiwod, 1997; Zhou et al., 1995). On the other hand a prolonged occurrence of high temperatures may curb flights as the upper thermal threshold is routinely surpassed.

New trade route pathways could open such as a result of climate change such as the opening up of the North West shipping Passage in the Arctic due to the loss of perennial sea ice paving the way for new pest host interactions (Stroeve et al., 2008). Similarly, people displacement due to climate change may result in more people movement by accidentally or deliberately introducing new pests to new areas.

The direct impact of climate change will be to alter the frequency and quantity of pests associated with each potential pathway. If it can be identified that a high priority pest may be less of a threat under certain climatic conditions predicted in the future, changes to management procedures such as surveillance activities can be altered accordingly.

3.2.3 Probability of Establishment and Spread

Assessing the probability of establishment relies on knowledge of the pest biology in areas where it currently occurs and determining the likelihood that the pest will survive in a new environment. Climate change is likely to impact on this potential in a number of ways. Increasing temperatures directly impact the growth, development, survival, fecundity, feeding behaviour, range and abundance of insects (Bale, 2002). In some cases this may lead to faster development times and shorter life cycles (Bale, 2002; Harrington et al., 2001). An increase in development rate could help reduce predation as less time is spent in the vulnerable nymphal and larval stages. Increases in number of generations per season under higher temperatures have also been recorded for Lepidoptera, Coleoptera and Hemiptera (Gomi et al., 2007; Jönsson et al., 2007; Kiritani, 2006). For example, increased winter survival of non diapausing insects such as the Green peach aphid (*Myzus persicae*), rapidly increased population densities (Bale et al., 1988). Conversely, certain species of Auchenorrhyncha (leaf, tree and plant hoppers, spittlebugs) hatched earlier from hibernation under increasing temperatures but the rate of nymphal development did not increase, indicating the effect is likely to be species specific (Masters et al., 1998).

Increasing temperatures are also known to impact on species distributions (Cannon, 1998; Root et al., 2003). Temperate species are likely to extend their distributions to higher altitudes and latitudes while cold-adapted species may experience restricted distributions (Bale, 2002; Marçais et al., 2004; Watt et al., 2009). Close synchrony of host-specific predators and their host plants is required for successful life cycle completion but may be disrupted from increasing temperatures. Relative asynchrony may disadvantage some species that have close associations with budburst and emergence (Straw, 1995) or may benefit other species which can take advantage of longer periods of growth (Zhou et al., 1995).

Increasing temperatures will also influence the growth and development of pest and pathogens resulting in shorter life cycles, faster generation times and increased populations (Brown and Hovmøller, 2002; Scherm and Coakley, 2003). For reviews see (Chakraborty, 2005 ; Chakraborty et al., 1998; Manning and Tiedemann, 1995). Warmer winters and higher overall temperatures will favour the winter survival of pathogens and accelerate pathogen and vector life cycles (Harvell et al., 2002). In China, for example an increase in the prevalence of the warm climate disease powdery mildew (*Eisiphe grammis*) and decrease in the cool climate disease wheat stripe rust (*Puccinia striiformis*) was attributed to an increase in average annual temperature from 1950 to 1995 (Chakraborty et al., 2000). Conversely, very hot dry summers have reduced infestations of many fungal diseases relying on humid conditions such as septoria leaf spot diseases (*Septoria tritici* and *S. nodorum*) (Patterson et al., 1999).

Shorter life cycles may also increase virus evolution rates potentially leading to more efficient strains or larger populations (Yang et al., 1998). Changes to distribution and frequency of virus epidemics are also indicated (Zvereva and Kozlov, 2006).

Changes in plant physiology due to higher temperatures can alter host resistance by suppressing defence responses resulting in an increase in disease severity (Fuhrer, 2003). Structural changes in the plant due to increased temperature, such as increased lignification may also enhance the level of resistance (Chakraborty, 2005).

The impact of elevated CO_2 (eCO_2) on herbivorous insects has been comprehensively reviewed – see (Coviella and Trumble, 1999; Stiling and Cornelissen, 2007). Changes to host plant physiology occur under eCO_2 include increased C:N ratio and altered concentrations on non-structural carbohydrates, starch and fibre content and other plant chemicals (Hunter, 2001). Some herbivores respond to plants grown under eCO_2 by compensatory feeding (increasing consumption rates to compensate for lower food quality) (Bezemer and Jones, 1998). However, the response varies with different feeding guilds (Coviella and Trumble, 1999). Low nutritional quality of the plant can cause decreases in insect growth rates and the extension of development time (Kopper and Lindroth, 2003; Stiling et al., 1999) which in turn can lead to increases in mortality rates as the herbivores extend their exposure time to natural enemies (or higher proportions of pathogenic bacteria and viruses) ultimately reducing herbivore abundance (Bale, 2002).

The impact of climate change at this stage of the PRA process is determined by the effect on pest biology either directly or through the indirect effects of changes to host plant physiology. Since numerous studies have examined the effect of increased temperature, eCO_2 and changes to weather patterns on pests, pathogens and weeds it is relatively simple to make broad scale predictions e.g. cool climate pests may find a hotter climate less conducive to survival and move to a more suitable environment such as a higher altitude to avoid the temperature increase (Bale, 2002). However, specific changes to a pest of particular interest will need to be examined more closely. Possible outcomes from re-examining establishment and spread in reference to climate change may be re-prioritising pest threats and changes to management protocols.

3.2.4 Assessment of potential consequences

This stage of the risk assessment is to determine what the likely consequences of the pest were to enter, establish or spread in the PRA area. The assessment includes direct and indirect effects of the potential pest as well as economic and environmental consequences. Direct pest effects include plant life and health and indirect pest effects are considered in relation to eradication and control, domestic trade, international trade and the environment. Each of the four criteria are considered at local, district, regional and national levels and are described using four categories: indiscernible, minor significance, significant and major significance (definitions below) (Plant Biosecurity, 2011).

- Local: 'an aggregate of households or enterprises (a rural community, a town or local government area'.
- District: 'a geographically of geopolitically associated collections of aggregates (generally a recognised section of a state or territory, such as 'Far North Queensland')'.

