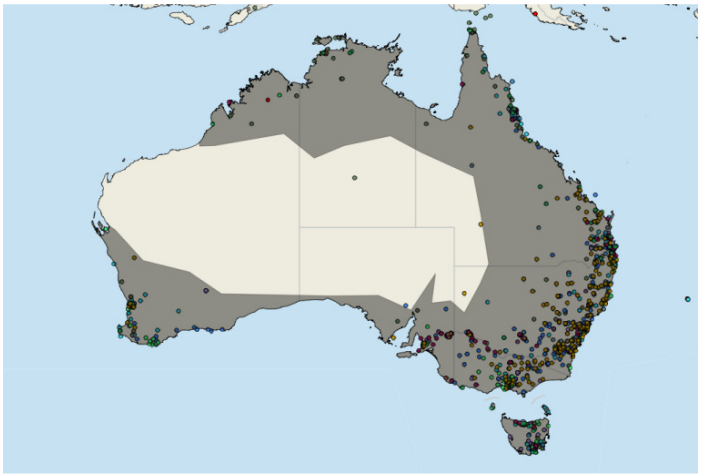
Developing tools for predicting responses of viticultural pests and their natural enemies under climate change: modelling, management and extension



Mask created from the generalised climate zones to limit models to relevant geographical areas- the areas which all species could have accessed through dispersal and human-mediated transport

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Developing tools for predicting responses of viticultural pests and their natural enemies under climate change: modelling, management and extension

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1. Abstract:

The project aim was to inform the industry on potential changes in pest impact under climate change. Extensive information on vines, vine pests and the predators and parasitoids that contribute to pest control was sourced from literature reviews and combined with model outputs and results of laboratory testing to predict likely pest impacts on grape production under climate change. For selected pests including light brown apple moth, computer models of potential distribution change indicated range contraction. In contrast for other pests including mealybugs, laboratory tests indicated a high tolerance to temperature extremes and likely persistence and perhaps increase in pest issues. Predicted climate change was expected to impact pests through effects on vine physiology and phenological changes in synchronization with natural enemies phenology. The importance of establishing a repository for longitudinal distribution data of pests and their enemies was highlighted.

2. Executive summary:

The project provides information on potential impacts of climate change on pest occurrence in vineyards through predicting change in abundance of both the pests and the natural enemies that contribute to their control. This was done through literature reviews of potential changes in vines and insects under climate change, modelling changes in distribution based on current occurrence records and laboratory testing of thermal limits of mealybugs and an important natural enemy. The overall objective was to identify the risk of emerging and future pest and disease threats and provide information to facilitate implementation of pest control strategies to manage the challenges of climate change.

Increasingly accurate climate records available for predictive modelling provide a valuable resource when associated with current distribution data for crops, pests and natural enemies. Globally, the wine industry has been able to model change in climate suitability for different grape varieties in preparation for response to climate change. This has been possible because an accurate data base exists of current variety location and phenology within location. The lack of an accurate database of insect (pest and natural enemy) occurrence hinders accurate prediction of likely outcomes in response to increased temperature and decreased rainfall. The modelling available is rapidly improving and developing; the industry is currently limited in its ability to take advantage of this. While the current initiatives to move collected data from State departments of agriculture, museums, universities and CSIRO should be encouraged, a data repository and support tools are needed for the industry. In some cases, this will mean improving identification tools for growers.

Predictions of response to climate change can be based on understanding of life history traits of individual pest or natural enemy species. From knowledge of number of degree days required to complete a life cycle, and upper and lower limits to survival, the potential range where these conditions are met can be mapped to provide a map of predicted distributions and a list of locations where the insect is likely to occur. Such mechanistic modelling requires information about individual insects requiring investment in understanding individual pests identified as being of particular concern. Sufficiently detailed information is available for a limited number of vineyard pests most notably light brown apple moth. Given the paucity of local information, much can be learnt from overseas studies and it is vital to optimize access to international literature pertinent to climate change impacts on insects.

The potential for change in distributions can also be predicted from known current distributions. Computer modelling based on current distributions can form the basis for prediction of change with climate change. To do this, the climatic conditions at the locations where the pests currently occur are used via climate matching to map present distribution. With access to reliable distribution records computer modelling can then be used, for limited

cost, to map the potential distribution with changes of temperature and rainfall predicted under various climate models.

We accessed sufficiently detailed distribution information for five (longtailed mealybug, soft brown scale, vine garden and elephant weevils) of the 12 species of potential insect pests initially identified as of interest and likely to provide sufficient information (longtailed, citrophilus and obscure mealybugs, grapevine, frosted and soft brown scales, fig longicorn, common and large auger beetles, elephant, garden and vine weevils). While these were able to be mapped with an acceptable degree of accuracy, our searches identified an issue with available distribution data on which to base current and hence future distribution mapping. The development of accurate maps of current occurrence of pests would greatly improve the industry's ability to predict future change. This is not only a grape industry issue; records of the pests searched are provided to the Australian Pest and Disease database and so come from a variety of sources. However a concerted effort across industries is required to provide more distribution points and validated points for future modelling.

Another problem we repeatedly ran into was the lack of accurate information on vineyard pests. Recognition of a pest occurrence as 'mealybugs' may be sufficient for applying control methods (chemical or natural enemies) but at least three species are commonly found in vineyards and species records are needed to build up distribution records. As future modelling depends on accuracy of current distribution information, this is compromised by a lack of species level identification. The recognition of pest species is needed to progress with modelling based on current pest occurrence. One option is to provide tools or services for growers to capture this information for centralized collation.

Modelling software based on distribution records is a cost effective means to predict changes in distribution. The thermal testing results presented here can add to accuracy of predictions made with correlative modelling but establishing thermal limits and phenological parameters for individual species in the laboratory is very time consuming and labour intensive. In the laboratory we tested thermal limits of two mealybugs and a ladybird beetle natural enemy and found pest and natural enemy able to survive extremes of temperature (minimum and maximum temperatures -6°C and 43°C for mealybugs, slightly lower maximum temperature for ladybird beetle); outside the limits of what might be predicted from distribution data. Mechanistic modelling incorporating these limits would also require life history trait information such as phenology and fecundity under different temperatures.

For models constructed so far, there was little evidence of increased pest pressure from distribution changes; most of the distributions were expected to fragment and move southwards to some degree. Natural enemy distributions mapped here followed the same trend. However, these predictions do not incorporate the impact of relative changes in vine, pest and natural enemy phenology and vine health in response to increased temperature and reduced water availability and further study is required. Moreover, models only predict ranges under equilibrium and provide no information on ability of pests or natural enemies to adapt to novel environments: such adaptability would not be unexpected and could of course influence outcomes.

Future research should include consideration of impacts on pests and natural enemies of changes in vine health, especially under conditions of water stress and temperature stress. What are the impacts on pests and their natural enemies? Communication to the wider industry of the importance of accurate distribution records and value of identifying pests to species level is vital to detect and more accurately predict change. This is also important for recognizing threats from invasive species which are likely to be greater under climate

change; as there are significant pests threatening Australian industry[1], recognition tools are particularly pertinent. For pests which are difficult to accurately identify, especially mealybugs, resources may need to be established to allow growers to send samples for molecular identification. We have successfully tested and established molecular means of identification of Australian mealybugs based on work by our collaborators.

Information on climate change effects was passed to growers, consultants and agronomists through diverse avenues: publications in industry journals, participation in workshops and through response to email and telephone queries. We continued to regularly provide responses to grower queries about increasing abundance and diversity of natural enemies and their contribution to pest control through information about chemical impacts and adjacent remnant and shelterbelt vegetation. Natural enemy diversity and abundance continues to provide protection from pest outbreaks due to local climate change or other factors.

We have reached a wide audience of landholders following invitations to speak at workshops in several wine growing regions over the last three years. We have published in the industry publications and also the scientific literature, organized a half day workshop on 'Sustainable pest control in a changing climate' for, the Victorian Viticultural Association, and organised a workshop at 14th Australian Wine Industry Technical Conference on viticultural pests under climate change. We also taught (2009-2012) in the Wine Technology and Viticulture course at School of Land and Environment, University of Melbourne where we provided information on environmentally sustainable pest and disease management under a changing climate.

3. Background:

There is abundant evidence that climate change is influencing pest species distributions, outbreaks and impact on crops: emerging as key threats of climate change on production (Hoffmann *et al.* 2008; Hill *et al.* 2012a). Changes in water availability, temperature and carbon dioxide (CO_2) will also alter crop phenology and physiology and affect pests (Thomson *et al.* 2010). A range of invertebrate natural enemies, predators and parasitoids, provide important control of pests, hence it is important to understand impacts on natural enemies, pests and their interactions.

To successfully predict shifts in pest outbreaks and make informed decisions requires substantial background information on pests and their environmental interactions (Harrington *et al.* 1999). In the wine grape industry, predictive models are needed for grape pests including those known to transmit disease and economically important pests that cause direct damage. Light brown apple moth is currently the most economically significant and widespread insect pest of grapes and a range of other pests cause problems in particular years or regions. Several species of mite can cause economic damage to vines, leaf and shoot distortions and retarded shoot growth. Mealybugs have become increasingly important vineyard pests, increasing in both distribution and abundance. Mealybugs are an economic problem in grape vines because of direct damage to the crop and costs for their control but also their role in transmitting grapevine leafroll viruses: these are vectored by scale and mealybugs, increasing their economic importance. Trunk insects may be increasing in importance also and this may be related to vine stress.

Effects of climate change on pest outbreaks indirectly depend on effects on natural enemies (Gutierrez *et al.* 2008). Natural enemies are already known to respond negatively to stressful

[1]Two of the priority biosecurity pests identified in the GWRDC Strategic Plan ***"Ensure sector prepared in event of exotic pest incursion, in particular incursion by high priority pest"*** are mealybugs

conditions. Vines may not only show stress in response to climate changes but indications are that along with other plants, there will be changes in composition due to increased CO_2, changes in phenology due to increased temperature and increased stress due to reduced water (Jones 2005). These changes will also impact on pests and natural enemies. Parasitism in water stressed crops can be greatly reduced (Calatayud *et al.* 2002) and natural enemies contributing to control can change at different temperatures. The outcome of interactions will depend on relative effects on plants, pests and natural enemies. Once distribution data and biological information become available, modelling can be used to make predictions about changes in these pest pressures under climate change (Hill *et al.* 2012b). Mechanistic models can include interactions with the crop under altered temperature, water and CO_2 conditions to improve successful predictive outcomes (Stacey 2003; Gutierrez *et al.* 2008; Gao *et al*. 2008).

There are indications that change is already occurring with climate change. This project set out first to examine the international literature for information about likely impacts and further to map current and future distributions of these pests.

4. Project aims and performance targets:

The aim of the project was to identify the risk of emerging and future pest and disease threats and provide information to facilitate implementation of pest control strategies to manage the challenges of climate change.

- Review available literature on potential changes in vines in response to CO_2 and potential impact on pests
- Access current distribution points for vineyard pests (light brown apple moth, mealybugs, scale, weevils, trunk insects and mites) and beneficials (brown lacewings, ladybird beetles and selected parasitoids) and use this to model current distributions and predict potential changes in pest and beneficial distributions with climate change
- Determine response to thermal stress of two pests, mealybugs and light brown apple moth and two beneficials the ladybird beetle *Cryptolaemus montrouzieri* and *Leptomastix dactylopii* Howard, an important homopteran parasitoid.

Table 1: Planned project outputs and performance targets as proposed in original application with revised outputs italicized (amended in schedule of agreement November 2011).
[a]Revised output

Outputs	**Performance targets**
Year 1: 2009-2010	
1. Review of potential changes in vines in response to CO_2 and potential impact on LBAM and mealybugs	1. Literature review, grower and advisor interviews
2. Review of potential changes in viticultural practice occurring in response to climate change	2. Literature review
3. Modelling distribution changes in current and future climates	3. Determine the nature of the data required for modelling
4. Knowledge of	4. Literature review for current knowledge and identification of gaps

thermal and humidity responses across different life cycle stages for selected pests	
Year 2: 2010-2011	
1. Identification of missing or incomplete data required for model development	1. Test of models for two species (mealybugs as starting point and initiate LBAM model)
2. Increased knowledge of thermal and humidity responses across different life cycle stages for LBAM and mealybugs.	2. Laboratory experiments with physiological measurements Field experiments at two sites
3. Knowledge of interaction between mealybugs, leafroll viruses and potential for virus spread under future climates	3. Literature review Results incorporated into models for future climates. Information from growers
4. Map of current distributions of LBAM, mealybugs, scale, rust mite, *selected trunk borers and weevils*[a], based on existing knowledge and surveys	4. Contact growers, industry advisors, establish web based system of data collection and validation
Year 3: 2011-2012	
1. Functioning predictive model for mealybug, LBAM	1. Derive model
2. Predicted changes to individual pests (mealybugs, LBAM) and natural enemies	2. Input variables to model.
3. Increased knowledge of thermal and humidity responses across different life cycle stages for mealybugs	3. Laboratory experiments with physiological measurement Field experiments at two sites
4. Knowledge of interaction between mealybugs, leafroll viruses and potential for spread under future climates	4. Literature review Results incorporated into models for future climates information for growers
5. Predicted changes in LBAM, mealybug, scale, mite, selected	5. Input complex results combined with the vineyard surveys done by University of Melbourne for mealybug and scale and incorporated into models for future climates

trunk borer and weevil distributions and virus spread under different scenarios	
6. Knowledge and advice and production of a factsheet	6. Disseminate knowledge through Industry publications and workshops. Develop factsheet
7. Map of current distributions of selected natural enemies e.g. brown lacewing, two parasitoids, ladybird beetles and predatory mite based on existing knowledge and surveys	*7. Contact rowers, industry advisors, establish web based system of data collection and validation*
8. Final report to GWRDC	8. Final report submitted

5. Method:

Overview:

To consider the potential impact of grape pests under a changed climate, three methods were used: **review** of current Australian and international literature, **modelling** current and future distributions for selected pests and beneficials using distribution data from a range of sources and determination of **thermal limits** for a pest and its important predator. Modelling software was then used to model current distributions for a range of pests and natural enemies with the thermal data contributing to increased accuracy of the targets to inform on questions

-will there be changes in pest distributions?
-will there be changes in beneficial distributions?
-will there be changes in vine and pest phenology such that more damaging interactions will potentially occur?

5.1 Literature review:

A wide range of the available literature was accessed to contribute to the review process. Literature accessed included scientific publications (ISI Web of Science database), industry publications and industry guidelines from departments of agriculture both in Australia and internationally. Key words searched: climate, temperature, rainfall, drought, warming, water deficit, carbon dioxide, greenhouse, vine*, grape*, vitis, pest, moth, Lepidoptera, Epiphyas, Tortricidae, scale, mealybug, Hemiptera, Homoptera, predator, parasitoid, enemy. The search was completed on September 30 2012. Outcomes are discussed under the following headings:

- Potential changes in vines in response to CO_2 and temperature and changes in viticultural practice occurring in response to climate change
- Potential impacts of changes in vine and pest phenology such that more damaging interactions will occur
- Thermal responses of mealybugs and light brown apple moth
- Mealybugs, leafroll viruses and potential for virus spread under future climates

5.2 Modelling current and future distributions of selected pests and natural enemies

The mapping of current species distributions and prediction of future species distributions is being aided through the increasing availability of electronic databases holding occurrence records, and the increasing accuracy and availability of long term climatic datasets. By coupling such information through different correlative distribution modelling techniques, species-environment relationships may be determined and allow for suitable climate space to be predicted. Once robust models have been constructed, it is then possible to extrapolate them into future climate space to examine how climate change may influence these broad-scale species-environment relationships, so to direct future research.
All species have physiologically based environmental constraints that influence their distribution and abundance, and a mechanistic approach can incorporate detailed knowledge of the requirements or limits of a species determined from laboratory studies to predict distributions. While correlative models provide a good basis to investigate climate chage impacts, where there is some physiological knowledge for a species, it may be more appropriate to construct a mechanistic model. For example, successful completion of a life cycle depends on accumulation of hours of a temperature above a minimum threshold below which development does not occur over time (often measured as degree-days), but survival is also limited by upper and lower temperature limits. Areas where the species can occur may then be estimated from knowledge of number of degree days that may accumulate in an area and where extremes of temperature may prevent population establishment.

The challenge for applying mechanistic approaches is the current lack of appropriate data for many pests. We used correlative modelling for species for which we could access adequate distribution data and mechanistic modelling for light brown apple moth from previously published data.

5.2.1 Mapping current distributions

We used bioclimatic envelope or ecological niche models to describe species current distributions. Such models use associations between aspects of climate and known occurrences of species across landscapes of interest to define sets of conditions under which species are likely to maintain viable populations. Correlative distribution modeling methods interpret the ‘ecological niche’ or climate requirements for an organism from the known locations. The climate information from these locations is used to predict the places where the organism might occur (that is to say where the climate is suitable). Accuracy of mapping requires a reasonable number of well distributed occurrence points and is increased by ‘absence’ records-that is that the organism has been looked for and found not to be present. Absence records are less common. There were no absence records for the species investigated here: using records of occurrence, we chose to use the presence-only modelling method, MAXENT (version 3.3.2) for current pest and natural enemy distributions. MAXENT is a presence-only based method that correlates known distributions with predictor variables such as environmental variables, and gives model output in terms of habitat suitability. This method allows us to correlate all known distribution points with important climatic variables that define the species distributions. From these we generated important information on how climate will influence future distributions. MAXENT has been applied to a variety of ecological modelling applications (e.g. Giovanelli *et al.* 2008; Ficetola *et al.* 2010; Lozier & Mills 2011) and has also been used to project models into future climate space (e.g. Penman *et al.* 2010; Yates *et al.* 2010).

Selection of Pests: The importance of current vineyard pests was verified by reference to survey of vineyard pests and diseases in the 2009-2010 vintage (Scholfield *et al.* 2010) (Table 2), with pests indicated in application confirmed to be those of economic importance. At the same time, survey results also exposed loss of opportunity and information collection in recording pests.

Table 2: Ranking of common grape industry pests (data taken from Scholfield *et al*. 2010).

	Pest Industry Rank	Financial Estimate Rank	Comment	Mean national economic impact $m/annum
Fungal diseases	1,2,4	1-3		191
LBAM	3	4		18
Weevils Including garden weevil	7	9	severe but localized impact in WA	0.3
Trunk Insects Fig longicorn and elephant weevil	9	12	Severe but localized impact Hunter Valley, Langhorne Creek	0.02
Phylloxera	10	10		0.2
Mealybugs and scale	13	11		0.1

As expected, insect pests lag behind diseases: light brown apple moth has largest industry wide economic impact ($18.2 m/annum) with garden weevil ($0.26 m/annum), mealybugs and scale ($0.08 m/annum), trunk boring insects ($0.01 m/annum). Viruses and transmissible organisms ranked behind light brown apple moth at $12.28 m/annum: as at least some of these (including important grapevine leafroll viruses) are vectored by scale and mealybugs, importance and potential economic impact of these is increased. Initial work on this project demonstrated the need for increased accuracy of pest record data. Accuracy of prediction of future distributions depends on accurate distribution knowledge and industry collection of distribution data can be greatly improved. Light brown apple moth (LBAM) *Epiphyas postvittana* Walker (Lepidoptera: Tortricidae) is indeed what it says but 'mealybugs' and 'scale' records both encompass a range of species. Surveys undertaken as part of this project of a number of vineyards in Victoria, South Australia and Western Australia indicated three commonly occurring mealybug species: longtailed *Pseudococcus longispinus* (Targioni Tozzetti), citrophilus *Pseudococcus calceolariae* (Maskell) and obscure mealybugs *Pseudococcus viburni* (Signoret). All three are widely distributed: longtailed and citrophilus of Australian origin, with longtailed so widespread it is now regarded as cosmopolitan. Obscure mealybug has recently been confirmed by host parasitoid relationships as of South American origin. Similarly, there may be several of six species of 'scale' in a single vineyard (Rakimov 2010) and again the recording of scale is missing important species information. The three most commonly occurring scale species from surveys carried out 2005-2008 throughout wine growing regions by Rakimov (2010)[2] and scale factsheet[3]: grapevine scale *Parthenolecanium persicae* (Fabricius) (71% of sites), frosted scale *Parthenolecanium pruinosum* (Coquillett) (49%) and soft brown scale *Coccus hesperidum* (Linnaeus) (9%), were considered here. Phylloxera is a quarantine pest and was not considered here.

[2] In this survey scales were collected from 54 commercial wine vineyard sites around Australia, as well as an additional 9 sites consisting of table grape vineyards, and residential and public amenity grapevines with most major wine grape growing regions of Australia visited at least once.

[3] http://www.dpi.vic.gov.au/agriculture/pests-diseases-and-weeds/plant-diseases/grapevines/ag1369-soft-scales-coccidae-on-grapevines-in-australia

The continuing drought raised the profile of trunk borers and weevils and these were added to the project. Insects which bore into the wood and canes of grapevines with potential impact on vines include fig longicorn (*Acalolepta vastator* Newman, Coleoptera: Cerambycidae), common and large auger beetles (*Xylopsocus giggicollis* (Macleay) and *Bostrychopsis jesuita* (Fabricius), Coleoptera: Bostrichidae), several weevils (Coleoptera: Curculionidae): native wood boring elephant *Orthorhinus cylindrirostris* (Fabricius) and vine *Orthorhinus klugi (*Boheman). There are other weevils such as garden weevil (*Phlyctinus callosus* Shoernherr) and the recently arrived (1984) black vine weevil (*Otiorhynchus sulcatus* (Fabricius) that damage roots and foliage. Sporadic increase in occurrence of two fruit and vine boring moths *Maroga melanostigma* (Wallengren) and *Echiomima* sp (Lepidoptera: Oecophoridae) was observed during the course of the project though distribution records are few and whether the increase in this pest was related to climate change impacts on the pests or to stress related to resources or impacts on vines remains to be seen. These pests were not further considered. Fig longicorn causes the most economic loss in viticulture with elephant weevil regarded as the second most economically important. However, several of the other trunk borers cause problems in some regions or in some seasons: vine weevil, common auger beetle and large auger beetle can occasionally cause damage which can be locally severe. Examples include weevils at Langhorne Creek (Coventry *et al.* 2004) or fig longicorn in the Hunter Valley (Goodwin & Pettit 1994).

Mite species considered were those most commonly reported as causing problems in Australian vineyards (bud and blister mites-different strains of *Colomerus vitis* (Pagenstecher), rust mite (*Calepitrimerus vitis* Nalepa) (Acari: Eriophyidae) and bunch mite (*Brevipalpus* spp.) (Acari: Tenuilpalpidae). Searches resulted in extremely limited data for occurrence of any mite species, so mites were not further considered.

Selection of natural enemies: Common natural enemies included brown lacewings *Micromus tasmaniae* Walker (Neuroptera: Hemerobiidae) and ladybird beetles. From the very large number of ladybird beetle (Coleoptera: Coccinellidae) species occurring in south eastern Australia, we focused on a number of species commonly found in our vineyard surveys over a wide area of south eastern Australia (Thomson & Hoffmann 2008; 2009, 2010a; 2013,Thomson *et al.* 2010c). *Diomus sydneyensis* (Blackburn), minute two-spotted ladybird *Diomus notescens (*Blackburn), transverse ladybird *Coccinella transversalis* Fabricius, large spotted ladybird *Harmonia conformis* Boisduval and mealybug destroyer *Cryptolaemus montrouzieri* Mulsant were considered. At least one of these, *D. notescens*, is known to prey on light brown apple moth eggs (MacLellan 1973). Ladybird beetles are also important predators of scale and mealybugs. Data were also searched for records of several parasitoids: *Trichogramma* (Hymenoptera: Trichogrammatidae), important egg parasitoids, and *Dolichogenidea tasmanica* (Cameron) (Hymenoptera: Braconidae), larval parasitoids of light brown apple moth, and the most common scale parasitoid *Metaphycus maculipennis* Timberlake (Hymenoptera: Encyrtidae) collected from all surveyed sites and grape growing regions (approximately 75% of all parasitoids collected) in extensive field surveys (Rakimov 2010). Distribution data for all species of parasitoids selected was inadequate for modeling approaches.

Data records accessed: Distribution information was researched from a variety of databases and field records. The databases used were: Australian Plant Pest Database (APPD), The Atlas of Living Australia (ALA) and the Global Biodiversity Information Facility (GBIF). The Australian Plant Pest Database (APPD) (http://www.planthealthaustralia.com.au) is a national, online database of pests and diseases of Australia's economically important plants, providing the rapid location of voucher specimens and efficient retrieval of detailed data. With access to over 14 existing plant pest collections (‘contributing databases'), the APPD has access to over one million pest voucher specimens making it possible to quickly retrieve details of insects, nematodes, fungi, bacteria and viruses that affect plants of economic and ecological significance. The Atlas of

Living Australia (http://www.ala.org.au/) is the Australian node of the Global Biodiversity Information Facility (GBIF) (www.gbif.org/). The Atlas of Living Australia is an online database which provides tools to enable users of biodiversity information to find, access, combine and visualise data on Australian plants and animals. Current distribution data for pests were searched from the APPD. Where available, data for each pest species was also sourced from ALA and GBIF. Data was accessed for natural enemies, from ALA and GBIF.

Industry records: Although data was requested from growers at meetings held from 2009-2012 and via email request, industry information on pests was inadequate. Though seven species of scale are listed in the survey, 'scale' are reported as a lumped category. Similarly though previous information and our surveys indicate the presence of at least three species of mealybugs,' mealybugs' are recorded as one category and so on. Growers monitor for light brown apple moth to determine pest pressure and the need for control. This data is either not kept or is difficult to access. Again a potential source of information is not captured. Overall, we were able to use very little data from industry. Lack of support tools for identification meant that although we added a request for data to our website, no useful data points were added. Recent surveys have not collected this data so we were unable to expand our database.

Environmental data: To use as predictor variables, BIOCLIM variables were obtained from WorldClim (http://www.worldclim.org accessed December 2010; (Hijmans *et al.* 2005), which offers high-resolution layers of averaged monthly climate data (1950-2000) from globally distributed weather stations. The primary 19 BIOCLIM variables are derived from averaged monthly temperature and precipitation data (Nix & Busby 1986) and describe means, trends and seasonal variations of temperature and precipitation, which are more likely to represent physiological limits for species (Graham & Hijmans 2006). These observations are then interpolated across the landscape and made available as gridded cells that are suited to modelling purposes. These variables have been used widely for climate modelling for a range of different species' distributions and different lengths of sampling time (e.g. (Giovanelli *et al.* 2008; Lozier & Mills 2009; Murienne *et al.* 2009; Wang *et al.* 2010a). Grid cells were at a resolution of 30 arc seconds, approximately 0.83 km^2 at the equator.

While some studies use all 19 BIOCLIM variables as a "complete" dataset (e.g. Giovanelli *et al.* 2008), we selected a more informative subset (e.g. Rodder *et al.* 2009). To do this, each species was considered independently. An issue with using correlative models for climate change predictions is that predictor layers such as temperature and precipitation are often correlated, and these can lead to issues with both identifying key climate variables and projecting models into new climate scenarios. To test for spatial correlation, values of each BIOCLIM layer for each species locality were extracted and Pearson's coefficient tests were performed between each pair of variables using R (R Development Core Team 2009). A correlation matrix for the 19 temperature and precipitation variables was constructed and any pair where $r \geq 0.80$ were considered correlated (see Lozier & Mills 2011). After correlated variables were identified, preliminary models were constructed and the MAXENT jack-knife test was used to examine the importance of each variable and its relationship to each species (see Ficetola *et al.* 2007). For pairs of variables that were correlated, the variable that added the least unique information and added least to model performance was omitted. The models were run again on the reduced dataset in a step-wise fashion. To ensure that reducing the number of predictor variables was not compromising model performance, AUC (Area Under the Curve for the ROC) (Receiver-Operator Characteristic) value was examined for each run of the model (see Ficetola *et al.* 2007; Lozier & Mills 2009). The output for each run was examined to ensure that the model was not over-predicting habitat suitability. This process was repeated until the model was built on a subset of the most informative predictor variables, without compromising AUC. An advantage of this method is that a reduced number of predictor variables can help avoid multicolinearity issues (Ficetola *et al.* 2007). For each model with final predictor variable set, MAXENT was run with

25% of the training dataset randomly chosen as a test dataset. Each final run of the model was run with 10-fold cross-validation. The remainder of the MAXENT modelling parameters were left at program default (see Phillips & Dudik 2008).

Many of the distribution records held in the databases employed in this study are also likely to have large collection biases. To account for such biases in these data that are likely to influence models, we created a sampling bias grid for each species using ArcGIS density functions (Gaussian Kernels). The density was calculated and then areas were weighted from 1 (not spatially dense) to 10 (highly spatially dense). Additionally, presence-only algorithms such as MAXENT aim to fit environmental data as tightly as possible to the given distribution information, however, for species where there is incomplete sampling in all areas this may result in under-prediction of suitable habitat. Through modifying different fitting parameters it is sometimes possible to account for this and produce more accurate models. We changed regularization and model features to examine how model fitting was affected by data availability.

5.2.2 Mapping distributions under future climate scenarios:

For species with adequate current locality data available, distribution maps were prepared by building ecological niche models for each species using the correlative modelling program, MAXENT and determined predictor variables useful for describing the climate space of each species. The models were projected into a range of future climate change scenarios to assess how climate change may alter species-specific distribution patterns in Australia. All final models were projected to an ensemble forecast of Global Circulation Models (GCMs) based on the A1FI (fossil intensive) SRES. We projected the models for the time periods 2030, 2050 and 2070.

The A1FI (fossil-intensive) SRES (Special Reports on Emission Scenarios) (Solomon *et al.* 2007) future climate change scenario was used in this study. The SRES reflect different societal responses and emissions rates whilst accounting for population growth (Solomon *et al.* 2007). This particular scenario incorporates a "fossil intensive" projection of emissions incorporated with alternative directions of technological change. BIOCLIM variables were constructed for an ensemble of 23 General Circulation Models (GCM) from the 4th Assessment Report, for three time periods, 2030, 2050 and 2070 (Solomon *et al.* 2007). These were built on a national 9-second Digital Elevation Model (DEM) v3 (GeoScience Australia) aggregated to 36 seconds (~1km), and the change grids and downscaling methods supplied in ANUCLIM v6.1 (Fenner School of Environment and Society, ANU). An ensemble of multiple GCMs filters out individual model bias and allows for greater confidence to be placed on outcomes for future projections (see Beaumont *et al.* 2008). We set a presence / absence threshold at 10% of habitat suitability values from the original models for each species.

We used QGIS (Quantum GIS Development Team, 2012. Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project http://qgis.osgeo.org) to produce the maps, and the vector layers were obtained from the Natural Earth database (http://naturalearthdata.com; accessed July 2012). The maps show the state boundaries of Australia and also the major river systems in Australia, particularly the Murray-Darling Basin.

Light brown apple moth is not only the most important insect pest in grapes in Australia but also is of concern in the United States. This species provides a valuable opportunity to apply a mechanistic approach. Investment by the industry over a number of years has resulted in a great deal of information regarding the parameters of light brown apple moth. For example, light brown apple moth requires 673.6 degree days above the minimum threshold of 7.5℃ for a generation and at the same time, the upper limit to its survival is 31.5℃ (Danthanarayana 1975a, b). These sorts of parameters can be put into a model and the potential range where these conditions are met calculated to indicate the current range

suitable for light brown apple moth and to then predict potential range under climate change. Models based on physiological parameters can be particularly useful in predicting the potential range for an invader and have been used to predict the possible range of light brown apple moth in the United States (Lozier & Mills 2011).

Knowledge of current distributions can also be used with CLIMEX modelling software: CLIMEX focuses on the distribution of a species in relation to climate. This includes climate matching to determine the potential of geographical regions for invasive species to establish. Further, models are built around the response of a species to temperature and moisture (and solar, but these are rarely used for pest invertebrate species). These variables limit distributions by imposing restrictions on population growth and persistence.
DYMEX, a further development of CLIMEX, also allows for basic interactions to be incorporated. The DYMEX modelling package allows for population growth parameters to be tied to environmental conditions to examine the suitability. DYMEX models allow for complex life histories to be examined at each life stage for a species and for full development to be characterized

5.3 Thermal limits of mealybugs and ladybird beetles:

The extent to which herbivores can track crops and natural enemies can track changes in herbivore hosts will depend on their relative resistance to thermal extremes. Direct effects of temperature are likely to be larger and more important than any other factor in assessing potential responses of insects to climate change (Bale *et al.* 2002). Predicting insect response to elevated temperatures is largely based on studies carried out over a range of temperatures to determine lethal constraints to survival under predicted temperature changes or establishment in a new area. Laboratory studies can be used to determine temperature thresholds above or below which a species becomes incapable of development or activity. We determined limits to activity for two of the commonly occurring species of mealybug, citrophilus and longtailed and the predator, the ladybird beetle *Cryptolaemus montrouzieri* "mealybug destroyer".

Citrophilus mealybugs were accessed from a commercial insectary (Bugs for Bugs Munduberra Queensland www.bugsforbugs.com.au) and a laboratory colony established. Field surveys were also undertaken in the Yarra Valley region in Victoria and longtailed mealybugs were collected in vineyards in Western Australia and New South Wales [4] and from Victoria. Colonies from both the field and the commercial supplier were established and reared under constant conditions (25℃, 16:8 (L: D)). Citrophilus mealybugs tested were from Bugs for Bugs and from the field (Yarra Valley Victoria) (additionally reared at 22℃), and longtailed mealybugs from four populations collected from the field (Western Australia, New South Wales and Victoria). Natural enemies were obtained from Bugs for Bugs: one species of ladybird beetle, *Cryptolaemus montrouzieri* and a mealybug parasitoid *Leptomastix dactylopii* Howard. Colonies were established in controlled temperature cabinets and reared at 25℃ 16:8 (L: D). Attempts to collect *C. montrouzieri* in the field (Yarra Valley) were unsuccessful and our previous experience with this species suggests it may be in low abundance in this area. Adult *C. montrouzieri* are approximately 4 mm in length from the front of the head to the rear of the abdomen. Sufficient supply of *Leptomastix dactylopii* was not able to be accessed due to colony failure from the supplier, thus experiments were discontinued.

Two different methods for determining acute thermal tolerances were used: dynamic and static. In the first method, animals were subjected to increasing or decreasing experimental temperature until 'physiological failure' (unable to move) "Critical Thermal Maximum CT_{max} or Critical Thermal Minimum (CT_{min}) following the procedure of Hazell *et al*. (2008). These

[4] Kind assistance of Stewart Learmonth, Margaret River WA and Tony Somers, Hunter Valley NSW in collecting mealybugs and forwarding to us is gratefully acknowledged.

experiments were performed within an aluminium block attached to a propylene glycol filled bath (Grant bath model GP 200 – R2 Thermo regulator). Cooled or heated fluid was pumped through a network of holes drilled into the block (Fig. 1) and selected insects housed in a circular depression (the 'arena'; depth 7.5 mm, diameter 25 mm) (Fig. 1) and covered with a thin sheet of Perspex. Data on the temperature within the arena were recorded using a thermocouple positioned in the sidewall of the arena 1 mm above the base, attached to an electronic thermometer (Type K thermocouple TC-08 Thermocouple data logger, Pico technology). The walls of the arena were coated with Fluon (Blades Biological, U.K.) to prevent climbing up the sides and out of the field of view. For all experiments, the temperature within the arena was initially set at the rearing temperature 22℃ or 25℃. Insects were placed in the centre of the arena and allowed to settle for 5 min before visual recording started. For upper thermal limit, the temperature was increased at 0.5℃/min from the rearing temperature to 35℃ and then from 35℃ to selected maximum temperature (40.0, 42.5, 43.0, 43.5, 44.0, 44.5 and 45.0℃) at 0.1℃/min. For the lower temperature limit, temperature was decreased at 0.5℃/min from rearing temperature to 10℃ and then further lowered from 10℃ to -2.0, -3.0, -4.0, -5.0 and -6.0℃ at 0.1℃/min. Initially, activity was monitored using Dino-Lite AM411 digital microscope (AnMo Electronics Corporation, Taiwan) and DinoXcope software (AnMo Electronics Corporation, version 1.3.4). Video was analysed frame-by-frame using the VLC media player (VideoLAN,version 1.1.10, available at: http://www.videolan.org/, accessed July 2011). In later experiments the arena was viewed directly by an observer. The temperatures at which each insect walked and last moved were recorded. Each experimental temperature in the arena was repeated 4 times with 10 insects.

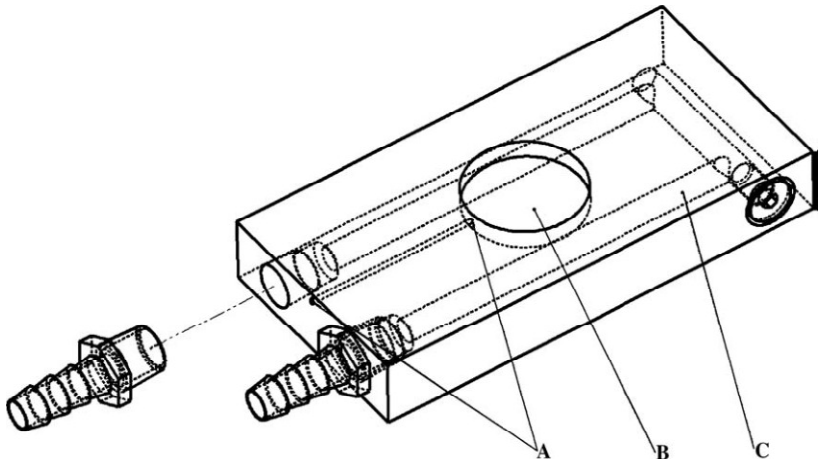


Figure 1. Design of the aluminium block system. A. passage for the thermocouple; B. The arena; C, channels bored into the block to allow heated or cooled liquid to be pumped around the block (from Hazell *et al*. 2008).



Figure 2. Arena with six *Cryptolaemus montrouzieri.* Maximum set temperature 45℃, temperature at time of image capture 43℃, two (1 and 4) are seen unable to move, the remainder have not reached critical limit at this time.

In the second approach, test organisms are placed in vials which were immersed in a water bath at a set temperature for 2 hours, then removed and response determined 2 hours and 24 hours after removal. For each replicate, insects (ten 2nd instar mealybugs or one 6 – 24 h old ladybird beetle) were placed in a vial, the vials sealed with Parafilm® and placed in a water bath. Initial tests of survival of immersion for 2 hours at temperatures ranging from 30.0℃ -40.0℃ resulted in 100% survival; hence 40.0℃ was selected as lowest temperature for testing. Water bath temperatures selected for testing were (upper) 40.0, 42.5, 43.0, 43.5, 44.0, 44.5 and 45.0℃ and lower (-2, -4 and -6℃) for 2 hours.Type K thermocouple (TC-08 Thermocouple data logger, Pico technology) was inserted into one empty glass vial to record the real time temperature. After a 2 hour treatment, the insects were removed from the water bath and insects immediately examined under a microscope (Leica X40). Mortality was recorded 2 hours after treatment. They were then returned to 25℃ for 24 hours recovery and then scored again for mortality. Survival was defined as response to stimuli. There were 6-10 vials per experiment and each experimental temperature was repeated four times.

While both methods worked well for *Cryryptolaemus montrouzieri,* initial experiments with mealybugs placed in arenas were inconclusive, as the mealybugs did not move sufficiently for recognition of responses. To this end, only the second assay was used for the mealybugs.

6. Results/Discussion:

6.1 Literature reviews: We sourced information from more than 100 papers with over half referring to grapes (‘vine’, ‘grape’ and ‘vitis’). At least three processes are encapsulated in ‘climate change’: climate warming, increased carbon dioxide and change in water availability. Effects of temperature were most commonly commented on with 36 papers on ‘climate’ and an additional 13 on ‘temperature’ and three ‘warming’. There were just six specifically referring to carbon dioxide and sourcing references to changes in water availability was more difficult with no papers accessed through ‘drought’, ‘rainfall’ or ‘water deficit’. Interest in pests relevant to viticulture is demonstrated by the large number of references (72) referring to Lepidoptera, scale and mealybugs with a more limited number (16) predicting impacts on natural enemies (predators and parasitoids).

6.1.1 Potential changes in vines in response to CO_2 and temperature and changes in viticultural practice occurring in response to climate change:

Environmental changes associated with climate change include increased carbon dioxide [CO_2], increased temperature and decreased water availability. Each of these has potential to change vine production and several reviews of likely impact on grape growing have been completed both in Australia (Jones 2005; Webb *et al.* 2007; Hall & Jones 2009) and overseas (Jones & Davis 2000; Jones *et al.* 2005; Jones 2009).The following discussion focuses on impacts on vines which have potential to impact on pest incidence and natural enemy involvement.

Carbon dioxide concentration [CO_2]. Besides global warming, plant photosynthetic CO_2 fixation is the main process affected by an increase of CO_2, mainly by enhancing CO_2 fixation of RubisCO, the enzyme responsible for the first major step in photosynthesis. This induces stomatal closure with reduced water loss. Consequently, a large number of studies have shown that increased CO_2 may lead to increased crop photosynthesis, growth and yield and to reduced transpirational water loss from the canopy (Polley 2002; Bunce 2004; Long *et al.* 2004; Ainsworth & Long 2005). As a result, in general, increased CO_2 enhances plant biomass though this is related to availability of other growth resources (water and nitrogen) (McCarthy *et al.* 2010), thus there is potential for increased growth and yield of plants grown at elevated CO_2 (Burkart *et al.* 2009). Grapes grown in Italy with Free Air CO_2 Enrichment (FACE) (elevated CO_2 in open topped chamber experiments) stimulated grapevine photosynthesis and hence yield but the effect of suboptimal nutrient and water availability needs to be assessed to determine grapevine responses to climate change (Moutinho-Pereira *et al.* 2009). A 40-45% increase in fruit dry weight for atmospheric CO_2 concentrations of 550 ppm (compared to the seasonally adjusted CO_2 concentration of 383 ppm in August 2007) has been reported with no apparent loss in grape and wine quality (Bindi *et al.* 2001).

However, while plants grown under elevated CO_2 frequently show increased yield and growth, they also show altered composition, especially increase in carbon: nitrogen (C/N) ratio (i.e. reduced protein for carbohydrate). This effect has been shown in vines grown with elevated CO_2 (Moutinho-Pereira *et al.* 2009) and more information is needed as to the impacts of this not only on the crop but also on pests.