- Regional: 'a geographically or geopolitically associated collection of districts in a geographic areas (generally a state or territory, although there may be exceptions with larger states such as Western Australia)'.
- National: 'Australia wide (Australian mainland states and territories and Tasmania)'.
- Indiscernible: 'pest impact unlikely to be noticeable'.
- Minor significance: 'expected to lead to a minor increase in mortality /morbidity of hosts or a minor decrease in production but not expected to threaten the economic viability of production. Expected to decrease the value of non-commercial criteria but not threaten the criterion's intrinsic value. Effects would be generally reversible'.
- Significant: 'expected to threaten the economic viability of production through a moderate increase in mortality /morbidity of hosts or a moderate decrease in production. Expected to significantly diminish or threaten the intrinsic value of non-commercial criteria. Effects may not be reversible'.
- Major significance: 'expected to threaten the economic viability of production through a large increase in mortality /morbidity of hosts, or a large decrease in production. Expected to severely or irreversibly damage the intrinsic value of non-commercial criteria'.

Assessment and quantification of these variables will determine the likely management options for a likely pest threat. Further, the consequences of a pest becoming more or less of a threat due to climate change will become apparent in this stage of a PRA. As consequences are assessed at a geographical level, one must also factor in changes to the host plant distributions e.g. a particular crop may not be grown in the same area as it once was due to a warmer climate. Therefore threats to particular areas may decrease but increase elsewhere.

3.3 PRA Stage 3: Pest Management

Pest risk management is the process of identifying and implementing phytosanitary measures to manage risks to achieve Australia's Appropriate Level of Protection (ALOP) which is currently aimed at reducing risk to a very low or negligible level and to ensure that any negative effects on trade are minimised.

Pre-border measures applied to traded commodities include inspection or testing for freedom of pests, conditions of the preparation of the consignment, treatment of the crop in importing country, harvesting plants at certain age or time of year, maintaining pest free areas and considering human assisted movement of produce, surveillance and border control. Post border management options involve established protocols to prevent the occurrence and spread of the pest. Requirements for the containment vary with each pest but may include monitoring of orchards, host plants for the presence of the pest, delimiting surveys, destruction of infected host plants, establishment of a certified scheme for the movement of host material and management of insecticide to avoid pest resistance. If the pest cannot be contained the next option is eradication where management options include establishment of quarantine zones, mandatory destruction of host plant material within the quarantine zone and regulations prohibiting transport of infected host materials outside infected areas.

Climate change may affect the status of the pest both in the importing country and the PRA area by directly affecting host biology or indirectly affecting the host on which the pest relies. Measures undertaken to contain or control the pest may need constant re-assessment if the pest status changes.

4. Mapping climate change to the Pest Risk Analysis Process

Section 3 clarified some of the possible impacts of climate change on pest threats and how they might be perceived in the various stages of pest risk analysis. We are now in a position to examine PRA more closely and identify (i) potential climate change influences and (ii) considerations that might need to be taken into account to adapt the system to climate change. Detailed requirements for each stage of the pest risk analysis process have been assembled from ISPM No. 11. (Pest risk analysis for quarantine pests including analysis of environmental risk and living modified organisms; (FAO, 2006). These are detailed in Table 1 below accompanied by potential climate change impacts and proposed measures for adaptation.

Table 1. Climate change influences on the different stages of the PRA process. Details from ISPM 11 (FAO, 2006).

PEST RISK STAGE 1: INTIATION		
INITIATION POINTS		
Identification of a pathway		
	POTENTIAL CLIMATE CHANGE INFLUENCE	**MEASURES REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE**
Proposal to import a commodity not previously imported or from a new area	This may become more frequent as climate change disrupts existing trade patterns.	No change necessary – PRA will be triggered appropriately by existing process
Importation for selection and/or scientific research on a species not yet introduced that could be a host of pests	Adaptation to climate change will increase demand for this type of importation	No change necessary – PRA will be triggered appropriately by existing process
Accidental or deliberate introduction of a commodity, pest or host	This may become more frequent as climate change displaces groups of people to new areas	No change necessary – PRA will be triggered appropriately by existing process
A change in susceptibility of a plant or pest	This may become more frequent as climate change alters host plant physiology and phenology	No change necessary – PRA will be triggered appropriately by existing process
A change in virulence/aggressiveness or host range of a pest	This may become more frequent as climate change alters pest behaviour and development	No change necessary – PRA will be triggered appropriately by existing process
Identification of a pest threat		
Discovery of an infestation or outbreak of a new pest	New organisms are likely to establish more frequently some of which would not currently trigger a PRA but should do under climate change	Assess the potential range and impact of the organism in relation to future climate to determine the need for a PRA
A new pest is identified by scientific research	Climate change unlikely to impact	No change necessary

A pest is reported to be more injurious than previously known	Due to changes in pest and host plant physiology as a result of climate change this may be reported more often	No change necessary
There is a change in the status or incidence of a pest in the PRA area	Status and incidence of pest may alter more rapidly due to climate change effects on pest, hosts and production systems	No change necessary – maintain network of reporting systems
A new pest is intercepted on an imported commodity	This could become more frequent as climate change disrupts existing trade patterns and displaces groups of people to new areas	No change necessary – maintain inspections and border control procedures
Review of phytosanitary measures		
A national review of phytosanitary regulations, requirements and operations is undertaken	Climate change unlikely to impact	No change necessary
An official control program is developed to avoid unacceptable economic loss	As the spectrum of pests shifts in response to climate change new official control programs may be initiated more frequently	No change necessary
A new system, process or procedure is introduced or new information made available that influences a previous decision	Increasing knowledge of pest impacts under climate change is likely to lead to previous PRAs being revisited	Systematic review of previous decisions to incorporate climate change effects may be more efficient than ad hoc responses
An international dispute on phytosanitary measures arises	Likely to become more frequent if climate change consequences for pest risk are assessed differently by trading partners	Establish whether there is a current or impending international disagreement about this pest arising from differing interpretations of climate change effect on risk

A phytosanitary situation in a country changes or political boundaries change	Climate change (e.g. water shortages, crop failures) may lead to political instability and re organisation	No change necessary
PEST RISK STAGE 2 –RISK ASSESSMENT Phase 1		
Categorisation		
	POTENTIAL CLIMATE CHANGE INFLUENCE	**MEASURE REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE**
Establishment as a 'quarantine pest'	Growth, development and behaviour of pests will alter due to climate change	Assessment must take into consideration possible changes to pest status as a result of climate change
PEST RISK STAGE 2 – RISK ASSESSMENT		
Phase 2: Probability of Entry		
	POTENTIAL CLIMATE CHANGE INFLUENCE	**MEASURE REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE**
Prevalence of pest in source area	Change in distribution and abundance of pests is likely in many source areas due to climate change	Assessments must be based on current information. Historical records will become increasingly less relevant
Likelihood of pest being associated with pathways at the source	Disruptions to current production systems in source area due to climate change may change the likelihood of pest association with pathways	Assessments must be based on current practices in source area and updated regularly
Seasonal timing of trade	Timing of crop growth in source areas is likely to change due climatic factors	Assessments must be based on current practices in source area and updated regularly
Illegal trade (intentional, unintentional)	Economic constraints bought about by climate change could increase trade in new varieties and associated pests Displacement of people to new areas due to climate change may increase illegal introduction of pests	Incursion data should be regularly reviewed for patterns