Water. Precipitation changes are predicted to be more variable but potentially result in greater growing-season stress on irrigation. A range of climate model simulations all suggest that for Australia, the moisture balance deficit will become larger under enhanced greenhouse conditions (IPCC 2007). Average decreases in the annual water balance in Australia range from about 40 to 120 mm per ℃ of warming. Possible consequent changes to water allocations to vineyard irrigation may, therefore, have a significant impact on the viability of some viticultural regions notwithstanding the effects of changes in average temperature. In addition to nutrient (especially nitrogen) deficit, water deficit may limit inflorescence initiation.

Temperature. In Australia, climate change scenarios for viticulture show that temperatures are projected to warm by 1.0-6.0ºC by 2070. There may be some advantage in this, such as decreased frost risk and less extreme winter minimum temperatures that would otherwise damage grapevines (Webb *et al.* 2007). However other consequences of increased temperature including increase in the number of hot days, changes in length of growing season, earlier start and earlier harvest, decrease in the area suitable for grape growing, change in varieties suitable for different regions and changes in crop phenology are more difficult to predict. In Europe, spatial modelling of future climate change impacts indicates potential shifts and/or expansions in the geography of viticulture regions with parts of southern Europe predicted to become too hot to produce high quality wines and northern regions becoming viable. Similar work in Australia has tied future temperature changes to

reduced wine quality with southerly and coastal shifts in production regions being the most likely alternative to maintaining viability (reviewed in Webb *et al.* 2007). Jones *et al.* (2005) suggest that the 'simple' mean growing season temperature (GST) effectively defines spatial variations in varietal potential and growing season climates. If a GST of 21°C is considered as the upper limit of quality winegrape production (Jones 2005), then, under the temperature increase scenario for 2070, large areas of the northern viticultural regions of Australia may not be suitable for quality winegrape production (Webb *et al.* 2007; Hall & Jones 2009). The latitudinal location of Australia, being close to the equatorial limit of winegrape production for the Southern Hemisphere and with little land mass poleward, means that the total area of viable viticultural climates of Australia would be reduced, the level of reduction being proportional to the magnitude of the increase in temperature. The area of Australia estimated by the modelling process to experience GSTs between 13 and 21°C reduces from 986 000 km^2 for the 1971–2000 base period to 736 000 km^2 by 2030, 576 000 km^2 by 2050 and 449 000 km^2 by 2070 (Jones *et al.* 2005).

Apart from changes in suitable varieties and areas, temperature increase will affect vine **phenology**, events in crop cycle including timing of bud burst, time from bud burst to harvest and timing of harvest itself. Grape growing regions are classified in heat summation cumulative 'GDD or growing degree days'. Mean daily temperature above threshold (typically 10°C) over a 7 month standard growing period October-April in southern hemisphere; each 1°C increment in mean temperature adds 214 GDD to the standard growing season (Keller 2010). For established viticultural regions under warmer atmospheric conditions, shorter seasons would likely be experienced and harvest would occur in warmer conditions earlier in the year. Succession of phenological stages of grapevines is commonly observed to be accelerated with a rise in temperature – earlier flowering, veraison and harvest. Climate change has shifted plant phenology in the Mediterranean region with a survey from a dataset of 200000 records for 6 phenological events of 29 perennial plant species (Gordo and Sanz, 2010). From 1952 to 1997, Jones and Davis (2000) report that warming in Bordeaux has led to shorter phenological intervals for vines. The length of the growing season is considered an important determinant of grape quality and consequent wine value. Modelling the effect of different warming scenarios on the phenology of grapevines in Australia by Webb *et al.* (2007) suggests shorter seasons would be experienced, chilling requirements might not be met in all regions and harvest would occur in warmer conditions earlier in the year.

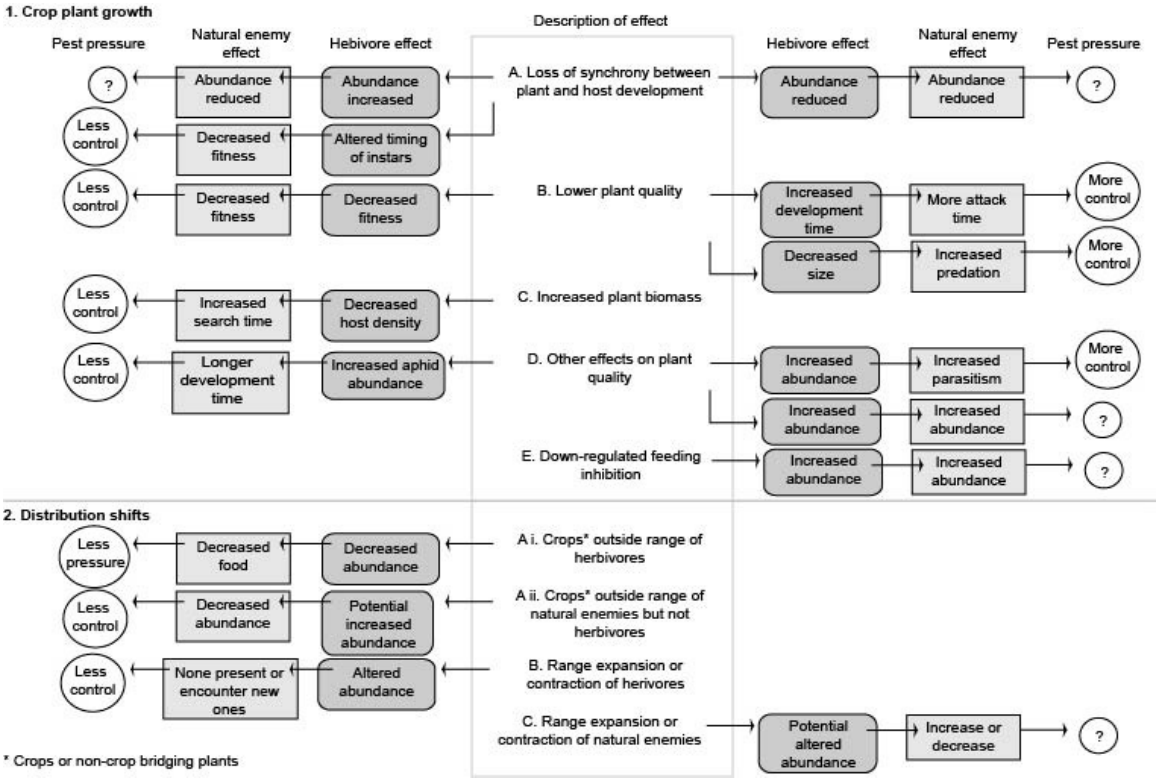
There is opportunity for environmental variables and management practices to alter each yield component of a cultivar and for vines to respond to and partially compensate for any such alterations. Warm temperatures, high irradiance, and adequate water and nutrient supply are required for the formation of the maximum number of inflorescence primordia. High temperatures (>35°C) early favour tendril formation, rapid shoot growth in spring may compete with flower formation. Berry number is most vulnerable to environmental stress at or just after flowering (Keller 2010). Grapevines may compensate for differences in berry number per vine by changing rate of berry growth. Vineyard management tools, especially canopy management, irrigation and nutrition, are available to manipulate individual yield components. These are modified depending on short term weather conditions and can be used as tools for long term changes in climate.

The temperature of the final ripening month is regarded as a particularly important factor influencing wine styles. Studies under controlled conditions have demonstrated that temperature influences many components of grape development, including the breakdown of acids (Buttrose *et al*. 1971) and berry colour development (Buttrose *et al*. 1971, Kliewer 1977). In particular, prolonged periods with temperatures above 30°C can induce heat stress, which may lead to premature veraison, berry abscission, enzyme inactivation and reduced flavour development (Mullins *et al*. 1992).

These studies indicate that the challenges facing the wine industry include more rapid phenological development, changes in suitable locations for some varieties, a reduction in the optimum harvest window for high quality wines, and greater management of already scarce water resources. Industry responses/changes in management practices to elevated CO_2, temperature and water availability include selection of appropriate varieties, canopy management and water use.

6.1.2 Potential impacts of changes in vine and pest phenology such that more damaging interactions will potentially occur?

Changes in water availability, CO_2 and temperature all have potential to impact not only on vines but also on pests and natural enemies and the outcome can be difficult to predict.



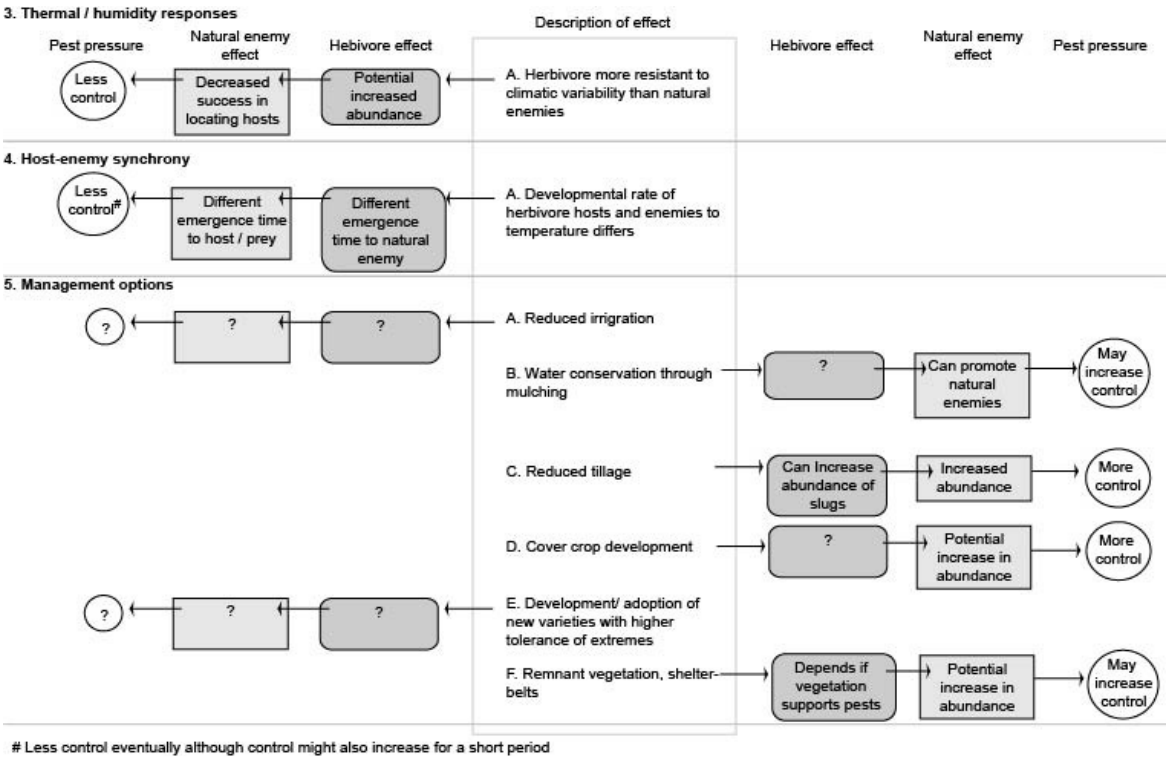


Figure 3. Outline of potential effects of climate change on natural enemies of herbivorous pests as assessed through interactions with pests and their crop host plants (from Thomson *et al.* 2010a).

Elevated CO_2. The relationship between elevated CO_2, crop pests and natural enemies is complex. On one hand there is plant consumption of herbivory itself with reduced protein/increased carbohydrate foliage resulting from crop grown with increased atmospheric CO_2 differentially affecting performance of herbivores depending on mode of feeding (Bezemer & Jones 1998). Foliage feeders like light brown apple moth and grapevine moth caterpillars will eat more but effects on whole cell feeders like mites and thrips are variable and impact on phloem feeders like mealybugs is much less clear and at this stage there is little information. Limited studies suggest there may be no impact on phloem feeders: one study of the impact on mealybugs of host plant (Chrysanthemum) grown in elevated CO_2 (Chong *et al.* 2004) showed no effect on Madeira mealybug *Phenococcus madeirensis* Green.

Increased availability of food resulting from increased growth is not necessarily beneficial to herbivores: reduced quality food may result in reduced fitness. While herbivorous insects respond to low-quality plants by increasing consumption, sometimes managing to compensate for reduced food quality, in general the fitness of insects is reduced (Bezemer & Jones 1998). Effects include increased development time and reduction in growth rates and body size at elevated CO_2 (Zvereva & Kozlov 2006).

There are even some more unexpected effects: elevated CO_2 can increase the susceptibility of plants to herbivory through changing gene regulation (1E in Fig. 3). Herbivory of soybean under field conditions is affected by down-regulating gene expression for a protease specific deterrent to coleopteran herbivores (Hamilton *et al.* 2005; Zavala *et al.* 2008).

Water. There are different potential impacts of decreased water availability on grape growing- here we limit discussion to interactions of changes in water availability to pest impacts. An important issue is whether vine stress will increase susceptibility to attack from pests, especially borers. Climate change models tend to predict not only increases in average temperature but also reduced rainfall and more frequent droughts. These changes

have the potential to stress vines, and stressed vines may be more susceptible to trunk boring insects. Stressed or weak vines may allow entry and establishment of elephant weevil into vineyards (Coventry *et al.* 2004). They may also facilitate the establishment of large and common auger beetles and fig longicorn. Under future conditions, taking steps to maintain good vine vigour may help reduce both the incidence and severity of attack on vines. This links directly to industry-supported research into irrigation management such as “Improving water use efficiency and “Drought tolerance with rootstocks” in response to reductions to water allocations.

Again, less obvious impacts have emerged in detailed studies of responses of potential impact of climate change on pest control. In cassava *Manihot esculenta* Crantz, parasitism of mealybugs is reduced under conditions of water stress associated with drought conditions (Calatayud *et al.* 2002). Apparently the immune response of mealybugs is improved when these insects are grown on water stressed plants, leading to an increased rate of encapsulation ranging from 30% to 50% in three different species of encyrtid mealybug parasitoids (Calatayud *et al.* 2002). It remains to be seen if this is response is also seen in mealybugs of importance in vineyards in Australia.

As we have already seen**, temperature** changes can have a range of effects, changing plant phenology, potentially changing the stage of the vine when pests and their natural enemies are present, changing the area suitable for vine growth, changing the suitable range for pests and for natural enemies of vineyard pests. The implications of shifts in the range of grape growing for pest control depends on prediction of pest ranges in relation to any change in grape growing areas. If the area suitable for grapes is diminished does that mean greater pest pressure for the remaining area? The direct effects of predicted temperature elevation on insect herbivore performance will be generally positive (Bale *et al.* 2002; Zvereva & Kozlov 2006); that is to say, they will grow faster and emerge more quickly in the spring, with possible consequences for the number of generations per year for pests with more than one generation and the time of first emergence for all pests including those with a single generation such as weevils and trunk borers. For instance the spittle bug, *Neophilaenus lineatus* L. (Hemiptera: Cercopidae), is expected to complete development 2-3 weeks earlier in response to a 2°C rise based on current data (Whittaker & Tribe 1998). An important issue in understanding likely impact of climate change is the extent to which interacting species may alter their phenologies to different degrees, leading to mismatches between herbivores and plants, predators and prey and hosts and parasitoids (Visser & Both 2005; Klapwijk *et al.* 2010). The speed of development of herbivores will generally increase under climate change unless it is influenced by poorer nutrition, and evidence accumulating from altered phenologies for a variety of plant and animal taxa indicates insect phenology shows a steeper advance than plant phenology (Gordo & Sanz 2005). Change in crop phenology can be detrimental to the herbivores if they emerge when the crop is suboptimal. A study of pollinators and flowering plants in the Mediterranean region indicates decoupling of availability of flowers and appearance of pollinators (Gordo & Sanz 2005). Changes in synchrony of pest and crop can have both negative and positive impacts on pest abundance. Olive flowering time has advanced but at lower rate than appearance of its pest olive fruit fly *Bactrocera oleae* (Gmelin) (Diptera: Tephritidae). The first females of *B. oleae* to emerge actually find less developed olives during oviposition and this may affect their chances for successful reproduction (Gordo & Sanz 2005). Responses to temperature increase of winter moth *Operophtera brumata* L. (Lepidoptera: Geometridae) and bud burst in oak have been different, leading to loss of synchronisation (Visser & Holleman 2001; van Asche *et al.* 2007). Winter moth eggs which hatch either before or after the oak bud burst have reduced fitness because the first instar larvae will either starve or have to eat older leaves which contain more tannins leading to smaller females with reduced egg load. Changes can also provide greater opportunity for pests. The Colorado potato beetle *Leptinotarsa decemlineata* (Say) *(*Coleoptera: Chrysomelidae) is appearing earlier whereas sowing of potato plants has not

changed hence pest may have had more time to forage on potato plants, completing more generations and possibly doing more economic damage (Gordo & Sanz 2005).

A potential consequence of climate change promoted alteration to development and life cycles (phenology) is change in voltinism (number of generations per year) – these are obviously related, faster development increases possibility of increased generation number per year. As in almost all insects, development rate is directly linked to temperature. Higher spring temperature means earlier emergence enlarging the window in which successive generations develop during the season. At the same time, higher annual temperature promotes faster development of successive generations which increases the likelihood of an added generation late summer. Lepidopterans appear to be particularly sensitive to climate changes- with observed changes including phenological advance and species specific changes in migratory potential, voltinism and physiology (see Martín-Vertedor *et al.* 2010 for more detail). There is observational evidence that European vine moth *Lobesia botrana* Denis and Schiffermüller (Lepidoptera: Tortricidae), a key vine pest in Spain tends to advance spring emergence and display a fourth flight in a region where 3 flights is 'traditional' (Martín-Vertedor *et al.* 2010), an occurrence never reported before. This moth has a larval diapause late summer and displays between 1-5 flights depending on latitude and altitude. In fact, analysis of temperature increase in this region showed that the greatest increase was in mean spring temperature – so the effect on the moths was greater than predicted by increase in annual temperature. Advance similar to that reported for the 2nd and third flight peaks for *L. botrana* (12 days) has been reported for other Lepidoptera: advance of 11 days (1952-2002) of first sighting of *Pieris rapae* (Peñuelas *et al.* 2002; Gordo & Sanz 2005), eight of 17 species of butterflies (1988-2002) showed significant advance of flight dates ranging from 10 days in *Ochlodes venata* to 28 days in *Lasiommata megera* (Stefanescu *et al.* 2003). Longer growing seasons due to milder conditions have been observed to allow more generations of aphids (McVean *et al.* 1999) and the European corn borer (Trnka *et al.* 2007).

Diapause in insects is typically associated with an interaction between day length and temperature (Denlinger 2002) and altered patterns of diapause could influence generation number. In the grape berry moth, *Paralobesia viteana* (Clemens) (Lepidoptera: Tortricidae), voltinism is predicted by the number of degree days that accumulate before the post-summer photoperiod when oviposited eggs develop into diapausing larvae instead of adults. This will lead to increased numbers of generations under warming at some times of the year (Tobin *et al.* 2008). If vine phenology and moth phenology are both influenced by climate change (i.e. both advanced), the outcome will depend on the potential extent of mismatching. If vine phenological stage in which moth may develop affects survival (as has been shown for European vine moth) this is clearly important. If a mismatch develops between vine phenology and pest life cycle, then in fact the pest population may decline in the year following the increase in voltinism: that is, increased generations per year do not necessarily result in increased pest pressure (Martín-Vertedor *et al.* 2009). It is possible that harvest could be over before latter generation(s), even with possible decline in pest numbers due to lack of food availability. It is also possible that faster development of vines would mean harvest taking place before last flight (whether same number of generations occurs/year or increased generations occur) and hence food for pests is decreased maybe leading to decreased pest pressure.

Plant effects on beneficials might also involve changes in the expression of volatile organic compounds and the secretion of extrafloral nectar that are induced by insect feeding, which are now well recognized as providing protection from herbivores (Heil 2008). Increases in temperature under climate change could influence the production and release of volatile compounds.

Host-parasitoid synchrony. Differences in response to temperature changes and the extent of temperature changes may alter the synchrony between herbivores and their natural enemies. Climate change may alter host-parasitoid interactions directly if hosts and parasitoids respond differently to ambient temperatures disrupting synchrony or indirectly via the host (Klapwijk *et al.* 2010). Temperature has a large effect on herbivore phenology (Bale *et al.* 2002), and temperature changes may alter the synchrony between herbivores and their natural enemies (4A in Fig. 3). The effects of these changes on the natural enemies of herbivore hosts can be unclear, particularly over the longer term (Godfray 1994; Hance *et al.* 2007). If parasitoids emerge earlier than hosts because their development shows a sharper response to temperature, a very large population of parasitoids might cause a marked decrease in herbivore hosts, and this could even lead to eventual extinction of the parasitoid population. There may be few or no available hosts in the vulnerable stage and, depending on the extent of the mismatch, many parasitoids could die before hosts become available. However a late arrival of parasitoids might prevent much control and again lead to local extinction. A disconnect between host and parasitoid can also arise because of increased climate variability. Poor synchrony between a parasitoid and its host has been documented in a number of cases. For instance, hibernating parasitoids of leaf miners emerge at a time when no hosts are available, and this results in a low level of parasitism of the first generation of horse chestnut leafminers, *Cameraria ohridella* Deschka & Dimic (Lepidoptera: Gracillariidae), in the field (Grabenweger *et al*. 2007). Hance *et al.* (2007) also point out that changes in synchronization are particularly important when herbivores have evolved altered emergence patterns in response to parasitoids. In this case, any effects of climate change and weather variability on emergence patterns of the hosts or parasitoids that alter synchrony may be disastrous for the hosts.

Changes in distribution. The effectiveness of natural enemies in pest control may be reduced by changes in the distribution of crops, hosts and the enemies themselves (2A–C in Fig. 3). Crop ranges are predicted to move as climate change occurs, and herbivores may track these changes. The outcome will depend partly on the ability of natural enemies to concurrently expand their range or for new natural enemy populations to control the pest in its expanded range

Sources of interaction with climate change then are varied- number of generations/year, timing of generations, timing of generations with vine phenology, changes in varieties and susceptibility of varieties and changes in vine stress due to increased temperature and decreased water as well as changes in areas suitable for crop growth and changes in pest and natural enemy distributions.

Light brown apple moth. As a leaf feeder light brown apple moth would be predicted to eat more of plants with increased C:N ratio resulting from higher [CO_2] to ensure adequate protein intake. A second change involves phenology in response to temperature leading to changes in emergence time and number of generations per year. Currently there are different numbers of generations in different regions related to temperature (Walgama 2008). In Victoria for example, three generations can be designated the first or summer generation (January-April), the second or autumn-winter generation (May-September) and the third or spring generation (October-December) respectively. It is evident that during the warm summer months from December to March there is some overlapping of stages, since eggs and immature stages are found throughout this period, but the distinct peaks of the three generations described overshadow this. High summer temperatures may prolong development, as do low winter temperatures. What does this mean for caterpillar abundance? Will there be more or less population pressure at critical stages of grape development and harvest? Larvae of the summer generation are still present at harvest of most varieties. These larvae can provide sites for infection. In some seasons at least another generation may develop on the grapevines during late summer.

Larvae present at budburst can chew off whole shoots or developing bunches – this damage usually does not warrant control, would increased larval abundance increase the impact of those present at bud burst? Similarly for abundance during late spring and early summer: feeding on bunches during late spring and summer can result in crop losses of 10%. With the impact of a change in growing season (earlier start, earlier harvest) would this mean more light brown apple moth at harvest or at a time when spray is limited? In particular, the modelling suggests that by 2070, Northern Tasmania would likely have a similar growing conditions and season-end date to that currently experienced in Coonawarra-are there implications of this for light brown apple moth which are currently higher abundance in Tasmania when compared to Coonawarra?

The number of generations of light brown apple moth is related to temperature, hence increased temperature is likely to result in more generations of light brown apple moth with possible consequences for its increased presence at different stages of crop cycle.

Mealybugs. Differences in lifecycle of the mealybugs that occur in Australian vineyards may impact on their importance and this may be altered under increased temperature. The three commonly occurring species(citrophilus, longtailed and obscure) have some differences in their biology: obscure and citrophilus mealybugs lay eggs in an egg sac, a woolly/waxy bundle, whereas longtailed effectively produce live 'crawlers' which can actively disperse quickly, rather than depositing eggs. Longtailed mealybugs produce fewer offspring, around 100 single eggs, which hatch almost immediately whereas citrophilus and obscure mealybugs egg sacs contain up to 600 eggs which hatch in several days. Overseas where obscure co-occurs with longtailed, it is said to be more damaging in that it readily feeds more readily on leaves and produces more honeydew. There are also suggestions that the number of generations per year at the same location may be different for different species. We just don't know enough about mealybugs in Australian vineyards to comment on this. In at least one study, fecundity of female mealybugs is reported to be reduced at higher temperatures (Chong *et al.* 2004) and again there are implications if this is the case for local mealybugs. Though records for individual species are not extensive, current data indicates some difference in occurrence: obscure prefers warmer conditions occurring in Queensland, some of the warmer northern inland grape growing areas of eastern Australia and parts of south west Western Australia but there are limited records from Victoria and Tasmania. There are no records of citrophilus from WA and limited from Victoria. Longtailed mealybug is said to be the most widespread recorded from all states. Is there potential for change in distribution with climate warming?

While mealybugs are commonly identified as 'mealybugs' in vineyards (e.g. GWR 04/08), there are reasons why it would be good to know what is actually present. There are many reports that mealybugs are increasing as a problem. Is this related to some change in management or a changed climate? A changed climate could potentially drive changes in species distributions or the number of generations. The distribution of animals can often be related to variation in their response to temperature, these may differ even for related species. Currently there are differences in distribution of the three common species: are these related to climate differences? The lack of comprehensive species distribution data makes it difficult to model current and hence future distributions. Longtailed mealybugs produce live young, does this make them more or less susceptible to climate change? Mealybugs were reported to be a greater problem in hot-dry wine regions in a recent survey (GWR 08/04**)**. Does this suggest mealybugs will become a greater pest under climate change as regions move towards hotter and drier?

Mealybugs are phloem feeders: meta analyses of effects of herbivory on plants conclude impact of sap feeders (including phloem feeders) is more severe due to lower abilities of woody plants to compensate for sap feeders damage in terms of both growth and photosynthesis (Zvereva & Kozlov 2006; Zvereva *et al.* 2010).

Biocontrol implications for light brown apple moth and mealybugs are similarly varied. Diverse parasitoids are important biocontrol agents of both light brown apple moth and mealybugs. At present the effects of increased temperature on the host and its parasitoid are unknown, with potential loss of synchrony contributing to decreased control. Parasitism of vine mealybug is reduced in warmer areas of California: levels in excess of 70% have been recorded in cooler parts but rarely exceeds 20% in south where temperatures are 5-10°C higher (Daane *et al.* 2004). Behavioural changes can also have an impact on pest effectiveness. Mealybugs seek cooler sites under the bark or in the root zone during periods of high temperatures, where it is also less likely to be attacked by natural enemies. Hence mealybugs may be less exposed to parasitism at elevated temperatures as they are less likely to leave refuges under bark and elsewhere.

Weevils and trunk borers. There are very limited references to the weevils or trunk insects of concern in Australia in the scientific literature: we must look at general principles for information as to possible effects of how CO_2 and temperature changes may affect these grape pests and their potential interaction with effects on plant growth (including vines). The leaf eating weevils garden weevil and vine weevil would consume more foliage: leaf eating vine weevils (though this is a different species (*Otiorhynchus sulcatus* F.) to 'our' vine weevil) have been shown to consume significantly more foliage to compensate for lower leaf nitrogen in raspberry plants (Johnson *et al.* 2010) but the effect of enhanced CO_2 on the wood boring weevils and trunk borers is difficult to predict.

Possibly from a management perspective, change in emergence time is likely to be important as control of borers is most effective if undertaken at time of emergence when adults are exposed. Increased temperature may influence the time of first emergence for all pests including those with a single generation such as weevils and trunk borers. The common thread for many of these pests is therefore the limited window for control applications. Knowledge of emergence contributes to potential for success of chemical control, and this has the potential to change as conditions become warmer and potentially drier. Monitoring and reporting become increasingly important in making accurate predictions, until it becomes clear which environmental factors control emergence of these pests. The direct effects of predicted temperature with faster growth and earlier emergence in spring will also be seen with possible consequences for time of first emergence of all pests including those with a single generation such as weevils and trunk borers. Johnson *et al.* (2010) reared vine weevils at an increased temperature (+4°C) and these weevils reached sexual maturity 8 days earlier and laid 20 times more eggs by the time they were 5 weeks old compared to those reared under normal conditions. This reinforces the potential devastating consequences of early emergence. In contrast, high temperatures were lethal to eggs (>30°C) and larvae (>25°C) in laboratory rearing of garden weevil (Walker, 1980) and Gerard and Arnold (2002) suggested increasing temperatures would reduce the impact of clover root weevils on pasture in New Zealand as warm, dry summers will prevent a summer larval generation.

A difficulty in controlling trunk insects is due to the short window when they are potentially exposed to chemical treatments. However, until more information emerges on the specific cues to which the insects respond, it is difficult to predict how the vulnerable window might shift under climate change. This depends on whether emergence and development depend on external cues or whether it depends on cues from the plant, in which case pest phenology will track plant phenology (but with the potential for increased damage from a higher reproductive output under warmer conditions).

6 1.3 Thermal responses of mealybugs and light brown apple moth

Mealybugs. Laboratory rearing data for mealybugs indicates that lower limits to successful laboratory rearing (completion of life cycles) are between 11.5-16.5℃, and upper limits between 32.1-35℃ for different species (Table 3a). However, experiments to determine fumigation requirements, together with limited data in the literature on critical thermal responses of mealybugs, suggest they are quite heat tolerant. There are laboratory values of critical thermal minimal threshold at 0℃ and then critical thermal maxima at 37℃ and 38℃ (Amarasekare *et al.* 2008; Wang *et al.* 2010b). However, experiments to establish required temperatures for successful fumigation of fruit indicate much higher thermal tolerance in longtailed mealybugs. Hot water immersion disinfestion procedures for mealybugs on persimmons reported 74 minutes at 44℃ was required to kill 99% of longtailed mealybugs (Lester *et al.* 1995b). Approximately 268 min at 47℃ or 215 min at 50℃ were required to obtain 99% *P. longispinus* mortality (Dentener *et al.* 1997) and 18% of longtailed mealybugs were able to survive air temperature of 40.6℃ (Hollingsworth & Armstrong 2005) (Table 3b).

Table 3: Thermal limits of listed species of mealybugs (a) from laboratory rearing and (b) limits required for successful fumigation.

a. Laboratory determination of temperature limits of mealybugs to complete entire life cycle and thermal limits of adults					
Species	Reference	Limits to complete life cycle in laboratory trials		Thermal limits	
		Minimum temperature threshold	Maximum temperature threshold	T_{min}	T_{max}
Papaya mealybug *Paracoccus marginatus* Williams and Granara de Willink	Amarasekare *et al.* 2008	15℃	32.1℃	-	37℃
Cotton mealybug *Phenacoccus solenopsis Tinsley*	Wang *et al.* 2010b	11.5℃		0℃	38℃
Madeira mealybug *Phenacoccus madeirensis* Green.	Chong *et al.* 2003	15℃	30℃	-	-
Pink hibiscus mealybug *Maconellicoccus hirsutus* (Green),	Chong *et al.* 2008	14.5℃	35℃	-	-
Vine mealybug *Planococcus ficus*	Gutierrez *et al.* 2008	12.5℃	34℃		
Vine mealybug	Walton & Pringle 2005	16.5℃	30℃		
b. Fumigation					
Longtailed mealybug	Hollingsworth & Armstrong 2005	Hot air: Mortality 11% 2 hour exposure 37.8℃, rising to 82% at 40.6℃			
	Dentener *et al* 1996, 1997	Hot air: Mean LT_{99} (99% mortality) at 44℃ 12.4 hours; 4.5 hours at 47℃ and 3.8 hours at 50℃			
	Lester *et al.* 1995a	Hot water: Mean LT_{99} at 44℃ 74.2 min, decreased to 15.1 min at 54℃			

In contrast, data on life history traits (compiled from the literature) to predict impacts of climate change on vine mealybug (*Planococcus ficus*), suggested a lack of heat tolerance (Guttierez *et al*. 2008). Weather-driven and physiologically based, age–mass structured demographic models of the mealybug were parameterized using laboratory data and field

observations. In these models, temperature was used to define the thermal limits and development rates, and resource supply/demand ratios were used to scale daily per capita growth, fecundity and survivorship rates from maximum values at optimal conditions.

The models of Gutierrez *et al.* (2008) estimated duration of life stages, non-linear temperature-dependent developmental rates, maximum age-dependent fecundity, temperature-dependent scalars for growth and reproductive rates, egestion, host-stage preferences and sex ratios to determine development rate of vine mealybug as a function of temperature (Fig. 4a). Thermal limits were then estimated from the development rate resulting in lower and upper limits of 12°C and 35°C (Fig. 4b).

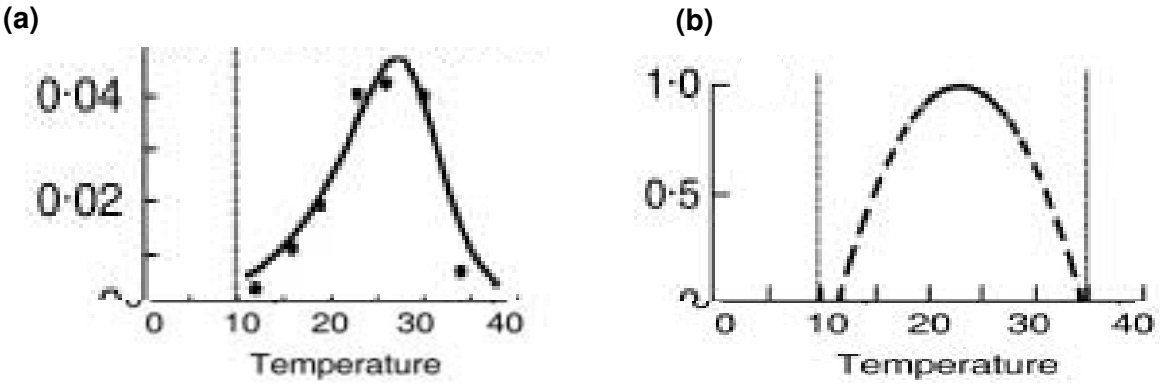


Figure 4. **a.** Development rate of vine mealybug as a function of temperature using data derived from the literature; **b.** Thermal limits of vine mealybug estimated from development rate (From Gutierrez *et al.* 2008).

Using the same methodology of extrapolation from life history trait information available in the literature (Fig. 5a), the authors predicted thermal thresholds of 14.5°C, and 38.5°C for the coccinellid predator *Cryptolaemus montrouzieri* (see Fig. 5b)

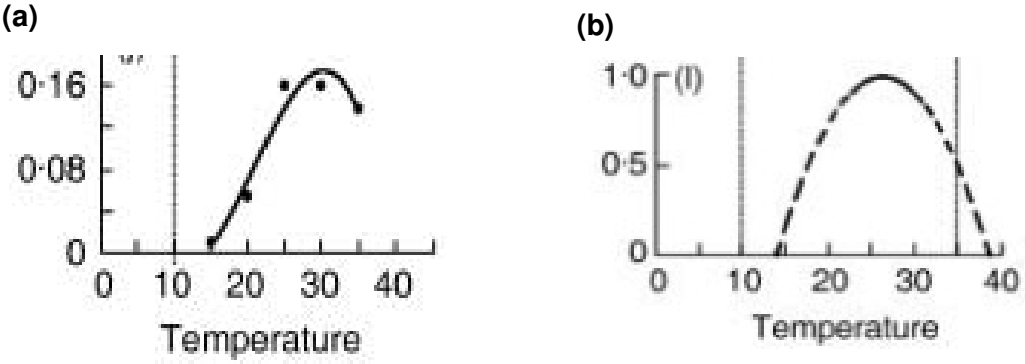


Figure 5. a. Development rate of *Cryptolaemus montrouzieri* as a function of temperature using data derived from the literature; **b.** Thermal limits of *Cryptolaemus montrouzieri* estimated from development rate (From Gutierrez *et al.* 2008).

The high lower threshold supports previous claims that *Cryptolaemus montrouzieri* does not readily survive cold winter temperatures (Bartlett 1974; Jalali *et al.*1999). By modelling the

biological traits and temperature tolerances of the predator and mealybug, the model predicts that *C. montrouzieri*'s abundance would be highest on average in hot climates of southern California**.** Simulation of population dynamics of the mealybug at 108 locations in California over a 10-year period using observed weather concluded the distribution of active stage of vine mealybug would decline with increased temperature (+2℃ and +4℃).

Light brown apple moth. A similar picture emerges from the literature for light brown apple moth. Data from life history analysis indicates survival is limited at high temperatures, but again determination of fumigation requirements and thermal testing of specific life stages indicates greater tolerance of high temperatures. For example, hot air treatments of fifth instar larvae on persimmons required 12.4 h at 44℃ (reducing to 4.5 h at 47℃ and 3.8 h at 50℃) to achieve 99% mortality (Dentener *et al.* 1997).

Results of Danthanarayana (1975a) indicate an upper developmental threshold of 31.3℃ for light brown apple moth eggs, and Burgi and Mills (2012) found time for 50% mortality (LT_{50}) ranged from 1.2–5.6 hours across a range of life stages from egg to pupa for the highest temperature tested (40.4℃) (Fig. 6) (Burgi & Mills 2012). This indicates 50% of eggs are able to survive 4 hours at 40.4℃ and pupae 5.6 hours.

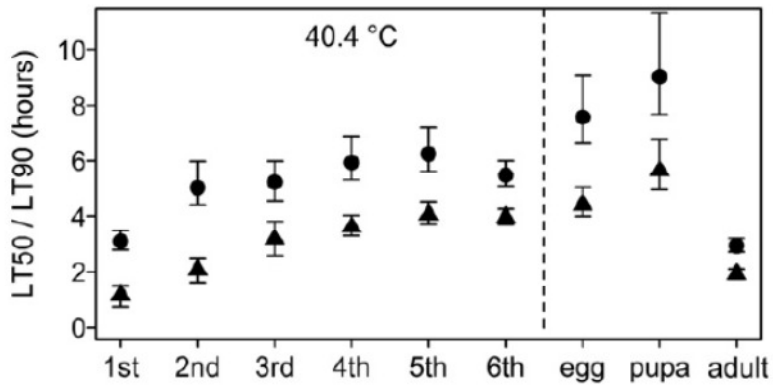


Figure 6. LT_{50} (95% CI) triangles LT_{90} (95% CI) (dots) values for *Epiphyas postvittana* life stages at 40.4℃ (from Burgi & Mills 2012).

Similarly, Whiting *et al.* (1991) also report heat tolerance at 40℃ LT_{99} with values for all four life stages of light brown apple moth (egg, larvae, adult, pupa) from 7 to 21 hours.

As all life stages and generations may be present throughout the summer months (Danthanarayana 1975a) the mixed stage structure could enhance survivorship of at least some life stages of the population during temperature extremes.

6.1.4 Mealybugs, leafroll viruses and potential for virus spread under future climates:

Mealybugs have become increasingly important vineyard pests, increasing in both distribution and abundance. Mealybugs are an economic problem in grape vines because of direct damage to the crop and costs for their control but also their role in transmitting grapevine leafroll viruses. Several mealybug species are found in vineyards, and the wide variety of plants mealybugs are able to use gives them plenty of alternative hosts.

The 'mealybugs' we see in vineyards are all females. There are males in vineyards also but they have quite a different appearance. The familiar female mealybug is a soft bodied insect 3-4.5 mm long, oval, flat, distinctly segmented and covered with a white, mealy wax that extends into spines (filaments) along the body margin and the posterior end. Though they have short legs, these cannot be seen from above. Adult male mealybugs are tiny (about 1

mm), fragile insects, looking more like a fly than a mealybug with one pair of wings, long antennae, and two white wax tail filaments. They are essential for successful reproduction, and fly or walk over the bark to the wingless females for mating. They live for only a few days and do not feed. Hence they are rarely observed amongst the vines. Female mealybugs are quite mobile with early stages (instars) more so. The first instar of mealybugs are 'crawlers' (about 0.3 mm): this is the most mobile stage and is usually the time they disperse through foliage, leaves and fruit. Their preference for crevices and cracks in the bark for reproduction and egg laying contributes to difficulties encountered in chemical control. Mealybugs have piercing-sucking mouthparts: feeding by inserting slender mouthparts into vine tissues and sucking the sap. Extensive feeding may reduce vine vigour but the more common issue leading to mealybug control is excretion of honeydew as they need to extract a large amount of sugar rich sap to fulfil their protein needs. The excess sugars are secreted as honeydew providing a base for growth of moulds with potentially serious consequences for crop quality.

Grapevine leafroll disease (GLR) is one of the most economically important and widespread diseases of *Vitis vinifera*, reducing yield and quality of grapes. There are 7 related leafroll viruses designated imaginatively GLRaV-1 to -7. Leafroll reduces the yield and quality of fruit from infected vines with yield losses of 10% to 20% fairly typical. Leafroll damages the phloem of infected vines, delaying sugar accumulation and reducing anthocyanin production. Fruit from infected vines is low in sugar, poorly coloured and ripens late. In some varieties, fruit maturity is delayed so that fruit on the affected vines may be pale or even whitish at harvest, while fruit on healthy vines is ripe and well coloured; late ripening may also expose the fruit to autumn rains that cause rot (Golino & Almeida 2008).The incidence and impact of grapevine leafroll virus is increasing in many grape growing regions with increasing in-field spread. In the past, little natural field spread of leafroll disease was apparently observed in vineyards. Unfortunately, this situation seems to have changed. In the early 1990s, field spread was observed in the UC Davis Foundation vineyard (Rowhani & Golino 1995).The rate of spread can be high, in one New Zealand vineyard visual assessment showed increased incidence from 11% to 100% in 5 years (Petersen & Charles 1997). More recently, the mapping of leafroll distribution in a 'Cabernet Sauvignon' vineyard in Napa County documented an increase in infection rate of approximately 10% per year over 5 years (Golino & Almeida 2008). Grapevine leafroll disease is detected by visual observation of symptoms in sensitive varieties but some varieties are tolerant and may remain symptomless (Krake *et al*. 1999). There are molecular tests available for detection.
Virus infected vines cannot be cured. Replacement of affected vines is the only treatment and mealybug control is crucial for limiting the spread of the disease. For more information of leafroll-associated viruses see the Grapevine leafroll associated viruses Factsheet available on the Innovators Network Resources site[5], especially the importance of avoiding introduction of leafroll virus infected vines to a vineyard by attention to origin.