Pest management procedures applied at source	Alterations in pest management procedures due to changes in pest status likely in many source areas due to climate change	Assessments must be based on current practices in source area and updated regularly
Probability of pest surviving transport and storage	Climate change unlikely to impact	No change necessary
Probability of pest surviving management and phytosanitary procedures	Management efficacy may be affected by altered pest life cycle stages at time of treatment due to climate change	Management procedures should be reviewed and adjusted as necessary to reflect any changes
Likelihood of pest transfer to a suitable host	Host distribution or suitability could alter due to climate change	Assessments must take into account changes to host plant distributions and abundance. This may require additional surveys.
Destination points of intended commodity	Proximity to host or alternate host may change under new climate conditions	Assessments must take into account changes to host plant distributions and abundance. This may require additional surveys.
By-products and waste produced	Climate change unlikely to impact	No change required
Time of year of import	Climate change may alter availability of commodity in source area and seasonal demand for commodity in PRA area	Monitor seasonal pattern of import in relation to availability and suitability of host plants
Unaided dispersal	Changes in wind patterns and frequency of extreme weather events may alter the risk of unaided dispersal	Base assessment of likely dispersal on best current information regarding wind pattern and extreme weather events under climate change

Phase 2: Probability of Establishment and Spread

	POTENTIAL CLIMATE CHANGE INFLUENCE	**MEASURE REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE**
Characteristics of pest – e.g. availability, quantity, distribution, reproductive strategy, host resistance, genetic and environmental adaptability	Adaptation of pests to direct and indirect effects of climate change may significantly alter these characteristics (e.g.	Detailed research into pest biology may be required to determine whether any adaptative shifts are occurring –

and threshold populations required for establishment	production of alates or apterae in aphids, shifts in gene frequency)	Earlier studies of pest biology may no longer be reliable
Suitability of environment	Growth, development and behaviour of pests will alter due to climate change	Research may be required into how environmental variables that are part of climate change affect these characteristics of the pest particularly in relation to novel climates
Availability, quantity, distribution and characteristics of host, alternate hosts	Host plant and alternate host plant distribution, abundance and suitability likely to be altered due to climate change	Assessments must take into account changes to host plant and alternate host plant distributions, abundance and suitability. This may require additional research, which may include investigation of potential new host associations
Availability, quantity, distribution and characteristics of vectors	Vector distribution, abundance and capacity may alter due to climate change Interaction of vector with host plants could alter due to climate change	Assessments must take into account changes to vector distributions, abundance and vectoring capacity due to climate change. This may require additional research, which may include investigation of potential new vectors
Availability, quantity, distribution and characteristics of natural enemies	Natural enemy distribution, abundance and impact may alter due to climate change Interaction of natural enemies with pest may alter due to climate change	Assessments should ideally take into account changes to natural enemy distributions, abundance and impact on pest. This is, however, particularly difficult to predict due to complex multi-trophic and multi-species interactions. A better approach may be to adjust assessment by reacting to trends identified via field observations at source
Cultural and control measures	Efficacy may be altered under climate change due to changes in pest, vector, host plant and natural enemy interactions. Also, specific control techniques may cease to be feasible e.g. periods of suitable weather for spraying may contract under future climates	Monitor trends in control practices, in particular failures of control that can be linked to changed weather patterns. Adjust assessment of risk according to any changes in feasibility of control measures
Phase 2: Spread only		

	POTENTIAL CLIMATE CHANGE INFLUENCE	MEASURE REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE
Presence of natural barriers	Some barriers may cease to function or others may arise due to climate change e.g. arid zones that restrict pest unassisted dispersal due to lack of hosts	Identify existing barriers that may become ineffective under climate change, or new barriers that may be developing, and if necessary adjust risk assessment
Unintended dispersal	Change in internal trade patterns due to climate change may alter dispersal probability	Monitor more closely transport of host plants, commodities or conveyances to a new area

PEST RISK STAGE 2 – RISK ASSESSMENT

Assessment of consequences - DIRECT PEST EFFECTS

Plant Life or Health

	POTENTIAL CLIMATE CHANGE INFLUENCE	MEASURE REQUIRED TO ADAPT SYSTEM TO CLIMATE CHANGE
Known or potential host plants	Host plant and alternate host plant distribution, abundance and suitability likely to be altered due to climate change, including introduction of new crop species or varieties that may be susceptible to the pest	When assessing consequences consideration should be given to susceptibility of new or expanding crops that are more suitable to a new climate
Types, amount and frequency of damage	Vector transmission rates and timing likely to be altered under climate change Amount and frequency of damage may change due to altered pest seasonal abundance and host plant phenologies under climate change	Research likely changes of pathogen transmission rates. Assess likely change in damage by combining knowledge of changes to host plant phenology with pest population responses to a changed climate
Control measures (including existing measures), their efficacy and cost	Efficacy may be altered under climate change due to changes in pest, vector, host plant and natural enemy interactions. Also, specific control techniques may cease to be feasible e.g. periods of suitable weather for spraying may contract under future climates	Monitor trends in control practices, e.g. failures of control that can be linked to changed weather patterns. Adjust assessment of risk according to any changes in feasibility of control measures

Effect of existing production practices	Timing and type of production practices likely to alter under future climates	Assessment of risk will need to be updated if widespread changes in production practices occur as a result of climate change
Environmental		
Reduction of keystone plant species	Distribution and health of existing keystone plants species likely to change under future climates, which will affect how important additional damage from the pest would be. Different plant species may be identified as keystone species as native vegetation communities respond to climate change	Assessment of consequences from the pest should be done in the context of the latest research on projected response of keystone plant species to climate change
Reduction of plant species that are major components of ecosystems	As previous item	As previous item
Endangered native plant species	Distribution and health of existing endangered native plants species likely to change under future climates, which will affect how important additional damage from the pest would be. Further species may be assessed as endangered due to climate change	Assessment of consequences from the pest should be done in the context of the latest research on projected response of endangered native plant species to climate change
Significant reduction, displacement or elimination of other plant species	Distribution and health of other plant species likely to change under future climates, which will affect how important additional damage from the pest would be	Assessment of consequences from the pest should be done in the context of the latest research on projected response of other plant species to climate change
Assessment of consequences - INDIRECT PEST EFFECTS		
Control and eradication		
Changes to producer costs or input demands, including control costs	Efficacy of control techniques may be altered under climate change due to changes in pest, vector, host plant and natural	Monitor trends in control practices, e.g. failures of control that can be linked to changed weather patterns. Adjust assessment of risk according

	enemy interactions. This may lead to use of different control techniques or affect frequency with which existing techniques have to be applied	to any changes in feasibility of control measures
Feasibility and cost of eradication and containment	Efficacy of eradication and containment measures may be altered under climate change due to changes in pest, vector, host plant and natural enemy interactions. This may lead to use of different eradication and containment measures, with consequences for costs. Alternatively, eradication or containment may be assessed as unfeasible and may be discontinued	Monitor progress of eradication and containment programs and identify processes by which climate change may be affecting outcomes Assess consequences from the pest based on feasibility of eradication or containment under future climate
Resources needed for additional research and consultation	Communicating climate change consequences for future management of the pest will add complexity to research and consultation and therefore increase costs	Take into account resources needed for research and consultation when assessing consequences of pest
Domestic and International trade		
Effects on domestic and international markets	Tolerance of markets for pest risk may be altered following climate change driven modification of trade patterns	When assessing the consequence of the presence of a pest for market access, consider whether there are any indications that market access requirements are likely to be reviewed
Changes to domestic or foreign consumer demand for a product from quality changes	Changes in consumer demand will be affected by price and quality of alternative products to substitute for one which has been damaged by the pest. Availability of these alternatives will be influenced by climate change	Estimates of pest consequences in the form of potential shifts in consumer demand, should take into account the possibility of a general decrease in availability of alternate products due to climate change
Environmental and non-commercial		
Environment and other undesired effects of control measures	Efficacy of control measures may be decreased under climate change, leading to	When considering consequences arising from detrimental effects of control measures, information

	reduced choice of control measures and possibly resulting in more damaging control measures being used	should be sought on whether some control measures may cease to be feasible under climate change
Social and other effects (e tourism)	Climate change will modify the social environment within which this consequence is expressed. Nevertheless, there seems to be no clear argument for why this consequence should generally be more or less severe due to climate change	No change necessary
Significant effects on plant communities	Distribution and condition of plant communities is likely to change under future climates, which will affect how important additional damage from the pest would be	Assessment of consequences from the pest should be done in the context of the latest research on projected response of plant communities to climate change
Significant effects on designated environmentally sensitive or protected areas	Conservation status of existing environmentally sensitive or protected areas is likely to change under future climates, which will affect how important additional damage from the pest would be. Different areas may be designated as environmentally sensitive or protected areas as policies in this area recognises threats from climate change	Assessment of consequences from the pest should be done in the context of the latest research on projected response of environmentally sensitive or protected areas to climate change and knowledge of forthcoming policy adjustments
Significant change in ecological processes and the structure, stability or processes of an ecosystem (including further effects on plant species, erosion, water table changes, increased fire hazard, nutrient cycling etc)	Stability of ecosystem structure and functioning is likely to change under future climates, which will affect how important disruptions initiated by the pest would be	Assessment of consequences from the pest should be done in the context of the latest research on projected response of ecological processes and ecosystem stability to climate change

5. Generic PRA Climate Change Template for assessing the risk of climate change to pest risk assessment

From the detail in Table 1 a Generic PRA Climate Change Template generic template was created to assess the risk of climate change to the pest risk analysis process. Each stage of the PRA process that was identified as requiring measures to adapt to climate change was listed in Table 2 below. At the end of each section a summary table is included (Table 2A) to establish an increased, decreased or unchanged risk and level of confidence in this overall change to risk factors.

Table 2: Generic Pest Risk Assessment Climate Change Template

PEST RISK STAGE 1: INITIATION			
INITIATION POINTS			
Identification of a pest threat			
	Information required	**Tick box**	**Tick box**
1. Discovery of an infestation or outbreak of a new pest	Is there recent or new information on the potential range and impact relevant to climate change?	No ☐ Yes ☐	If yes, does information suggest that the need for a PRA is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Review of phytosanitary measures			
2. A new system, process or procedure is introduced or new information made available	Has there been a review of pests under climate change, or a new system introduced to deal with climate change that has implications for this pest?	No ☐ Yes ☐	If yes, does information suggest that the need for a PRA is… Increased? ☐ Decreased? ☐ Unchanged? ☐
3. An international dispute on phytosanitary measures arises	Is there is a current or impending international disagreement about		If yes, does information suggest that the need for

	this pest arising from differing interpretations of climate change effect on risk?	No ☐ Yes ☐	a PRA is Increased? ☐ Unchanged? ☐
PEST RISK STAGE 2: RISK ASSESSMENT			
Phase 1: Categorisation			
Establishment as a 'quarantine pest'	Is there information suggesting that the status of the pest as a-quarantine pest should be reconsidered under climate change?	No ☐ Yes ☐	If yes, does information suggest that the need for a PRA is Increased? ☐ Decreased? ☐ Unchanged? ☐
PEST RISK STAGE 2: RISK ASSESSMENT			
Probability of Entry			
1. Prevalence of pest in source area	Is there any current information to suggest that pest prevalence in source area has changed due to climate change?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
2. Likelihood of pest being associated with pathways at the source	Is there evidence of changes to production systems at source due to climate change that could lead to a change in the pest being associated with a pathway?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
3. Seasonal timing of trade	Is there evidence of changes to current practices at source due to climate change that could affect the likelihood of the pest being associated with a pathway?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐

			Unchanged? ☐
4. Illegal trade (intentional, unintentional)	Are there any records of new patterns in incursion data due to climate change for this pest?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
5.Pest management procedures applied at source	Is there any information on changes to pest management procedures at source due to climate change that could have implications for the likelihood of the pest being on a pathway?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
6. Probability of pest surviving management and phytosanitary procedures	Is there any information on changes to pest biology due to climate change that could mean the pest is more or less likely to survive phytosanitary procedures?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
7. Likelihood of pest transfer to a suitable host	Is there any information on changes to host suitability due to climate change that could affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
8. Destination points of intended commodity	Is there any information on changes to the destination points due to climate change that could affect the likelihood of a pest finding a suitable host?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
9. Time of year of import	Is there any information on any changes to pest distribution and		If yes, does information suggest risk is...