The three species of mealybug that are found commonly in Australian vineyards, longtailed, obscure and citrophilus, have been confirmed to have grapevine leafroll viruses isolates vector potential: longtailed mealybug was reported to transmit leafroll disease agents in 1989 (Tanne *et al.* 1989) and citrus mealybug was reported to transmit grapevine virus A earlier (Rosciglione & Castellano 1985). Obscure, longtailed, citrophilus and citrus can all transmit GLRaV-3 isolates and longtailed mealybug (only) is also able to transmit GLRaV-5 (Golino *et al.* 2002). Other GLRV s (1, 2, 4, 6 and 7) are not known to be transmitted by these mealybugs at this time, although GLRaV-1 is transmitted by soft scale insects including *Parthenolecanium corni* (Bouché) (Martelli 2000) which has been recorded in Australia.

[5] http://www.gwrdc.com.au/wp-content/uploads/2012/09/2011-07-FS-Grapevine-Leafroll.pdf

Table 4: Known vectors of grapevine leafroll associated viruses found in Australian vineyards

Species	Known vector of leafroll viruses	Reference
Mealybugs		
Longtailed mealybug	GLRaV-3, 5 and 9 and GVA	Tanne *et al.* 1989; Golino *et al.* 2002; Golino &Almeida 2008
Obscure mealybug	GLRaV-3 and GVA and B	Golino &Almeida 2008
Citrophilus mealybug	GLRaV-3.	Golino &Almeida 2008
Citrus mealybug	GVA, GLRaV-3	Rosciglione & Castellano 1985
Scale		
Parthenolecanium corni	GLRaV-1, GLRaV-3	Martelli 2000

6. 2 Current and future distributions of selected pests and natural enemies

The following models were all built as exploratory methods and require further development and validation before being useful to the industry. This requires more occurrence records and determination of life history traits of individual pests and natural enemies.

6.2.1 Current distributions:

Adequate distribution information was available for a limited number of the pests investigated and mapping of current distributions was completed for five species. There are almost no records for mite species commonly found in vineyards. Availability of distribution data produced some surprises; data for the most important insect pest in vineyards, light brown apple moth was lacking, data for the most common scale (grapevine scale) was inadequate for modelling though data was sufficient for soft brown scale. Maps were produced using the distribution data collected from the various databases. The maps show the state boundaries of Australia and also the major river systems in Australia, particularly the Murray-Darling Basin. From these mapped distributions, each species is discussed in terms of suitability for modelling purposes, based on the availability of current distribution data.

Light brown apple moth (Fig. 7a), data covers the range of the species well, but is heavily biased towards the capital cities. The data serves best as validation for CLIMEX models already developed (Sutherst 2000; Lozier & Mills 2011). Longtailed mealybug data (Fig. 7b) are good for the Murray River region in Victoria and South Australia, though lacking for western Victoria and south-eastern South Australia and could be used for correlative modelling. Citrophilus (Fig 7c) and obscure mealybug (Fig. 7d) data are too sparse for correlative models: these data could be used as a source of validation when sufficient life-history parameters become available in the literature to build CLIMEX models. For the scale insects: data for grapevine scale (Fig. 7e) are sparse but reflect a wide range of environments, with a few more points, say for Victoria, it would be possible to build some simple correlative models for grapevine scale. These data could also be used as validation for any CLIMEX models built. Frosted scale (Fig. 7f) data are also too sparse to build correlative models. Again, knowledge of life-history parameters from the literature or laboratory trials could be used later to build a CLIMEX model, and the distribution data could be used as a source of validation. Soft brown scale (Fig. 7g) data are suitable for building correlative models, however, the stray point in the middle of the Northern Territory needs to be examined for accuracy, but probably should be removed.

Distribution data for fig longicorn (Fig. 7h) is heavily biased towards the capital cities and does not provide much spread across different environments, providing too few points to

build useful models for this species. Data here for common auger beetle (Fig. 7i) could be used to build correlative models, but would benefit greatly from understanding where this species exists through Victoria especially. Data for vine weevil covers a large geographical area and could be used to build correlative models, although the data is heavily biased around capital cities in the eastern states (Fig. 7j) and this needs to be accounted for when building the models. Garden weevil data is suitable for correlative models, again the data (Fig. 7k) for western Victoria and South Australia is lacking, but otherwise displays good coverage, even if biased towards capital cities. With this distribution data it is possible to build correlative models for the garden weevil, however the data is heavily biased around capital cities and this will need to be taken into account when building the models. Elephant weevil data (Fig. 7l) could be used for correlative modelling.

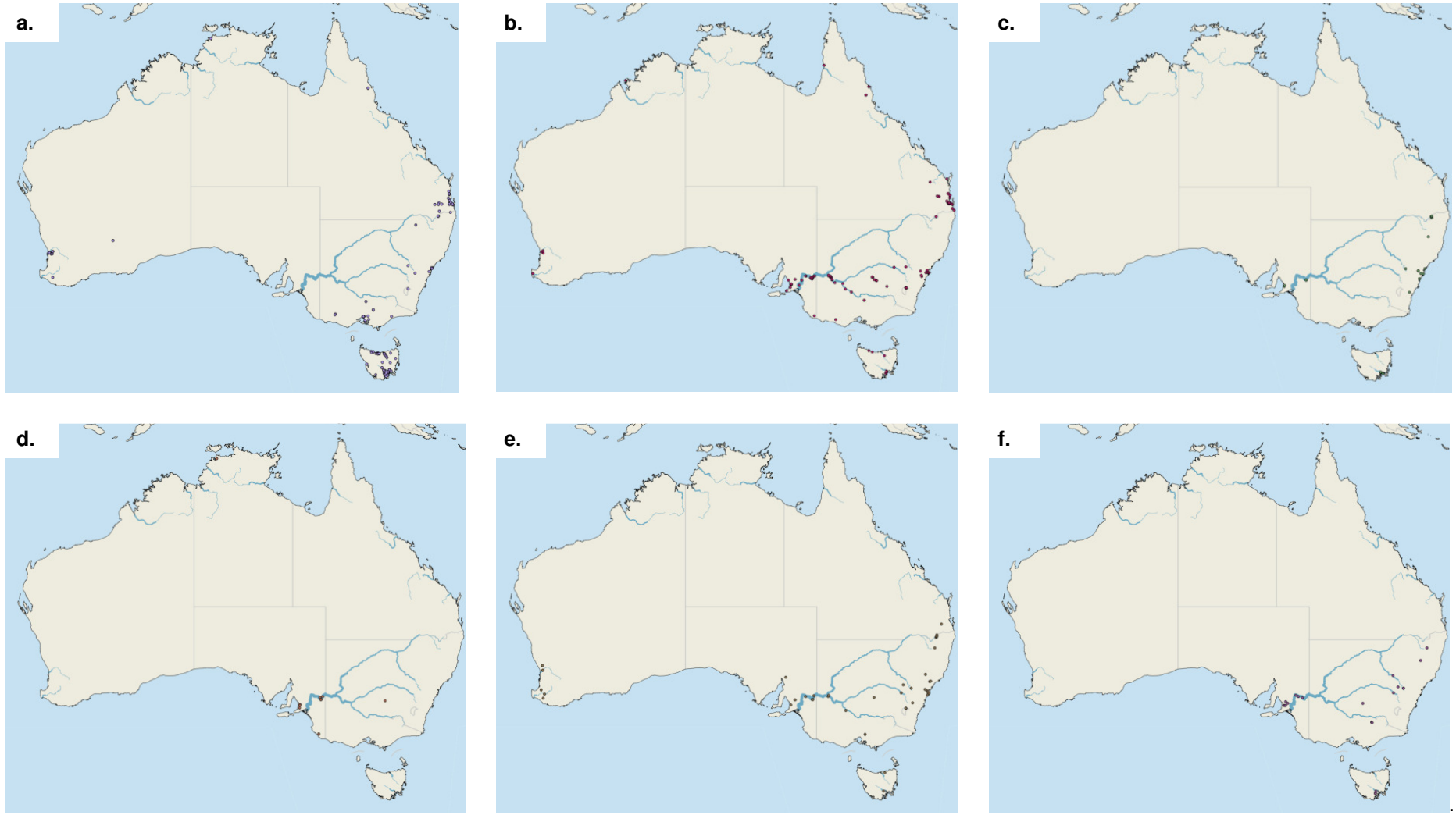


Figure 7 a-f. Current distributions common vineyard pests within Australia: **a.** Light brown apple moth; **b.** Longtailed mealybug; **c.** Citrophilus mealybug*;* **d.** Obscure mealybug; **e.** Grapevine scale; **f.** Frosted scale. Closed circles indicate distribution points from Australian Plant Pest Database, Atlas of Living Australia and Global Biodiversity Information Facility.

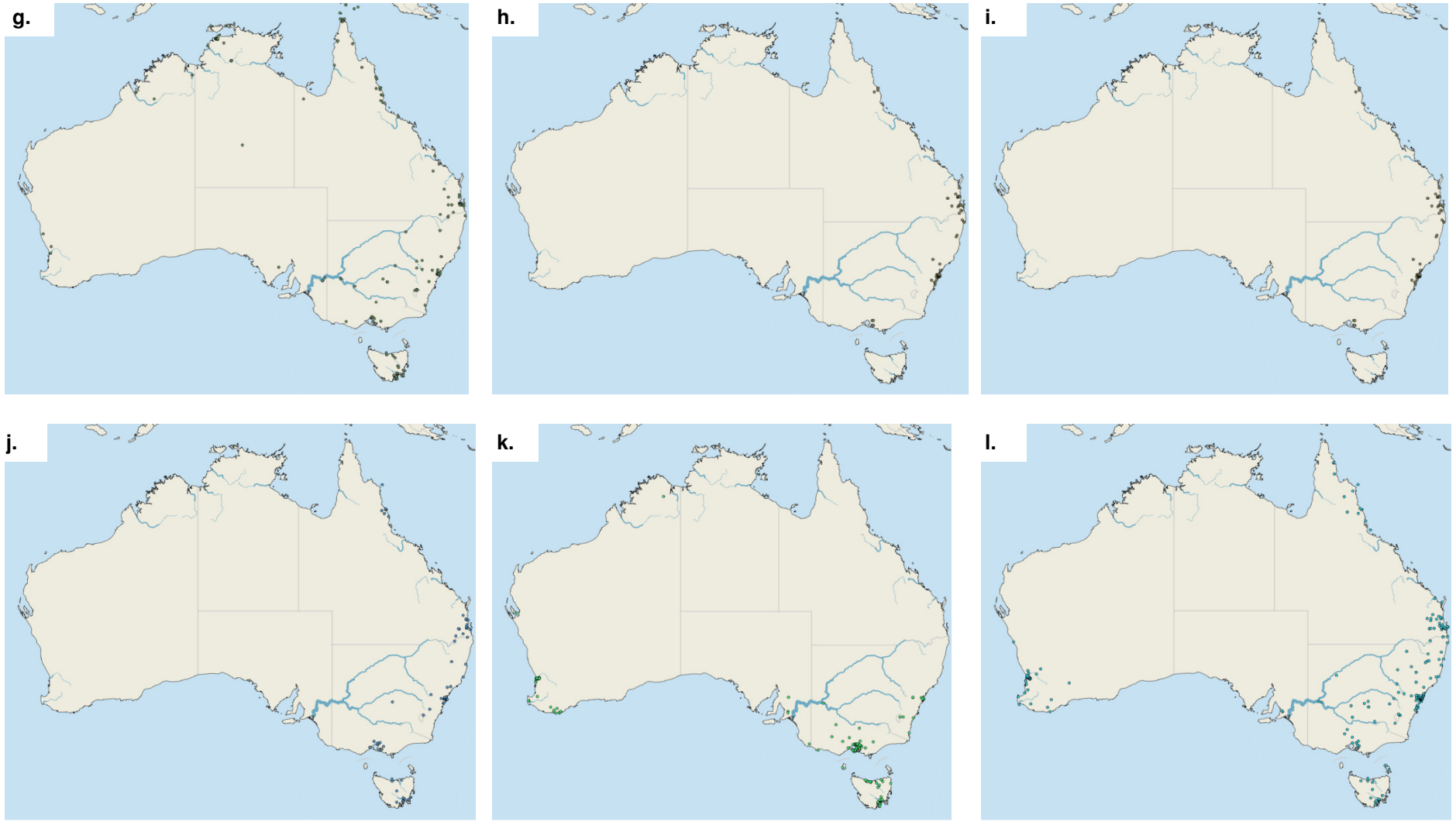


Figure 7 g-l. Current distributions of common vineyard pests within Australia: **g.** Soft brown scale, **h.** Fig longicorn; **i.** Common auger beetle; **j.** Vine weevil; **k.** Garden weevil; **l.** Elephant weevil. Closed circles indicate distribution points from Australian Plant Pest Database, Atlas of Living Australia and Global Biodiversity Information Facility.

Natural enemies. Brown lacewing data is underrepresented in Queensland, but the otherwise the good coverage in NSW, Victoria, South Australia, Tasmania and Western Australia (Fig. 8a) means that correlative models can be applied. There are a few papers looking at temperature and development of this species: in future, it might also be possible to build a CLIMEX model. *Diomus sydneyensis* (Fig. 8b) data is too limited for modelling using correlative methods. Distribution data for both *Diomus notescens* (Fig. 8c) and *Harmonia conformis* (Fig. 8d) cover a large geographic area and are both suited for correlative models. After a literature search it appears there is little to no information on *H. conformis* to build a CLIMEX model. Surprisingly again, distribution data for the well known 'mealybug destroyer' *Cryptolaemus montrouzieri* (Fig. 8e) is not suited for correlative models, but will be suited to validating CLIMEX.There will records for *Cryptolaemus montrouzieri* available in individual collections including state museums and ANIC. With appropriate funding, it would be possible to visit these locations and gather this information making possible correlative modelling. This is potentially true for other natural enemies and pests.

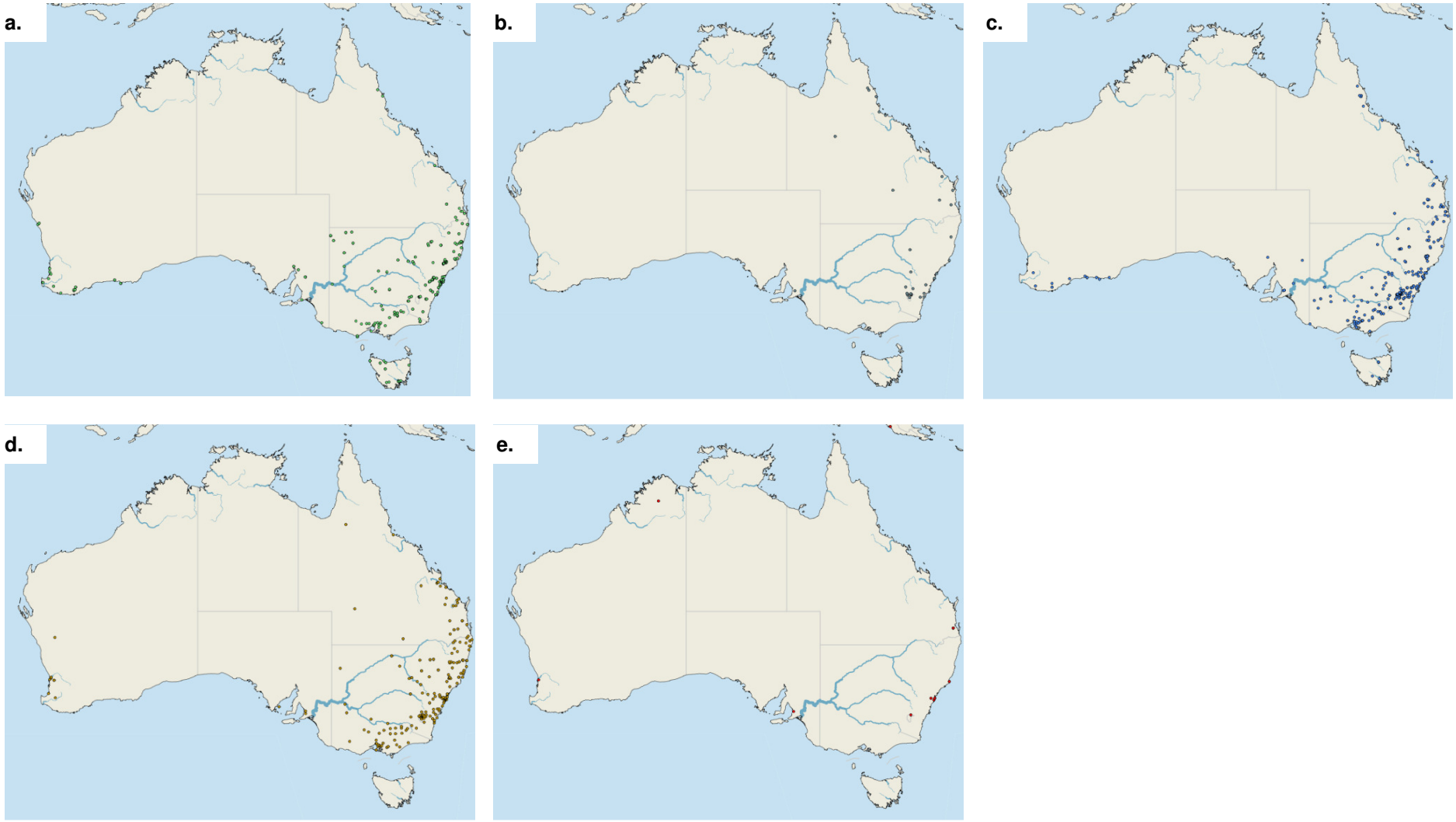


Figure 8. Current distributions common vineyard natural enemies within Australia: **a.** Brown lacewing *Micromus tasmaniae*; **b.** *Diomus sydneyensis*; **c.** Minute two-spotted ladybird *Diomus notescens;* **d.** Common spotted ladybird *Harmonia conformis;* **e.** *Cryptolaemus montrouzieri.*

For species with adequate data for modelling purposes (longtailed mealybug, soft brown scale, vine, garden and elephant weevils, and the natural enemies brown lacewings and minute two-spotted and common spotted ladybird beetles) we constructed correlative distribution models to look at species-environment relationships and how these may be affected by climate change.

Correlative models like MAXENT require the background, or geographical area to develop models, to reflect meaningful ecological processes and accessibility. To develop an appropriate area for modelling we took the distribution of all species in this study (excluding common auger found everywhere) and overlaid these across the different Koppen-Geiger climate classifications. These climate zones can be used to determine an appropriate background (accessible area) by characterizing broadly similar environments that species are known to occur in. Pest species of grape growing are likely to be transported in similar ways and thus we can assume they will have opportunity to reach all other areas that have other pest species. Likewise, natural enemies are likely to be either released or co-occur with the pest species and this means any species is likely to have had opportunity to access these areas. As the data is heavily biased, we can classify accessible regions in terms of a species locality falling in this climate zone. However, for regions where there are clear outliers (middle of Australia) we can exclude these. Additionally, many of the records were duplicated across databases so we reduced each dataset down to unique records only, by ensuring that each grid cell could only have one point.

The distributions of the species were overlaid (Fig.s 7a-l and 8 a-f) to identify the areas which all species could have accessed. For the pest species and natural enemies in this study, most of Australia should be used, except for the large area in the centre, and the appropriate background mask was used for all models (Fig. 9).

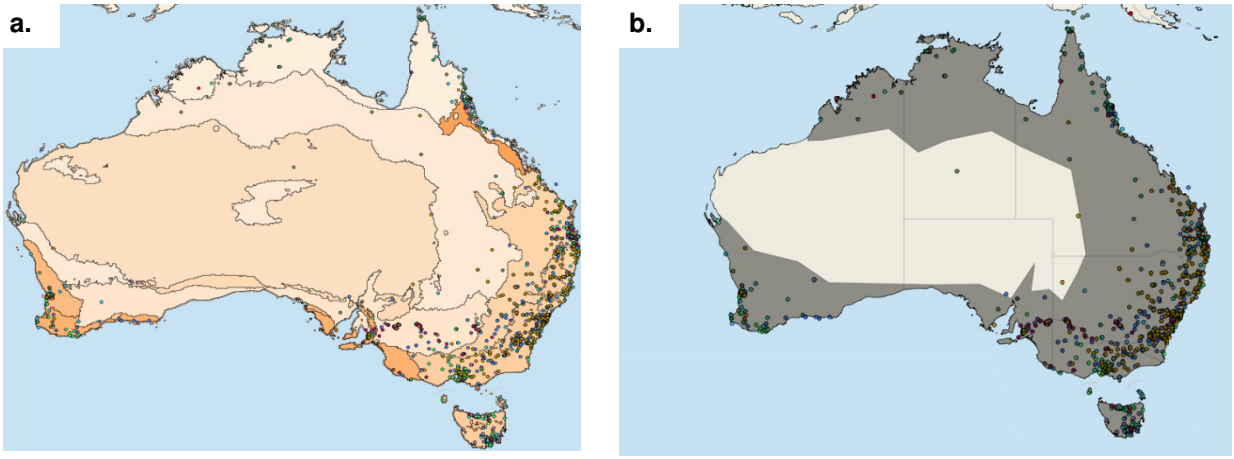


Figure 9. Selection of an appropriate background: **a**. Generalised climate zones with the distribution points of all species overlaid; **b.** Mask created from the generalised climate zones to limit the models to relevant geographical areas, that is, the areas which all species could have accessed through dispersal and human-mediated transport

Bioclimatic variables are derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. These are often used in ecological niche modelling (e.g., BIOCLIM, GARP). The bioclimatic variables represent annual trends (e.g., mean annual temperature, annual precipitation), seasonality (e.g., annual range in temperature and precipitation) and extreme or limiting environmental factors (e.g., temperature of the coldest and warmest month, and precipitation of the wet and dry quarters). A quarter is a period of three months (1/4 of the year). The BIOCLIM variables

used here were largely uncorrelated across the background defined based on distributions of pest species and climate zones (Fig. 10).