	abundance due to climate change at different times of year that could affect likelihood of pest being on pathway at source and find host plant in PRA area?	No ☐ Yes ☐	Increased? ☐ Decreased? ☐ Unchanged? ☐
10. Unaided dispersal	Is there any evidence that dispersal of the pest will change due to changes in wind patterns and extreme weather events brought about by climate change?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
PEST RISK STAGE 2: RISK ASSESSMENT			
Probability of Establishment and Spread			
1. Characteristics of pest – e.g. availability, quantity, distribution, reproductive strategy, host resistance, genetic and environmental adaptability and threshold populations required for establishment	Is there any information on changes in pest biology due to climate change that could change its probability of survival and spread?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
2. Suitability of environment	Is there information on any changes in pest biology due to climate change that may render the pest more or less suitable to the environment in the PRA area?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
3. Availability, quantity, distribution and characteristics of host, alternate hosts	Is there information on any changes to host and alternate host plant availability, abundance and distribution due to climate change that could affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
4. Availability, quantity, distribution and characteristics of vectors	Is there information on any changes to vector distribution, abundance and capacity that could		If yes, does information suggest risk is…

	affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☐	Increased? ☐ Decreased? ☐ Unchanged? ☐
5. Availability, quantity, distribution and characteristics of natural enemies	Is there information on any changes to natural enemy availability, abundance and distribution that could affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
6. Cultural and control measures	Is there any information on any changes to the efficacy of cultural and control methods due to climate change that could affect pest status?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
Spread only			
7. Presence of natural barriers	Is there any information to suggest that climate change has altered the presence and functioning of natural barriers which could lead to a change in pest status?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
8. Unintended dispersal	Is there any information to suggest that climate change has affected domestic trade patterns (transport of host plants, commodities or conveyances) in ways that could lead to a change in pest status?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
PEST RISK STAGE 2: RISK ASSESSMENT			

Assessment of consequences - DIRECT PEST EFFECTS			
Plant Life or Health			
1. Known or potential host plants	Is there any information to suggest that climate change will affect pest status to the extent that changes to host plant availability, abundance and distribution (including new and expanding crops) become apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
2. Types, amount and frequency of damage	Is there any information to suggest that climate change will affect pest status to the extent that changes to the types, amount and frequency of damage is apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
3. Control measures (including existing measures), their efficacy and cost	Is there any information to suggest that climate change will affect pest status to the extent that control measures efficacy and cost are altered?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
4. Effect of existing production practices	Is there any information to suggest that climate change will affect pest status to the extent that changes to the timing and type of production practices are altered?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Environmental			
5. Reduction of keystone plant species	Is there any information to suggest that climate change will affect pest status to the extent reductions in keystone plant species become apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐

6. Reduction of plant species that are major components of ecosystems	Is there any information to suggest that climate change will affect pest status to the extent that reduction in plant species that are major components of ecosystems become apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
7. Endangered native plant species	Is there any information to suggest that climate change will affect pest status to the extent that changes to endangered native plant species become apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
8. Significant reduction, displacement or elimination of other plant species	Is there any information to suggest that climate change will affect pest status to the extent that there will be a significant reduction, displacement or elimination of other plant species?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Assessment of consequences - DIRECT PEST EFFECTS			
Control and Eradication			
9. Changes to producer costs or input demands, including control costs	Is there any information to suggest that climate change will affect pest status to the extent that changes to producer costs, input demands and control costs will become apparent?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
10. Feasibility and cost of eradication and containment	Is there any information to suggest that climate change will affect pest status to the extent that changes in feasibility and cost of eradication and containment are recognised?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
11. Resources needed for additional research and consultation	Is there any information to suggest that climate change will		If yes, does information suggest risk is…

	affect pest status to the extent that extra resources for research, consultation and communication of climate change effects will be needed?	No ☐ Yes ☐	Increased? ☐ Decreased? ☐ Unchanged? ☐
Domestic and International trade			
12. Effects on domestic and international markets	Is there any information to suggest that climate change will alter pest status to the extent that domestic and international markets will be affected?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
13. Changes to domestic or foreign consumer demand for a product from quality changes	Is there any information to suggest that climate change will alter pest status to the extent that consumer demand will be affected?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
Environmental and non-commercial			
14. Environment and other undesired effects of control measures	Is there any information to suggest that climate change will alter pest status to the extent that the efficacy of control measures may be altered, leading to a change in the availability of measures that have few undesirable effects?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
15. Significant effects on plant communities	Is there any information to suggest that climate change will affect pest status to the extent that there will be a significant effect on plant communities?	No ☐ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
16. Significant effects on designated environmentally sensitive or protected areas	Is there any information to suggest that climate change will affect pest status to the extent that there will be a significant effect on environmentally sensitive	No ☐	If yes, does information suggest risk is... Increased? ☐

	and protected areas?	Yes ☐	Decreased? ☐ Unchanged? ☐
17. Significant change in ecological processes and the structure, stability or processes of an ecosystem (including further effects on plant species, erosion, water table changes, increased fire hazard, nutrient cycling etc)	Is there any information to suggest that climate change will affect pest status to the extent that the stability of the ecosystem structure and functioning will be affected?	No ☐ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐

Table 2A: Summary table of the Generic Pest Risk Assessment Climate Change Template (to be included at the end of each assessment stage).

Summary	
Number of factors for which climate change is relevant?	
Number of factors with available data (number of yes boxes ticked)?	
Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.	
Number of factors where risk has increased?	
Number of factors where risk has decreased?	
Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.	
Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data.	Low ☐ Medium ☐ High ☐

6. Case Study – Using the generic template to assess the biosecurity risk of the Asiatic Citrus Psyllid (*Diaphorina citri*) to Australia

The Asiatic citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Psyllidae) is a plant feeding insect. It is one of only two known vectors of the citrus disease huanglongbing or citrus greening (Aubert, 1987; da Graça, 1991) which is identified as one of the highest priority exotic pathogens of concern and a major threat to the AUD$446 million Australian citrus industry (Dempsey et al., 2002; Johns, 2004).

D. citri is distributed worldwide occurring in the following regions and countries: In Asia: the Arabian Peninsula (Saudi Arabia and Yemen), from Afghanistan through the Indian Subcontinent, Southeast Asia and East Asia (the Ryukyu Archipelago and Kyushu in Japan, in China and the coastal provinces of Guangxi, Guangdong, Fujian and Zhejiang), the Philippines and through the Indonesian archipelago to north eastern Papua New Guinea; in Hawaii and Guam; in the US States of Alabama, California, Florida, Georgia, Louisiana, Mississippi, South Carolina, and Texas, as well as the Commonwealth of Puerto Rico, Bahamas, Cayman Islands, Cuba, Jamaica, Dominican Republic, Guadeloupe, Venezuela, Brazil, Paraguay, Uruguay and Argentina; in the Indian Ocean, Mauritius and Réunion (Anon, 2008; Aubert, 1987; Conant et al., 2007; Halbert and Manjunath, 2004; Halbert and Núñez, 2004) (OEPP/EPPO, 2005; Poe and Shea, 2007; Weinert et al., 2004).

HLB does not occur in Australia (Bellis et al., 2005; Davis et al., 2000) but occurs throughout Asia and in neighbouring countries to Australia such as the Indonesian Archipelago, Timor Leste and New Guinea (da Graça, 1991; Davis et al., 2005; Weinert et al., 2004).

The disease HLB can affect all commercial and ornamental Citrus as well as numerous Rutaceae. Including the popular ornamental shrub *Murraya paniculata* which occurs widely throughout Australia (Beattie and Barkley, 2009; Halbert and Manjunath, 2004). Infection with the bacterium causes the production of unmarketable fruit which is small, lopsided, unevenly coloured, bitter tasting. Also at risk from the disease is also the six Australian indigenous species of Citrus (Finlay et al., 2009) which comprise 50% of all extant citrus species (Bayer et al., 2009; Mabberley, 2004; Zhang et al., 2008) and possess high genetic variability potentially useful for future rootstock and breeding (Sykes, 1997).

In order to determine the potential impact of climate change on the biosecurity risk of *D. citri* entering Australia and becoming established, the Generic PRA Template (Table 2) was filled in using *D. citri* as a case study (Table 3). There is a wealth of information on the pest risk *D. citri* poses to Australia and a PRA has recently been completed as part of a larger investigation on the risk posed to Australia's biosecurity from the '*Candidatus* Liberibacter species' and vectors associated with Rutaceae (Plant Biosecurity, 2011).

The initiation points, categorisation, probabilities of entry, establishment and spread of *D. citri* were examined in detail incorporating climate change (Appendix 1). From this the Generic PRA Climate Change Template was populated (Table 3) firstly with determination of whether there is climate change information available on the processes and probabilities presented in the PRA and secondly whether this information determined whether the risk from *D. citri* is likely to increase, decrease or remain unchanged.

Outcomes of applying the Generic PRA Climate Change Template to a pest (Table 3) are expressed as increase, no change or decrease to the risk at each stage. This information is then used to inform expert consideration of whether it is necessary to amend the existing probability scores for the species (Appendix 2). Expert analysis is required because a clear conclusion of increased risk arising from the template does not necessarily mean that the risk has increased sufficiently to require a change in the probability score of the existing PRA.

Table 3. Case Study - The Generic Pest Risk Assessment Climate Change Template applied to *D. citri*.

PEST RISK STAGE 1: INITIATION			
INITIATION POINTS			
Identification of a pest threat			
	Information required	**Tick box**	**Tick box**
1. Discovery of an infestation or outbreak of a new pest	Is there recent or new information on the potential range and impact relevant to climate change?	No ☐ Yes ☑	If yes, does information suggest that the need for a PRA is... Increased? ☑ Decreased? ☐ Unchanged? ☐
Review of phytosanitary measures			
2. A new system, process or procedure is introduced or new information made available	Has there been a review of pests under climate change, or a new system introduced to deal with climate change that has implications for this pest?	No ☑ Yes ☐	If yes, does information suggest that the need for a PRA is... Increased? ☐ Decreased? ☐ Unchanged? ☐
3. An international dispute on phytosanitary measures arises	Is there is a current or impending international disagreement about this pest arising from differing interpretations of climate change effect on risk?	No ☑ Yes ☐	If yes, does information suggest that the need for a PRA is... Increased? ☐ Unchanged? ☐
Summary - Initiation			
Number of factors for which climate change is relevant?		3	
Number of factors with available data (number of yes boxes ticked)?		1	

<table>
<tr><td colspan="3">Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.</td><td colspan="2">2</td></tr>
<tr><td colspan="3">Number of factors where risk has increased?</td><td colspan="2">1</td></tr>
<tr><td colspan="3">Number of factors where risk has decreased?</td><td colspan="2">0</td></tr>
<tr><td colspan="3">Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.</td><td colspan="2">2</td></tr>
<tr><td colspan="3">Net change to risk of establishment and spread. (Deduct factors with decreased risk from factors with increased risk. If result is positive risk has increased).</td><td colspan="2">INCREASED</td></tr>
<tr><td colspan="3">Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data.

Low = 0 or 1 ‘yes’

Medium = 2 ‘yes’

High = 3 ‘yes’</td><td colspan="2">Low ☐

Medium ☑

High ☐</td></tr>
<tr><td colspan="5"></td></tr>
<tr><td colspan="5">PEST RISK STAGE 2: RISK ASSESSMENT</td></tr>
<tr><td colspan="5">Phase 1: Categorisation</td></tr>
<tr><td>1. Establishment as a ‘quarantine pest’</td><td colspan="2">Is there information suggesting that the status of the pest as a-quarantine pest should be reconsidered under climate change?</td><td>No ☐

Yes ☑</td><td>If yes, does information suggest that the need for a PRA is...

Increased? ☑

Decreased? ☐

Unchanged? ☐</td></tr>
<tr><td colspan="5">Summary - Categorisation</td></tr>
<tr><td colspan="3">Number of factors for which climate change is relevant?</td><td colspan="2">1</td></tr>
</table>

Number of factors with available data (number of yes boxes ticked)?	1
Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.	0
Number of factors where risk has increased?	1
Number of factors where risk has decreased?	0
Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.	0
Net change to risk of establishment and spread. (Deduct factors with decreased risk from factors with increased risk. If result is positive risk has increased).	INCREASE
Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data. Low = 0 'yes' Medium High = 1 'yes'	Low ☐ Medium ☐ High ☑

PEST RISK STAGE 2: RISK ASSESSMENT

Probability of Entry

1. Prevalence of pest in source area	Is there any current information to suggest that pest prevalence in source area has changed due to climate change?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
2. Likelihood of pest being associated with pathways at the source	Is there evidence of changes to production systems at source due to climate change that could lead to a change in the pest being associated with a pathway?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑

			Decreased? ☐ Unchanged? ☐
3. Seasonal timing of trade	Is there evidence of changes to current practices at source due to climate change that could affect the likelihood of the pest being associated with a pathway?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
4. Illegal trade (intentional, unintentional)	Are there any records of new patterns in incursion data due to climate change for this pest?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
5.Pest management procedures applied at source	Is there any information on changes to pest management procedures at source due to climate change that could have implications for the likelihood of the pest being on a pathway?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
6. Probability of pest surviving management and phytosanitary procedures	Is there any information on changes to pest biology due to climate change that could mean the pest is more or less likely to survive phytosanitary procedures?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
7. Likelihood of pest transfer to a suitable host	Is there any information on changes to host suitability due to climate change that could affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☐