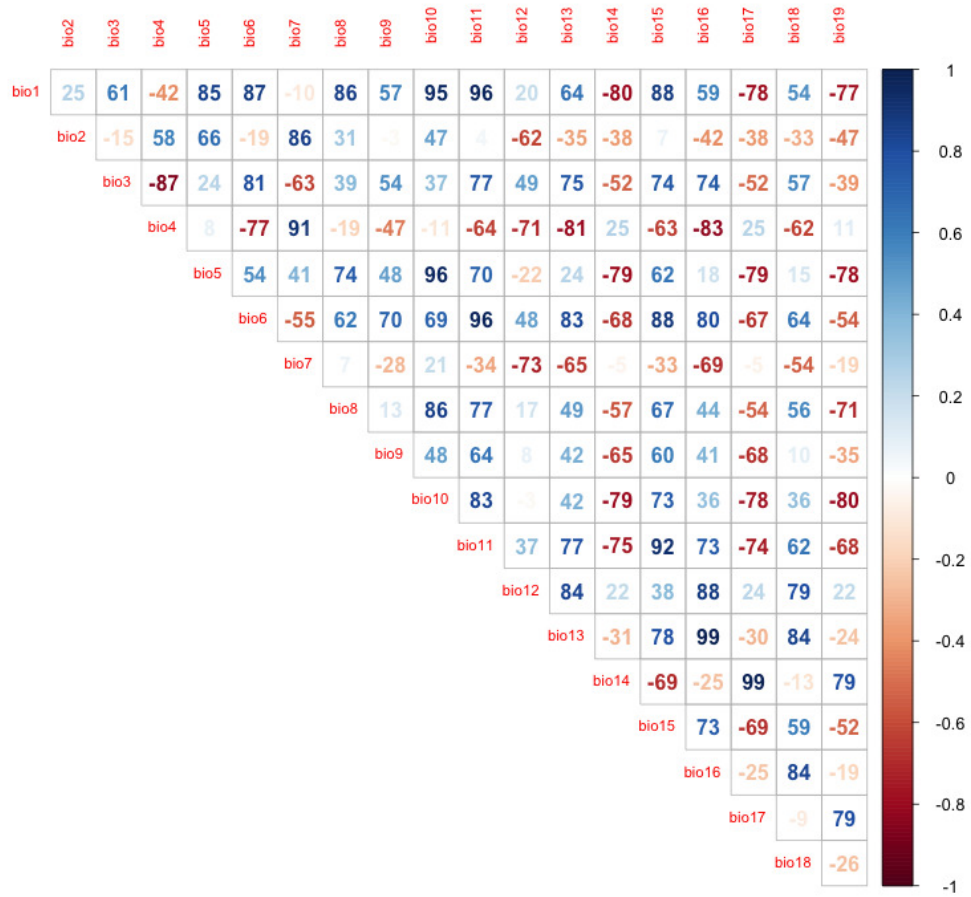


Figure 10. Correlation matrix for 19 temperature and precipitation variables across 20,000 random randomly selected points. Values above 70 (P = 0.70) were considered highly correlated during per species variable selection.

From the 19 BIOCLIM variables, using MAXENT we were able to determine three variables for each of five pests longtailed mealybug, soft brown scale, vine weevil, garden weevil, elephant weevil, and three beneficials brown lacewing and two ladybird beetles, minute two-spotted and common spotted that describe the different distributions within Australia (Table 5). Seven temperature variables “Mean Diurnal Range” (bio02), “Isothermality” (bio03) (bio02/bio07) (* 100), “Maximum Temperature of Warmest Period” (bio05),), “Temperature Annual Range” (bio05-bio06) (bio07), “Mean Temperature of Wettest Quarter” (bio08), “Mean Temperature of Driest Quarter” (bio09) and "Mean Temperature of Warmest Quarter” (bio10) and five precipitation variables “Annual Precipitation” (bio12), “Precipitation of Driest Period” (bio14), “Precipitation Seasonality (Coefficient of Variation)” (bio15) and “Precipitation of Driest Quarter” (bio17) and “Precipitation of Coldest Quarter” (bio19), were significant in at least one distribution.

For temperature variables, “Mean Diurnal Range” (bio02) influenced distribution of six of the eight species (pests longtailed mealybug, soft brown scale, vine and garden weevils and two natural enemies brown lacewing and common spotted ladybird beetle). “Maximum Temperature of Warmest Period” (bio05) influenced distribution of two pests, garden and elephant weevil, and “Mean Temperature of Wettest Quarter” (bio8), the two ladybird beetles (minute two-spotted and common spotted). "Mean Temperature of Warmest Quarter (bio10)" influenced longtailed mealybug and “Mean Temperature of Driest Quarter” (Bio09) minute

spotted ladybird beetle and “Temperature Annual Range” (bio07) vine weevil. In addition, “Isothermality” (bio03) influenced longtailed mealybug.

For precipitation variables, “Annual Precipitation” (bio12) influenced three species, vine and elephant weevils and brown lacewing, “Precipitation of Driest Period” (bio14) influenced brown soft scale and common spotted ladybird and “Precipitation of Coldest Quarter” (bio19) influenced a pest and a beneficial (garden weevil and brown lacewing). “Precipitation Seasonality” (bio15) influenced elephant weevil and “Precipitation of Driest Quarter” (bio17) influenced vine weevil.

The variables that were deemed important for each species distribution respectively could be used to direct future experiments to test different model predictions of response to climate change.

Table 5: Final eight species (five pests and 3 natural enemies) used for correlative (MAXENT) models and the variables used in each species-specific model.

	Temperature variable						Precipitation variables					
	Mean Diurnal Range	Isothermality	Max Temperature Warmest Period	Temperature Annual range	Mean Temperature Wettest Quarter	Mean Temperature Driest Quarter	Mean Temperature Warmest Quarter	Annual precipitation	Precipitation Driest Period	Precipitation Seasonality	Precipitation Driest Quarter	Precipitation Coldest Quarter
	bio02	**bio03**	**bio05**	**bio07**	**bio08**	**bio09**	**bio10**	**bio12**	**bio14**	**bio15**	**bio17**	**bio19**
Pests												
Longtailed mealybug *Pseudococcus longispinus*	X	X					X					
Soft brown scale *Coccus hesperidum*	X							X	X			
Vine weevil *Orthorhinus klugi*	X			X							X	
Garden weevil *Phlyctinus callosus*	X		X									X
Elephant weevil *Orthorhinus cylindrirostris*			X					X		X		
Natural enemies												
Brown lacewing *Micromus tasmaniae*	X							X				X
Minute two-spotted ladybird beetle *Diomus notescens*					X	X						
Common spotted ladybird beetle *Harmonia conformis*	X				X				X			

6.2.2 Future distributions

Light brown apple moth demonstrates the value of having adequate information for making predictions. When there is sufficient information for a species, accurate models can be built. It will be possible to build similar models for other species as more distribution records or life history trait data emerges.

The importance of light brown apple moth across a range of crops including grapes has resulted in accumulation of data informing on life history traits. To this end, light brown apple moth was used an example in development of CLIMEX 1.1 for Windows by CSIRO (Sutherst *et al.* 1999, 2000) and later in predicting the invasion potential of the moth to North America by Gutierrez *et al.* (2010) and Lozier & Mills (2011). Here we present outcomes from the Sutherst (1999, 2000) analyses and the recently published models for this species (Lozier & Mills 2011).

Parameters describing the optimal and limiting temperatures, degree-days per generation and other life history traits of light brown apple moth were taken from a series of papers by Danthanarayana (Danthanarayana 1975a, 1976 a, b, c, Danthanararayana 1983; Danthanarayana *et al.* 1995; Gu & Danthanarayana 1990 a, b, 1992). From these, the lower threshold for development of all stages was estimated as 7.5°C, giving a predicted generation time of 594 degree days (dd) with no eggs hatching above 31.3°C, an upper threshold for development for larvae and pupae of approximately 31.5°C. This is consistent with observations that the distribution of light brown apple moth in its native range of south-eastern Australia appearing to be strongly influenced by climate (Geier & Briese 1981) with strongly overlapping generations and all life stages and larval instars present throughout the warmer summer months (Danthanarayana 1975).

Optimal and limiting moisture conditions were estimated from a standard temperate template, and stress indices were based on interactive fitting of the model to the known distribution of light brown apple moth in Australia (Sutherst *et al.* 1999). From these requirements of light brown apple moth modelling an Ecoclimatic Index (EI) was calculated across south eastern Australia. The EI estimates the suitability of areas for light brown apple moth with the higher the value of EI, the more suitable a location is. An EI above 10 means the species could survive while above 30 is very favourable. CLIMEX modelling based on these parameters produced a map of areas of south-eastern Australia suitable for light brown apple moth to survive (Fig. 11). Modelling under proposed changes of climate (increased temperature 0.5°C, 1.0°C and 2.0°C) indicated decline in the area suitable for light brown apple moth (Fig. 12) and hence in its economic importance with proposed levels of temperature increase under climate change.

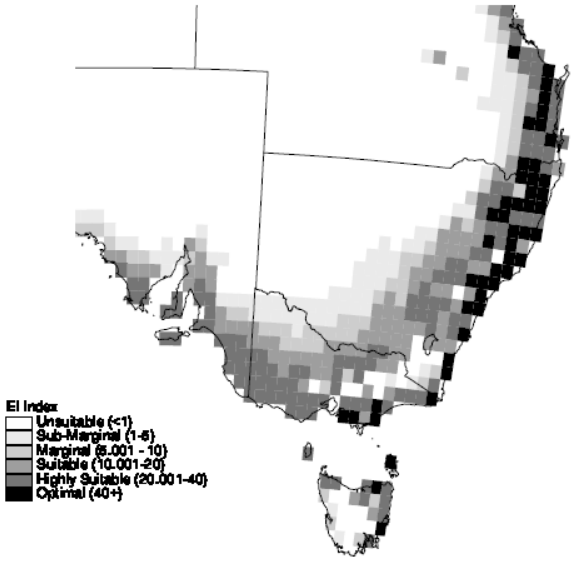


Figure 11. Geographical distribution of CLIMEX EI values for light brown apple moth in south eastern Australia. From Sutherst (2000).

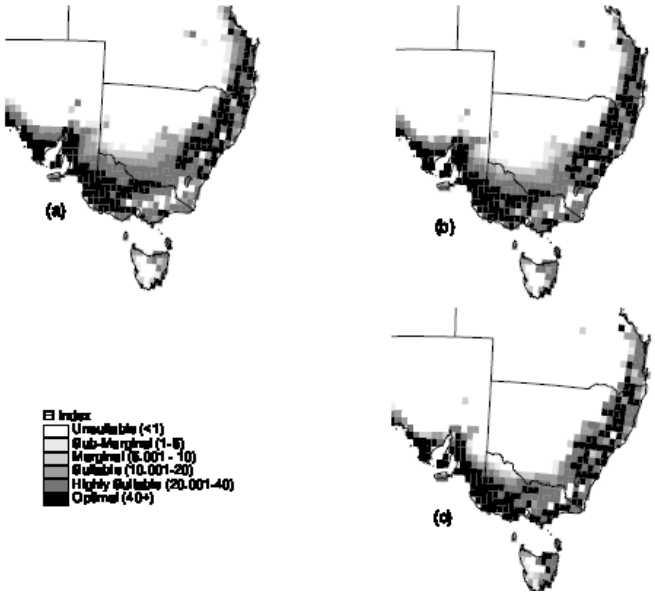


Figure. 12. CLIMEX values for light brown apple moth with temperature increases of **a.** 0.5℃; **b.**1.0℃; **c.** 2.0℃. From Sutherst (2000).

However, indications from laboratory testing (Whiting *et al.* 1991, Burgi & Mills 2012) suggest all life stages are able to survive periods of high temperature. Coupled with the likely existence of a range of life stages during times of thermal stress, it is possible that light brown apple moth could survive even quite extreme temperature events.

Mealybugs, scale, weevils and beneficials. MAXENT models of climate suitability were used to map present distributions of each of the listed species ("present" in Fig. 13 a-e and Fig. 14 a-c). MAXENT models of climate suitability for each of the species with sufficient

available distribution data were built on present (1950-2000 averaged) data and for the species-specific predictor variable sets (Table 5). The predicted range for each species of pest (Fig. 13 a-e) and beneficial (Fig. 14 a-c) is shown. For all the model outputs, we show the logistic output from MAXENT. Scales remain the same for each model and the different climate change projections (2030, 2050, 2070), but are not directly comparable between species. The models for longtailed mealybug (Fig. 13a) seem to be largely affected by missing data through Victoria. This has likely lead to an over-prediction of the models and shows the Great Australian Bight as holding suitable climate space for the longtailed mealybug. Overall there is a trend for suitable climate space to retreat south for this species (Fig. 13a). The models for soft brown scale are very relaxed, probably due to the distribution of points all over the eastern coast. Climate space changes very little for this species over the different time scales of projection, though climate generally becomes less suitable (Fig. 13b). Although the data was heavily biased around capital cities in the eastern states for the vine weevil, these models show that the distribution is largely confined to the east coast of Australia and is not likely to change much under climate change projections (Fig. 13c). The models for the garden weevil currently show suitable climate space along the east coast of Australia and in the south-western corner of Western Australia. Under climate change, suitable climate space fragments more and retreats south. The climate space for the elephant weevil retracts southward under these climate change projections, particularly within Western Australia. On the eastern side of Australia, the climate space retracts towards the coast (Fig. 13e).These models all require further analysis to assess their performance and validity before translating into meaningful management recommendations.

Figure 13. MAXENT model output of habitat suitability in Australia. Shading represents suitability of area in terms of climate space. Models built on present (1950-2000 averaged) data and for three predictor variables (Table 5). Future climate change projections for vineyard pests in Australia for 2030, 2050 and 2070 under A1FI SRES. Each projection uses the same set of variables as the present-day distribution models. **a.** Longtailed mealybug; **b**. Soft brown scale; **c**. Vine weevil; **d**. Garden weevil; **e**. Elephant weevil. Shading represents suitability of area in terms of climate space.