			Decreased? ☐ Unchanged? ☑
8. Destination points of intended commodity	Is there any information on changes to the destination points due to climate change that could affect the likelihood of a pest finding a suitable host?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☑
9. Time of year of import	Is there any information on any changes to pest distribution and abundance due to climate change at different times of year that could affect likelihood of pest being on pathway at source and find host plant in PRA area?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
10. Unaided dispersal	Is there any evidence that dispersal of the pest will change due to changes in wind patterns and extreme weather events brought about by climate change?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐

Summary - Probability of Entry	
Number of factors for which climate change is relevant?	10
Number of factors with available data (number of yes boxes ticked)?	4
Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.	6
Number of factors where risk has increased?	2
Number of factors where risk has decreased?	0
Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.	8

Net change to risk of establishment and spread. (Deduct factors with decreased risk from factors with increased risk. If result is positive risk has increased).	INCREASED
Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data. Low = 0, 1, 2 or 3 'yes' Medium = 4, 5 or 6 'yes' High = 7 or more 'yes'	Low ☐ Medium ☑ High ☐

PEST RISK STAGE 2: RISK ASSESSMENT

Probability of Establishment and Spread

1. Characteristics of pest – e.g. availability, quantity, distribution, reproductive strategy, host resistance, genetic and environmental adaptability and threshold populations required for establishment	Is there any information on changes in pest biology due to climate change that could change its probability of survival and spread?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐
2. Suitability of environment	Is there information on any changes in pest biology due to climate change that may render the pest more or less suitable to the environment in the PRA area?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐
3. Availability, quantity, distribution and characteristics of host, alternate hosts	Is there information on any changes to host and alternate host plant availability, abundance and distribution due to climate change that could affect the likelihood of the pest finding a suitable host?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☑
4. Availability, quantity,	Is there information on any		If yes, does information

distribution and characteristics of vectors	changes to vector distribution, abundance and capacity that could affect the likelihood of the pest finding a suitable host?	No ☑ Yes ☐	suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
5. Availability, quantity, distribution and characteristics of natural enemies	Is there information on any changes to natural enemy availability, abundance and distribution that could affect the likelihood of the pest finding a suitable host?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
6. Cultural and control measures	Is there any information on any changes to the efficacy of cultural and control methods due to climate change that could affect pest status?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Spread only			
7. Presence of natural barriers	Is there any information to suggest that climate change has altered the presence and functioning of natural barriers which could lead to a change in pest status?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐
8. Unintended dispersal	Is there any information to suggest that climate change has affected domestic trade patterns (transport of host plants, commodities or conveyances) in ways that could lead to a change in pest status?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐

Summary – Probability of Establishment and Spread			
Number of factors for which climate change is relevant?		8	
Number of factors with available data (number of yes boxes ticked)?		5	
Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.		3	
Number of factors where risk has increased?		4	
Number of factors where risk has decreased?		0	
Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.		4	
Net change to risk of establishment and spread. (Deduct factors with decreased risk from factors with increased risk. If result is positive risk has increased).		INCREASED	
Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data. Low = 0, 1, or 2 'yes' Medium = 3, 4 or 5 'yes' High = 6 or more 'yes'		Low ☐ Medium ☑ High ☐	
PEST RISK STAGE 2: RISK ASSESSMENT			
Assessment of consequences - DIRECT PEST EFFECTS			
Plant Life or Health			
1. Known or potential host plants	Is there any information to suggest that climate change will affect pest status to the extent that changes to host plant availability, abundance and distribution (including new and expanding crops) become apparent?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐
2. Types, amount and frequency of	Is there any information to		If yes, does information

damage	suggest that climate change will affect pest status to the extent that changes to the types, amount and frequency of damage is apparent?	No ☑ Yes ☐	suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
3. Control measures (including existing measures), their efficacy and cost	Is there any information to suggest that climate change will affect pest status to the extent that control measures efficacy and cost are altered?	No ☑ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
4. Effect of existing production practices	Is there any information to suggest that climate change will affect pest status to the extent that changes to the timing and type of production practices are altered?	No ☑ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
Environmental			
5. Reduction of keystone plant species	Is there any information to suggest that climate change will affect pest status to the extent reductions in keystone plant species become apparent?	No ☑ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐
6. Reduction of plant species that are major components of ecosystems	Is there any information to suggest that climate change will affect pest status to the extent that reductions in plant species that are major components of ecosystems become apparent?	No ☑ Yes ☐	If yes, does information suggest risk is... Increased? ☐ Decreased? ☐ Unchanged? ☐

7. Endangered native plant species	Is there any information to suggest that climate change will affect pest status to the extent that changes to endangered native plant species become apparent?	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐ Unchanged? ☐
8. Significant reduction, displacement or elimination of other plant species	Is there any information to suggest that climate change will affect pest status to the extent that there will be a significant reduction, displacement or elimination of other plant species?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Assessment of consequences - DIRECT PEST EFFECTS			
Control and Eradication			
9. Changes to producer costs or input demands, including control costs	Is there any information to suggest that climate change will affect pest status to the extent that changes to producer costs, input demands and control costs will become apparent?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
10. Feasibility and cost of eradication and containment	Is there any information to suggest that climate change will affect pest status to the extent that changes in feasibility and cost of eradication and containment are recognised?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
11. Resources needed for additional research and consultation	Is there any information to suggest that climate change will affect pest status to the extent that extra resources for research, consultation and communication of climate change effects will be	No ☐ Yes ☑	If yes, does information suggest risk is… Increased? ☑ Decreased? ☐

	needed?		Unchanged? ☐
Domestic and International trade			
12. Effects on domestic and international markets	Is there any information to suggest that climate change will alter pest status to the extent that domestic and international markets will be affected?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
13. Changes to domestic or foreign consumer demand for a product from quality changes	Is there any information to suggest that climate change will alter pest status to the extent that consumer demand will be affected?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
Environmental and non-commercial			
14. Environment and other undesired effects of control measures	Is there any information to suggest that climate change will alter pest status to the extent that the efficacy of control measures may be altered, leading to a change in the availability of measures that have few undesirable effects?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
15. Significant effects on plant communities	Is there any information to suggest that climate change will affect pest status to the extent that there will be a significant effect on plant communities?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐
16. Significant effects on designated environmentally sensitive or protected areas	Is there any information to suggest that climate change will affect pest status to the extent	No ☑	If yes, does information suggest risk is…

	that there will be a significant effect on environmentally sensitive and protected areas?	Yes ☐	Increased? ☐ Decreased? ☐ Unchanged? ☐
17. Significant change in ecological processes and the structure, stability or processes of an ecosystem (including further effects on plant species, erosion, water table changes, increased fire hazard, nutrient cycling etc)	Is there any information to suggest that climate change will affect pest status to the extent that the stability of the ecosystem structure and functioning will be affected?	No ☑ Yes ☐	If yes, does information suggest risk is… Increased? ☐ Decreased? ☐ Unchanged? ☐