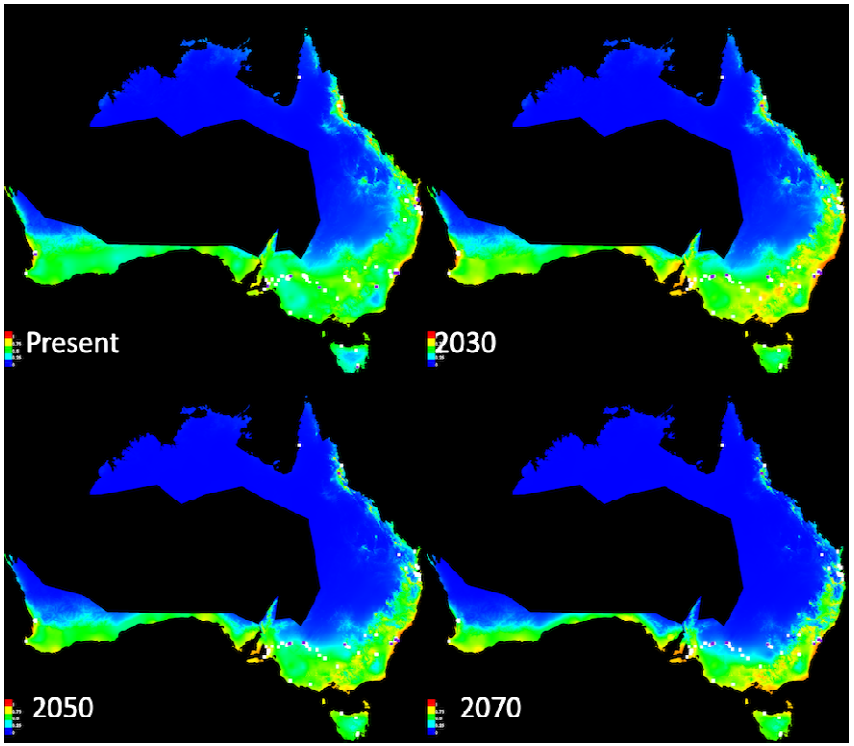


Fig. 13a. Longtailed mealybug - *Pseudococcus longispinus*

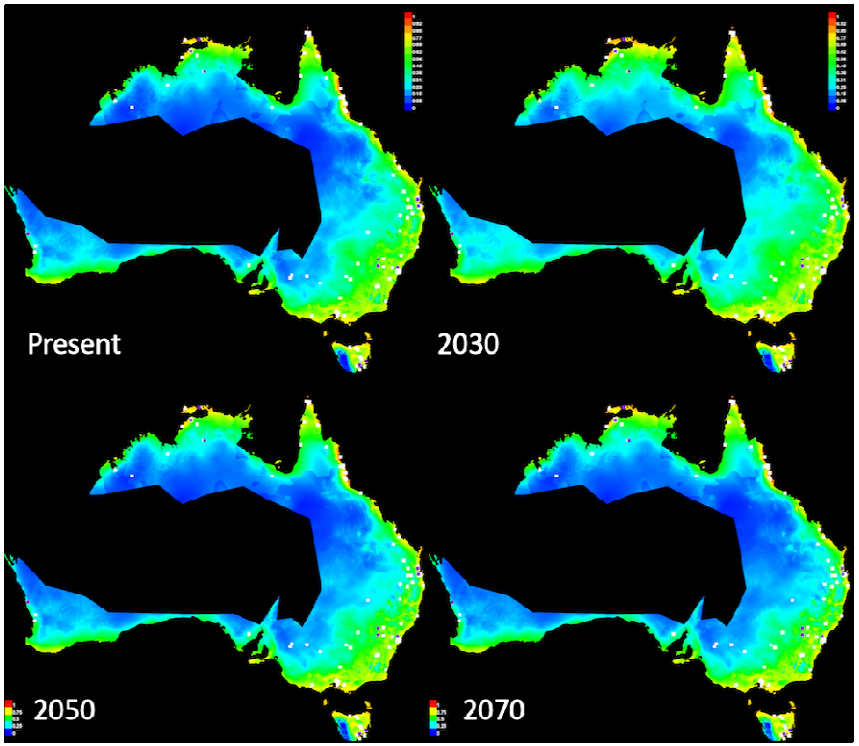


Fig. 13b. Soft brown scale *Coccus hesperidum*

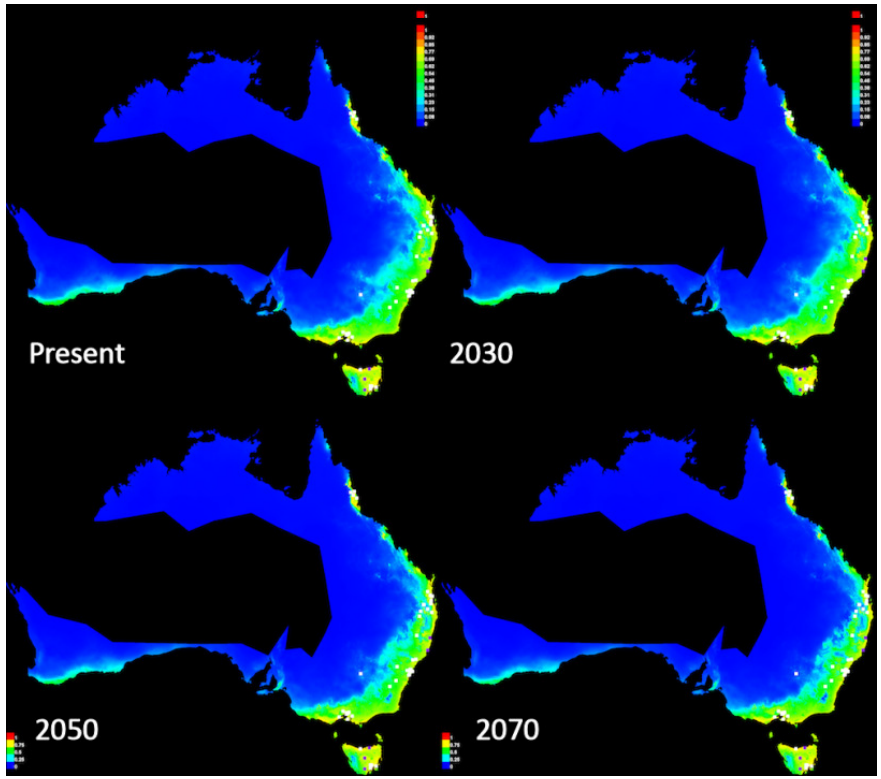


Fig. 13c. Vine weevil *Orthorhinus klugi*

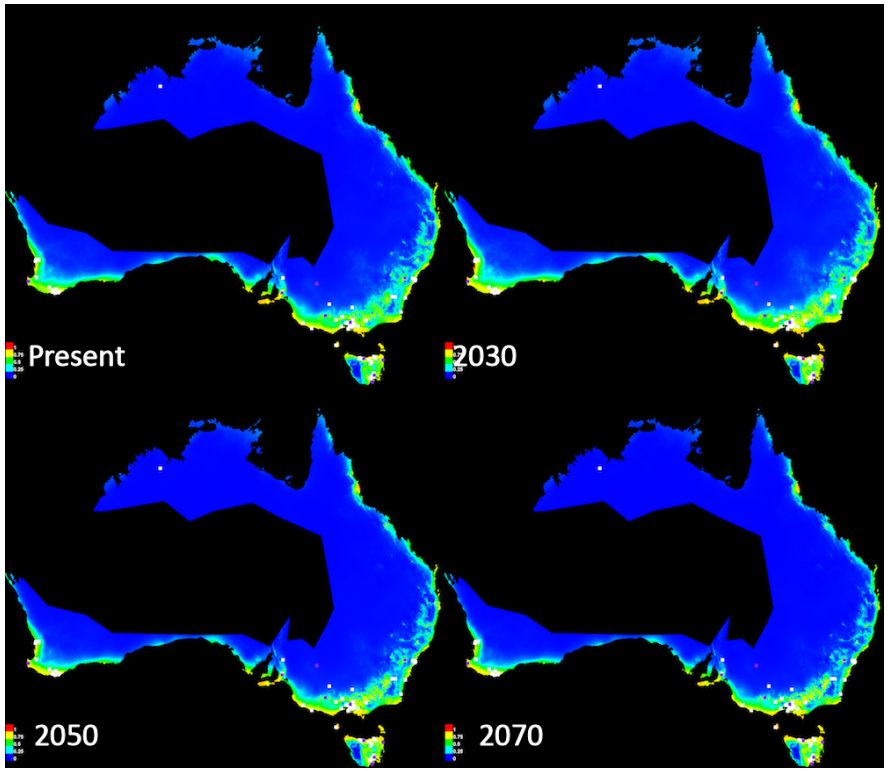


Fig.13d. Garden weevil *Phlyctinus callosus*

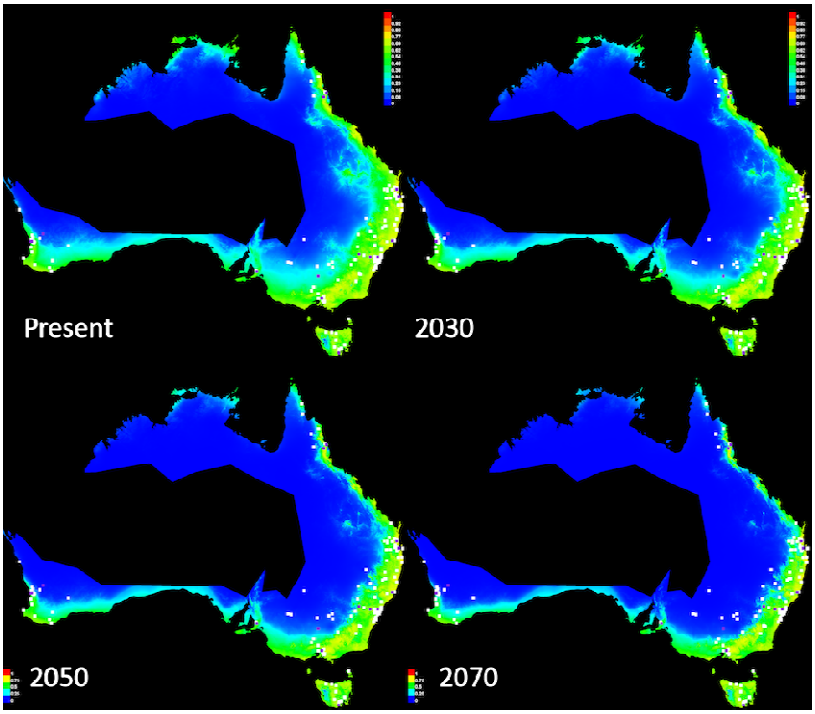


Fig. 13e. Elephant weevil , *Orthorhinus cylindrirostris*

Future distributions of natural enemies under climate change. The climate space for the brown lacewing *Micromus tasmaniae* remains largely the same in shape across these climate projections, though does retract south (Fig. 14a). The climate space for the minute two-spotted ladybird fragments and retracts to the south across these climate change projections (Fig. 14b) and the climate space for the common spotted ladybird retracts in the eastern states towards the coast, including noticeable fragmentation for the 2050 and 2070 projections (Fig. 14c).

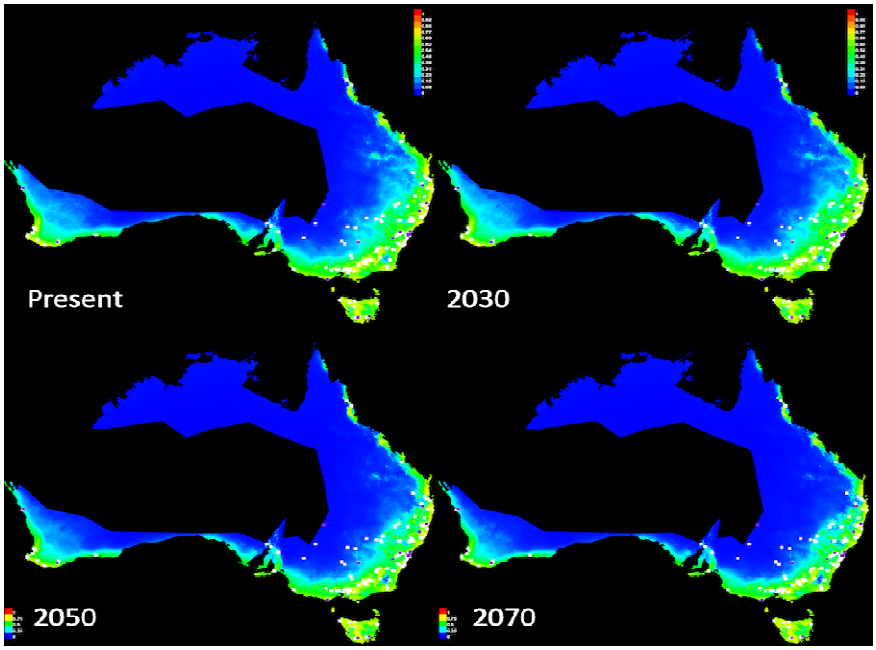


Fig. 14a. Brown lacewing *Micromus tasmaniae*

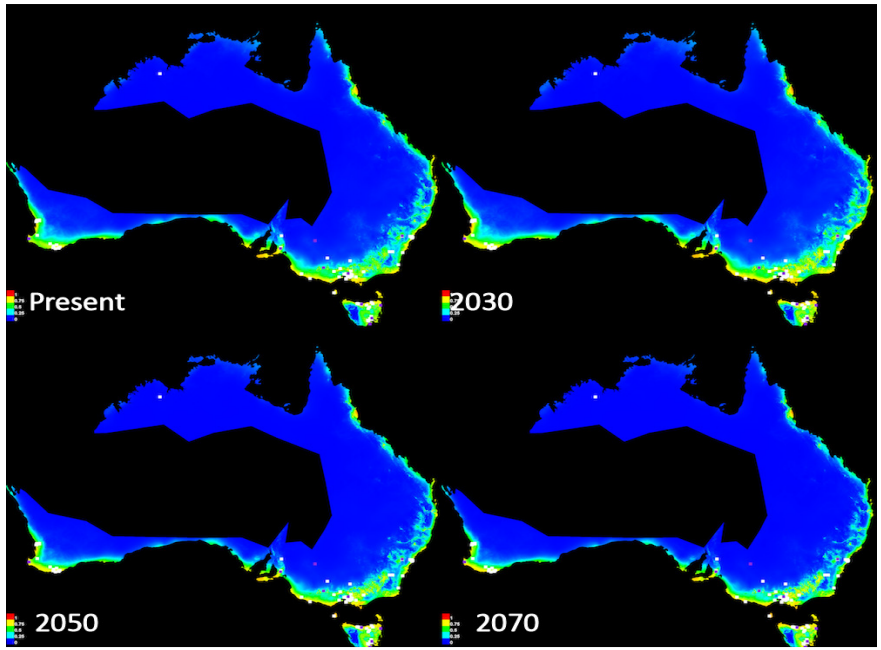


Fig. 14b. Minute two-spotted ladybird *Diomus notescens*

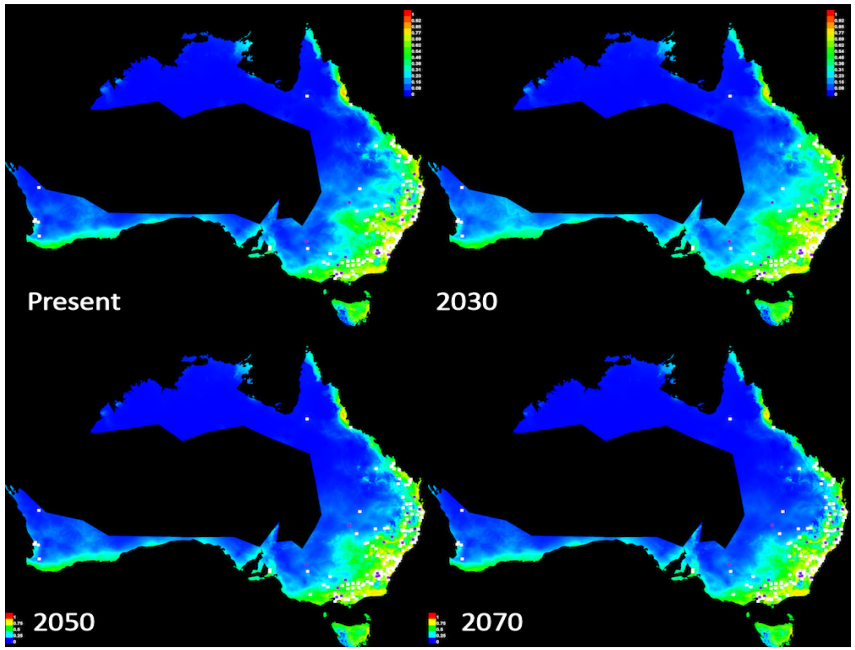


Fig. 14c. Common spotted ladybird *Harmonia conformis*

Figure 14. MAXENT model output of habitat suitability in Australia: **a.** Brown lacewing *Micromus tasmaniae;* **b**. Minute two-spotted ladybird *Diomus notescens;* **c**. Common spotted ladybird *Harmonia conformis.* Shading represents suitability of area in terms of climate space. Model built on present (1950-2000 averaged) data and for three predictor variables (Table 5). Future climate change projections for vineyard natural enemies in Australia for 2030, 2050 and 2070 under A1FI SRES. Each projection uses the same set of variables as the present-day distribution models

Climate is a major driver of invertebrate species distributions and climate change is expected to shift pest assemblages and pest prevalence across Australia. Current climate projections suggest warmer and drier conditions throughout southern agricultural regions of Australia, with trends already showing rising temperatures and reduced precipitation (Australian Bureau of Meteorology & CSIRO 2010). Climate change operating over a global scale greatly influences life history traits (Jaramillo *et al.* 2009), pest phenology (Harrington *et al.* 2007; Parmesan 2007) and species distributions (i.e. range shifts) (Karban & Strauss 2004; Hoffmann *et al*. 2008) through changing temperature and precipitation regimes. Though distributions are ultimately driven by a range of abiotic and biotic factors, climate (particularly temperature) is one of the major drivers shaping distribution patterns in most invertebrate species (Bale *et al.* 2002). Here, climate has been shown to broadly influence distributions of longtailed mealybug, soft brown scale, vine weevil; garden weevil; elephant weevil and natural enemies brown lacewing and two species of ladybird beetle. Although a full understanding of factors such as physiological mechanisms and land-use is required to predict seasonality and fine-scale distributions, predictions of broad climatic patterns that influence species distributions can be made by combining well sampled distributions with long-term averaged climate data (Hijmans & Graham 2006; Arthur *et al.* 2010). These models do not capture all ecological relationships for the species which means that they only provide a guide of how suitable climate space may change under this A1FI scenario.

There are issues with non-analogue climates and sampling bias that will confound these results to some extent. What the models may show is where the core of the distribution is likely to change. Microclimates and refuges and biotic interactions are likely to ultimately determine the distribution of these species. For more accurate assessments of climate change, these models should be used to direct future research efforts, targeting individual species for modelling.

6.3 Thermal limits

6.3.1 Thermal limits of mealybugs

In preliminary testing of high temperature stress, citrophilus mealybugs reared at 25°C showed no mortality following immersion for 2 hours at temperatures 30°C, 35°C and 40°C (data not presented) so the lowest experimental temperature tested was 42.5°C. There was little difference in survival assessed both at 2 hours and 24 hours after immersion, so only the 2 hour survival data is reported here. Mealybug survival was fairly consistent across a range of populations, rearing temperatures and species (Fig. 15).There was an upper limit of 45°C for three populations of citrophilus mealybugs: insectary populations (Bugs for Bugs) reared at 22°C and 25°C and a field collected population reared at 25°C (Fig. 15a). All three populations show the same response to increasing temperature, though the field-collected population is possibly more resistant. More testing is required. The upper limit was similar for populations of longtailed mealybugs across a wide geographic range (Fig. 15b), though again this represents single populations and greater diversity of populations tested would be useful. These data suggest adult mealybugs in vineyards may be quite tolerant of heat stress events.

Similarly, citrophilus mealybugs whether reared at 22°C or 25°C, were able to tolerate extremes of low temperature, with over 20% surviving -6°C for 2 hours (Fig. 15c).

These findings point to a greater tolerance to temperature extremes demonstrated in laboratory testing than indicated by temperatures extracted from climate matching to distribution points. It would therefore be interesting to look at activity in the field and changes in phenology under changing temperatures. Climate space is shifting but observed thermal tolerances like those assessed here are well beyond broad-scale climate averages. Our modelling indicated the important variables contributing to mealybug distributions were temperature related (Table 5) hence indicting mealybug distributions moving south, but these data should be regarded as preliminary. A lack of high temperature tolerance is also

suggested by our experience in laboratory rearing. We planned to test the tolerance of mealybugs reared at higher temperature (30℃) but were unable to rear any population at this temperature-consistent with upper limit suggested by Gutteriez *et al.* (2008). More research is needed to resolve the likely impacts of changes in both temperature and humidity on mealybug distributions.

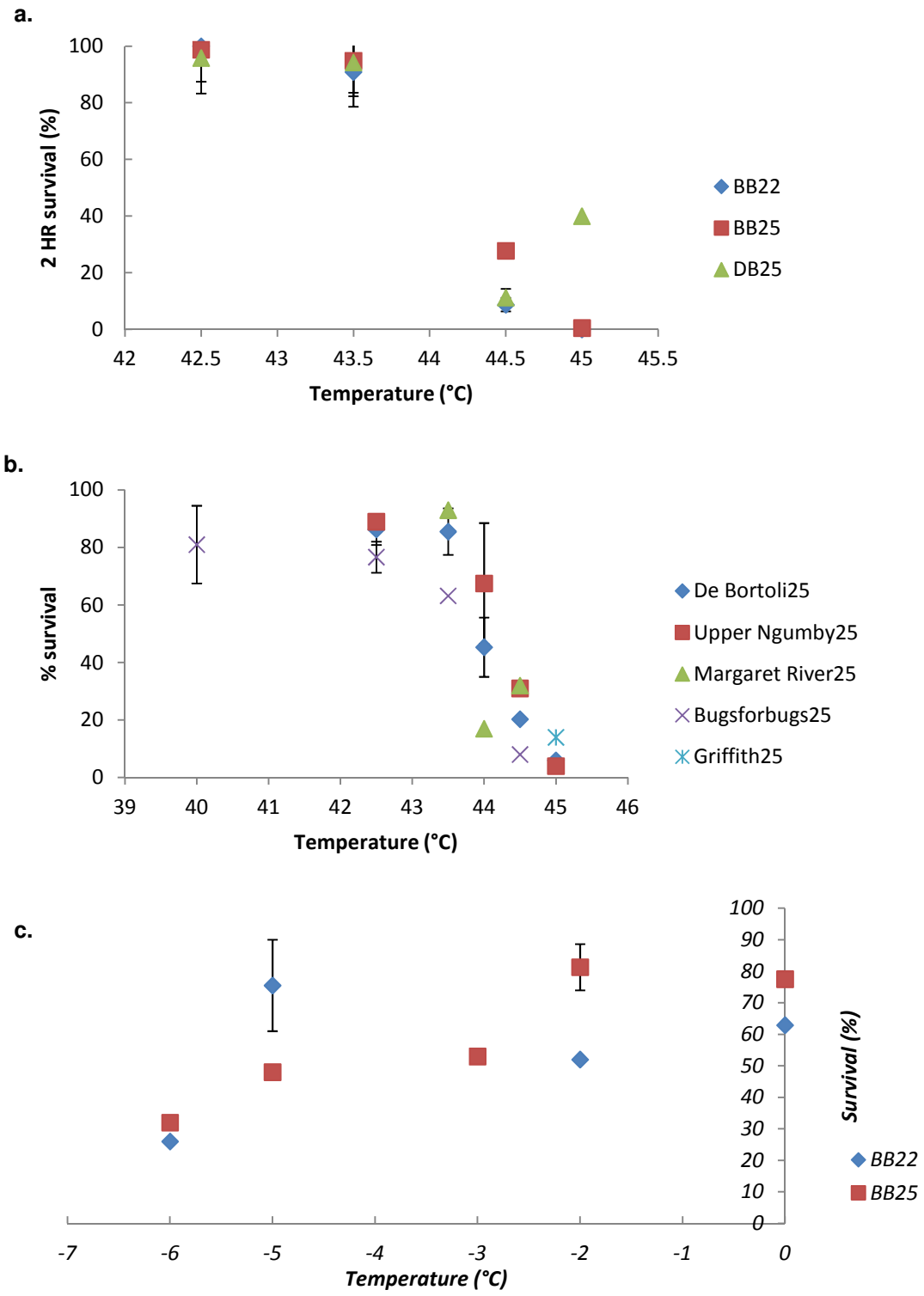


Figure 15. Survival of mealybugs following high and low thermal stress: **a.** Survival of citrophilus mealybugs Bugs for Bugs (BB) reared at 22℃ (BB22) and 25℃ (BB25) and field collected (DB25) following high temperature immersion for 2 hours; **b.** Survival of populations of longtailed mealybugs collected from vineyards in Victoria (De Bortoli and Upper Ngumby), New South Wales (Griffith) and Western Australia (Margaret River) and citrophilus mealybugs from Bugs for Bugs reared at 25℃ following 2 hour high temperature immersion; **c.** Citrophilus mealybugs Bugs for Bugs (BB) reared at 22℃ (BB22) and 25℃ (BB25) following low temperature immersion for 2 hours. For upper limits, temperature was increased at 0.5℃/min from the rearing temperature to 35℃ and then from 35℃ to selected maximum temperature (40.0, 42.5, 43.0, 43.5, 44.0, 44.5 and 45.0℃) at 0.1℃/min. For the lower temperature limit, temperature was decreased at 0.5℃/min from rearing temperature to 10℃ and then further lowered from 10℃ to -2.0, -3.0, -4.0, -5.0 and -6.0℃ at 0.1℃/min.

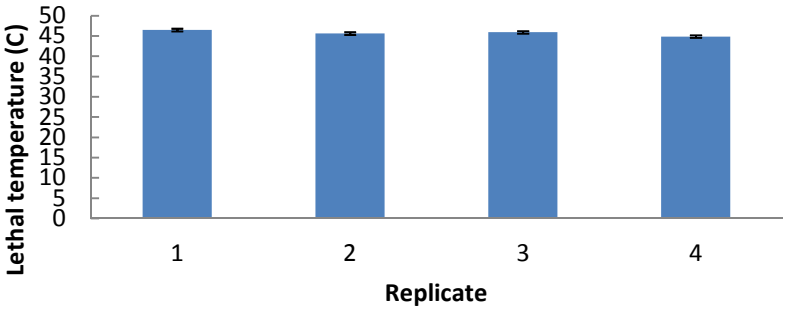
6.3.2 Thermal limits of ladybird beetles

Cryptolaemus montrouzieri is an Australian native, which has been successfully exported all over the world and is known to attack grape and vine mealybugs in addition to our current resident mealybugs. Like the mealybugs, *Cryptolaemus montrouzieri* reared at 25℃ also displayed a wide thermal tolerance range (Fig. 16). Maximum and minimum temperatures were consistent when the two methods (arena and immersion) were compared. The upper thermal limit estimated as temperature of last movement in the arena and survival of 2 hours immersion was consistent at about 43.5℃ (Fig.s 16 a and b). There was no significant difference in 2 hour and 24 hour survival (Fig 16b). In the arena, beetles were unable to walk from about 10℃, and the lower limit of movement was -4℃ (Fig. 16c). The lower limit to survival of low temperature stress was similar, at -4℃ (Fig. 16d).