Summary –Assessment of Consequences	
Number of factors for which climate change is relevant?	17
Number of factors with available data (number of yes boxes ticked)?	3
Number of factors with no available data (number of no boxes ticked)? There is thus no basis for changing these factors.	14
Number of factors where risk has increased?	3
Number of factors where risk has decreased?	0
Number of factors where risk remains unchanged? This is the sum of factors with no data (no ticked) plus factors with actual data suggesting no change is required.	14
Net change to risk of establishment and spread. (Deduct factors with decreased risk from factors with increased risk. If result is positive risk has increased).	INCREASED
Level of confidence in overall change to risk factors. The level of confidence is determined by proportion of factors with available data. Low = 6 or less 'yes' Medium = 7,8,9,10 or 11 'yes' High = 12 or more 'yes'	Low ☑ Medium ☐ High ☐

7. Discussion

An analysis was conducted that identified how climate change might affect each phase of pest risk analysis (PRA) as determined by the ISPM No. 11 (Table 1). This identified a large number of factors to which climate change was relevant. For example, the identification of pathways is paramount in determining the impact of a pest threat, and climate change would influence almost every component of a pest threat being present or not present on a pathway. Climate change has the potential to disrupt trade patterns at source, alter pest status and incidence and host plant physiology leading to changes in distributions of pests.

Following from this analysis a generic template was developed to guide pest risk assessors through the required steps for considering climate change in a structured, repeatable and transparent manner (Table 2). For each PRA stage completion of the template provides a conclusion as to whether risk has, on balance, increased, decreased or remained unchanged. Accompanying this conclusion for each stage is a confidence score that reflects the availability of relevant data to the assessor. Using the template to adjust PRA probability scores is not a straight-forward process. A simple indication of increased or decreased risk is not a sufficient basis for changing the PRA probability scores because the degree to which the risk has changed may not justify a new probability score; this decision should be a matter for expert judgement.

Use of the newly developed template was illustrated by applying it to *D. citri* as a case study (Table 3) with detailed background and explanations in Appendix 1. The result of the *D. citri* analysis showed increased risk in every stage of the PRA. In several cases the increased risk was thought to justify a change in PRA probability scores (Appendix 1 & 2). The overall assessment in the PRA for *D. citri* incorporating climate change did not significantly change the assessment completed by (Plant Biosecurity, 2011; Appendix 2B). Changes were reflected in the minor adjustments for each pathway which overall gave a higher risk rating for certain pathways but not for the PRA as a whole.

Application of this proposed template to a range of quarantine pests is desirable in order to establish how workable and acceptable it is across a range of pest organisms and commodity based risk assessments. Results from this process may prove useful in identifying common patterns of climate change influence. For example, particular stages of the PRA that often proves to be strongly influenced by climate change. Another benefit from applying this template more widely would be to highlight where there is a particular lack of knowledge for elements of the PRA process or categories of pest.

Comments from QUADS members suggested that when a pest is already established as a risk it may not be necessary to consider climate change. This is certainly the case with the *D. citri* case study where the inclusion of climate change did not alter the overall risk. There may be a case for including climate change in pest risk assessment of more marginal species where the overall unrestricted risk may change and could lead to re-prioritization of pest lists.

Incorporating climate change into a full PRA is a complex issue with many interrelating factors and uncertainties. The *D. citri* case study showed that it is cumbersome, time-consuming and resource intensive to factor in climate change to each individual component of the PRA. Rather it may be more prudent to focus more broadly on particular aspects of the PRA process to produce generic pathway initiated pest risk assessments where the approach is to assess the risk from groups of similar organisms based on biological conditions.

The process for achieving this would be to:

- Compile a list of known pest threats for each country, prioritised by pest status and economic value of potential commodity imports.
- Determine possible pathways for each pest threat and find commonalities.
- Determine if marginal or other potential pest species fit into categories This may require that more baseline biological data is gathered on known particular pests and potential future pests.
- Investigate potential climate change impacts based on commonalities.
- Devise common pre and post border management protocols to mitigate threats.

There remain a number of fundamentally important questions that need to be answered before a common position can be reached enabling the routine assessment of how climate change might affect pest risk, as in the template developed here. In particular the spatial and temporal scale at which the climate change effect is to be considered should be defined and agreed. Establishing a common position on these matters was beyond the scope of this project. It has been suggested that a future version of the template could incorporate guidance on these matters and also provide a link to reputable and current resources (references, tools, links to data bases, climate change scenarios etc, modelling tools with climate change scenarios embedded).

The original aim of this project has been met but in the process it has been shown that other approaches such as generic pathway initiated pest risk assessments may be more appropriate and also that if the template approach is to be pursued high level agreement on a number of contentious issues will be necessary.

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9. Plain English website summary

CRC project no:	CRC10196
Project title:	**Climate Change and Pest Risk Analysis**
Project leader:	Kyla Finlay
Project team:	Kyla Finlay, Jo Luck
Research outcomes:	Pest Risk Analysis (PRA) is a formal process used by Biosecurity Australia to identify and assess the risk from pests and pathogens of concern to Australia. This project developed a template to guide pest risk assessors through the steps to identify necessary adjustments to PRA to take account of climate change. The template allows this to be done in a structured, repeatable and transparent manner. Completing the template for each PRA stage reveals whether risk has increased, decreased or remained unchanged. Accompanying this conclusion for each stage is a confidence score based on how much relevant data is available. This template is the first one developed that allows climate change to be factored into PRA.
Research implications:	Climate change is potentially going to cause significant changes to the arrival, establishment and spread of many pests and pathogens. Now that the template is available it will hopefully stimulate further work on this important problem. The template will now ideally be applied to a range of quarantine pests and pathogens to establish how workable it is across a range of pest organisms. Results from wide application of the template may also prove useful by identifying common patterns of climate change influence. Another benefit from applying this template more widely would be to highlight where there is a particular lack of knowledge for elements of the PRA process or categories of pest.
Research publications:	Climate Change and Pest Risk Analysis Final Report (04/05/12)
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