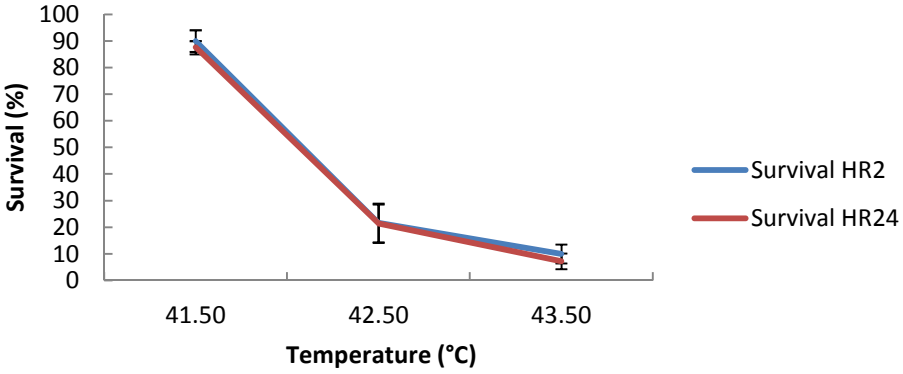
These results again indicate greater thermal tolerance than currently reported. *Cryptolaemus montrouzieri*, as its common name 'mealybug destroyer' suggests, is an important control agent of mealybugs and as such has been exported to many countries around the world with mixed success in providing control to the target mealybug. It has been suggested that this is due in part to lack of low temperature tolerance, which we did not find here. Gutierrez *et al.* (2008) suggest limits to survival and reproduction of *Cryptolaemus montrouzieri* at14.5℃ and 38.5℃ and vine mealybug at 12.5° and 34.0℃. The Gutierrez *et al.* (2008) models suggest increases in both range and density of this beetle with temperature increase (2℃ and 4℃) across California.

Due to lack of current distribution records, it was not possible to determine climatic variables influencing the distribution of citrophilus mealybug and *Cryptolaemus montrouzieri*. However, results for related species we were able to model (longtailed mealybug and the ladybird beetles *Diomus notescens* and *Harmonia conformis*) suggest that temperature is important in determining distributions of both mealybugs and ladybird beetles (Table 5). The relationship between temperatures that allow completion of all life stages, reproduction and responses to thermal extremes is not well understood (Terblanche *et al.* 2011). For individual species of interest, these relationships will require further investigation.

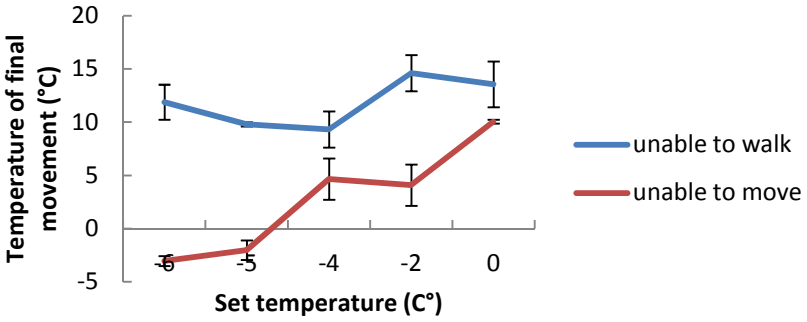
a.



b.



c.



d.

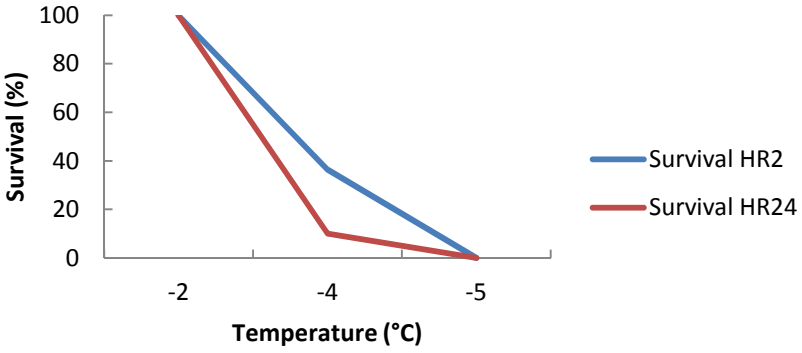


Figure 16. Critical thermal responses of insectary reared *Cryptolaemus montrouzieri* (reared at 25℃). (a) and (b): Critical thermal maxima temperature assessed in arena (a) and immersion (b): **a.** Temperature of last movement in arena (temperature increased 0.5℃/min 25℃ - 35℃, 35℃ to selected maximum temperature (40.0, 42.5, 43.0, 43.5, 44.0, 44.5 and 45.0℃) at 0.1℃/min; **b.** survival 2 and 24 hours following immersion for 2 hours at high temperature. (c) and (d): Critical thermal minima **c.** in the arena (temperature decreased 0.5℃/min 25℃-10℃,10℃ to -2.0, -3.0, -4.0, -5.0 and -6.0℃ at 0.1℃/min); **d.** following 2 hours immersion at low temperature.

7. *Outcome/Conclusion:*

The aim of the project was to inform the industry of likely change in pest impact both through changes in distribution or changes in crop due to anticipated precipitation and temperature decrease and increase respectively under commonly used climate change scenarios. Recognising the important contribution of natural enemies to pest control, impacts of changes in distribution and effectiveness of natural enemies were also considered. We were able to map current and future distributions of five pests and three natural enemies, though these predictions must be treated as preliminary and indicative of future research direction rather than definitive. Indications from modelling are that the range of both the pests and natural enemies considered here will reduce slightly under climate change scenarios selected. Useful information on current and future distributions requires more intense effort in collecting pest and natural enemy occurrence data. Impacts on pests cannot be considered in isolation: it is likely there will be changes in phenology of both pests and vines, these having potential to change pest impacts and natural enemy impacts on the pests.

7.1 Performance against planned outputs and performance targets

Planned output/performance target: '*Review of available literature on potential changes in vines in response to CO_2 and temperature and potential impact on pests':* Increase in carbon dioxide and temperature has potential to impact on vines both directly and through pest mediated impacts. An increase in both CO_2 and temperature has potential to be beneficial, with temperature increase resulting in reduced frost days and faster development and increased CO_2 resulting in increased growth, but conversely also negative with changes in grape characteristics. Awareness of responses of different varieties and cultivars to these changes can be used to inform growers of appropriate choice in potentially changed conditions and several reviews of these impacts have been undertaken. These studies indicate that the challenges facing the wine industry include more rapid phenological development, changes in suitable locations for some varieties, a reduction in the optimum harvest window for high quality wines, and greater management of already scarce water resources. Industry responses/changes in management practices to elevated CO_2, temperature and water availability include selection of appropriate varieties, canopy management and water use.

Changes in vine phenology will also interact with changes in pest (and natural enemy) phenology with the outcome depending on the relative changes of all three factors. There may be earlier emergence of single generation pests like trunk borers, faster generation time and increased number of generations in a year for multivoltine pests like light brown apple moth, and changes in relative vine stage and pest presence. Hence impacts of pest incidence will be related to changes in vine phenology, that is, the timing of events in the grape growing cycle and change in pest phenology in relation to this. Changes in life cycles of natural enemies of vineyard pests, coupled with potential changes in distribution, will also contribute to potential changes in the contribution of natural enemies to pest control

Water stress may be especially important in impacts of some pests, which may exert greater impacts on stressed vines. Hence it is important to consider pest response to water stress in vines in addition to vine responses.

Other pest issues may be linked to climate change: there are suggestions of increased occurrence of mealybugs and increased incidence of grapevine leafroll viruses. A greater incidence of invasive species has also be noted and there are several vine pests of invasive concern.

Planned output/performance target *'Access current distribution points for vineyard pests (light brown apple moth, mealybugs, scale, weevils, trunk insects and mites) and beneficials*

(brown lacewings, ladybird beetles and selected parasitoids) and use this to model current and distributions and potential changes in pest and beneficial distributions with climate change'. Varying responses to climate change will shift pest assemblages within agricultural systems, impacting the pest status and the occurrence of outbreaks of different species. Species distribution modelling in the form of ecological niche models allowed for distribution patterns to be correlated with broad predictor variables such as climate. Ecological Niche Models can be projected into future climate change scenarios to examine how climate space may change, ultimately identifying areas that will be suitable for population growth. In terms of management, this process can assist in targeting surveys of pests and in preparing growers for emerging problems. However, there are issues with non-analogue climates and sampling bias that confound results to some extent. What the models may show is where the core of the distribution is likely to change. Microclimates and refuges and biotic interactions are likely to ultimately determine the distribution of these species. For more accurate assessments of climate change, these models should be used to direct future research efforts, targeting individual species for modelling.

Accuracy of future predictions is strongly reliant on accurate records. Modelling relies on interpreting the suitable range of climate conditions from the current distribution, inadequacy of this information makes it difficult to make accurate predictions. The lack of comprehensive distribution information for almost all vineyard pests placed severe limits on the accuracy of our predictions, with availability of current distribution points for vineyard pests and beneficials less comprehensive than expected. Availability of distribution data produced some surprises; data for the important insect pest light brown apple moth was lacking, data for the most common scale (grapevine scale) was inadequate but sufficient for soft brown scale. Occurrence records reduced potential for mapping or modelling selected pests and natural enemies; adequate data was available for five of the 12 pests initially named. Improvement in records will come about over time as more records held in collections are added to the databases accessed here but also (and perhaps more quickly) by recognition by the industry of the importance of accurate pest records. While this is happening at the government level (e.g. APDD and ALA databases), addition of data from the many storage places where such data is held is slow. At this time, several vineyard pests are both recognized and recorded with insufficient accuracy, most noticeably 'mealybugs', and 'scale'. This emphasises the importance to the industry of providing recognition tools and developing a recording system for accurate pest records.

For the species with adequate current distribution data available, prediction maps were prepared. From current distributions we built ecological niche models for each species using the correlative modelling program, MAXENT and determined predictor variables useful for describing the climate space of each species. The models were projected into a range of future climate change scenarios to assess how climate change may alter species-specific distribution patterns in Australia. A common outcome from these models indicates increasing range fragmentation and to some degree range contraction to the south for both pests and natural enemies. It is important to view model outcomes in ecological framework considering phenological and field activity changes. Outputs reported here should form the basis for targeted future work.

Planned output/performance target '*Determine response to thermal stress of two pests, mealybugs and light brown apple moth and the beneficial the ladybird beetle Cryptolaemus montrouzieri*. The extent to which herbivores can track crops and natural enemies can track changes in herbivore hosts will depend on relative resistance to thermal extremes as well as their movement rates. We determined lethal constraints to survival under predicted temperature changes or establishment in a new area. Laboratory studies can be used to determine temperature thresholds above or below which a species becomes incapable of development or activity. We determined upper and lower limits to activity for species of mealybugs and a potential predator, the ladybird beetle, *Cryptolaemus montrouzieri*. Two

methods were used in the laboratory to determine acute thermal tolerance of the ladybird beetle and only one of these was useful for the mealybugs. Outcomes showed that both the mealybug and the ladybird beetle were tolerant of extreme temperatures and responses were similar. Mealybugs collected from different regions and mealybugs reared at different temperatures showed similar responses. These findings suggest that thermal extremes are unlikely to limit distribution changes. However more research is needed on the relationship between tolerance of thermal extremes and ability to survive and reproduce when such conditions are experienced. For the pests and natural enemy examined here, there appears to be inconsistent responses.

Specific performance targets pertaining to publication/communication of results were achieved with 8 peer reviewed and 4 industry (*Australian Viticulture* and *Australian & New Zealand Grapegrower & Winemaker*) publications (See Appendix 1) in addition to presentation at 21 conferences/field days/workshops.

7.2 Practical implications of the research

Climate change research indicates responses of the crop, the pests and natural enemies which contribute to their control all have potential to be affected and all three strands must be considered in predicting likely pest impacts on grape production under a climate changed future. Ongoing research should ensure access to adequate monitoring of local and international achievements in diverse areas: predictive computer modelling, developments in laboratory testing of thermal responses of insects; and what these responses mean in relation to predictive modelling. This research emphasises the importance to the industry of providing recognition tools and developing a recording system for accurate pest records.

Further, while pest control is an immediate problem, there are also future issues such as invasions of new pests to an area, whether introduced despite quarantine (such as vine mealybug or glassy winged sharp shooter), or whether from changes in distribution with climate change. Encouraging high levels of a diverse and abundant suite of natural enemies continues to be important in protection against new pest species, occurring either by range expansion or invasion. Provision of resources to support natural enemies remains important.

7.3 Economic and environmental benefits to the industry

Pest control has both economic and environmental costs to the industry and there is likely to be savings in both with understanding of likely pest impacts. The aim of the project was to provide information to the industry about potential effects of climate change on pests-acknowledging importance of natural enemies to pest control, several natural enemies were included here. Modelling indicates both pests and natural enemies examined here are influenced by temperature and precipitation, both of which are predicted to change under climate change: temperature is expected to increase and precipitation decrease over much of south eastern Australia.

Industry recognises the value of its sustainable approach to grape growing. Preparedness for changes in pest occurrence will improve ability to provide environmentally sustainable pest control, with benefit to industry and the broader community.

8: Recommendations:

The effects of climate change on natural enemies that are mediated by CO_2, temperature and moisture effects on plants can be complex. It is important that the industry maximizes access to research output from the grape industry and other industries both in Australia and internationally. Accurate collection of pest occurrence and outbreak records is clearly needed to strengthen industry position in predicting future change. This also points to the

need for recognition of the importance of accurate identification of pests. Identification requires readily available tools for growers but also acknowledgement that some pests are problematic. For such pests, where identification is difficult, as in the case of mealybugs, setting up a facility for molecular identification which is readily available to growers becomes important. Furthermore, recognition by the industry that potential of invasive species has increased under climate change also emphasises the importance of accurate identification.

Priorities for further R&D and extension include putting in place a system of data collection of pest occurrences, provision of accurate identification tools for pests where this is possible and provision of a procedure for molecular identification when this is not.

Further, as understanding of climate change impacts on pests increases, provision of resources to enhance natural enemy abundance and diversity remains important. Natural enemies continue to provide some degree of protection from pests whether within current distributions or with expansion to new areas.

Appendix 1: Communication:

Outcomes of this project have been communicated via 12 publications with several others in preparation. Available publications comprise 8 peer reviewed and 4 industry publications. Further communication has taken place by oral presentations at international and Australian meetings, including four invited presentations at international conferences, 2 at wine industry conferences and 14 industry presentations ranging from conference presentations to presentations to grower groups.

Further communication activities would enhance the uptake of this Project's findings:
Provision of resources to facilitate collection of pest occurrence including a web based system of pest occurrence data supported by web based tools and fact sheets to facilitate identification where this is practical (i.e. for those pests where accurate recognition in the field is possible), recognition by the industry that this is difficult for some important pests including mealybugs and support for provision of a molecular based identification system and opportunities to disseminate knowledge through field days and workshops.

Publications

Publications are listed below and copies of the published articles are attached where available (indicated *).

Book chapter

Linda Thomson and Matthew Hill. (In prep). Species distribution modelling in predicting response to climate change *In* Climate Change and Insect Pests. Ed Christer Björkman and Pikka Niemelä. Invited chapter.

Papers

Thomson, L.J, Hill, M.P. (In prep). Predicting change in mealybugs and a natural enemy in Australian vineyards.

*Thomson, L.J., Hoffmann, A.A., 2013. Spatial scale of benefits from adjacent woody vegetation on natural enemies within vineyards. Biological Control 64, 57-65.

* Nash, M.A., Thomson, L.J., 2012. Crush snail problem with targetted approach. Australian & New Zealand Grapegrower & Winemaker 576, 26-28.

*Thomson, L.J, Nash, M.A., Corrie, A., Smith, I, Hoffmann, A.A., 2012. Sustainable pest control-now and in a changing climate. Australian & New Zealand Grapegrower & Winemaker 584, 48-56.

*D'Alberto, C.F., Hoffmann, A.A., Thomson, L.J., 2012. Limited benefits of non-crop vegetation on spiders in Australian vineyards: regional or crop differences? Biocontrol 57, 541-552.
*Thomson LJ, Hoffmann, AA, 2011. Pest management challenges for biofuel crop production. Current Opinion in Environmental Sustainability 3:95-99 Invited contribution to Special Issue on Terrestrial Systems Edited by Andy Sheppard, Raghu Sathyamurthy, Cameron Begley, and Dave Richardson.
*Thomson, L.J., Hoffmann, A.A., 2011b. Trunk insects and weevils under climate stress and climate change. Australian & New Zealand Grapegrower & Winemaker 572, 64-70.
*Danne, A., Thomson, L.J., Sharley, D.J., Penfold, C.M., Hoffmann, A.A., 2010. Effects of native grass cover crops on beneficial and pest invertebrates in Australian vineyards. Environmental Entomology 39, 970-978.
*Thomson, L.J., Hoffmann, A.A., 2010a. Natural enemy responses and pest control: Importance of local vegetation. Biological Control 52, 160-166.
*Thomson, L.J., Hoffmann, A.A., 2010b. Potential pest and natural enemy responses under climate change. Australian & New Zealand Grapegrower & Winemaker 563, 30-32.
*Thomson, L.J., Macfadyen, S., Hoffmann, A.A., 2010a. Predicting the effects of climate change on natural enemies of agricultural pests. Biological Control, 52 296-306. Invited contribution to Special Issue of Biological Control *'Biological control: current state, future prospects.* Editors: Gurr, G.A., Ash, G. and Pilkington, L.
*Thomson, L.J., McKenzie, J., Sharley, D.J., Nash, M.A., Tsitsilas, A., Hoffmann, A.A., 2010b. Effect of woody vegetation at the landscape scale on the abundance of natural enemies in Australian vineyards. Biological Control 54, 248-254.
*Thomson, L.J., Hoffmann, A.A., 2009. Vegetation increases the abundance of natural enemies in vineyards. Biological Control 49, 259-269.

Presentations

Conference Presentations

Linda Thomson and Ary Hoffmann. Predicting the effects of climate change on mealybugs and their natural enemies in grapevines in Australia. Australian Entomological Society Hobart, November 2012.

Linda Thomson. Building vineyard biodiversity. 8th International Cool Climate Symposium. Hobart, February 2012. Invited presentation.

Linda Thomson and Ary Hoffmann. Predicting the effects of climate change on mealybugs and their natural enemies in grapevines in Australia. XXIVth International Congress of Entomology. Daegu South Korea, August 2012. Invited presentation.

Linda Thomson and Ary Hoffmann. Impact of climate change on activity and abundance on natural enemies of insect pests. XXIVth International Congress of Entomology. Daegu South Korea, August 2012. Invited presentation.

Linda Thomson and Ary Hoffmann. Woody vegetation and abundance and diversity of some natural enemies in vineyards. Australian Entomological Society Meeting. Perth, September 2010.

Linda Thomson. Assessing characteristics of vegetation to enhance abundance and diversity of natural enemies in vineyard ecosystems. Niagara Falls Canada, May 2010. Invited presentation.

Linda Thomson. Sustainable use of agrochemicals. 12the IUPAC international Congress of Pesticide Chemistry. Melbourne 4th-8th July 2010. Invited presentation.

Industry Presentations/Workshops

Ary Hoffmann and Linda Thomson. Sustainable pest control in a changing climate. GWRDC Management meeting. Adelaide, February 2012.

Linda Thomson. 'Sustainable pest control- now and in a changing climate' Victorian Viticultural Association. Melbourne. May 2012.1/2 day workshop.

Linda Thomson. Enhancing natural enemy diversity and abundance in vineyards – an overview Vineyard Biodiversity and Insect Interactions workshop. Adelaide Hills, September 2011.
Linda Thomson. Monitoring insect populations in your vineyard. Vineyard Biodiversity and Insect Interactions workshop. Adelaide Hills, September 2011.
Linda Thomson. Vegetation for natural enemies. Vineyard Biodiversity and Insect Interactions workshop. Adelaide Hills, September 2011.
Linda Thomson. Enhancing natural enemy diversity and abundance in vineyards – an overview Vineyard Biodiversity and Insect Interactions workshop. McLaren Vale, September 2011.
Linda Thomson. Monitoring insect populations in your vineyard. Vineyard Biodiversity and Insect Interactions Workshop. McLaren Vale, September 2011.
Linda Thomson. Vegetation for natural enemies. Vineyard Biodiversity and Insect Interactions Workshop. McLaren Vale, September 2011.
Linda Thomson. Enhancing natural enemy diversity and abundance in vineyards – an overview Vineyard Biodiversity and Insect Interactions Workshop. Langhorne Creek, September 2011.
Linda Thomson. Monitoring insect populations in your vineyard. Vineyard Biodiversity and Insect Interactions Workshop Langhorne Creek, September 2011.
Linda Thomson. Vegetation for natural enemies. Vineyard Biodiversity and Insect Interactions Workshop – Langhorne Creek September 2011.
Linda Thomson and Ary Hoffmann. Viticultural pests under climate change. 14th Australian Wine Industry Technical Conference. Adelaide, July 2010.
Linda Thomson. Enhancing natural enemies in your vineyard-vegetation. 14th Australian Wine Industry Technical Conference. Adelaide, July 2010.
Ary Hoffmann and Linda Thomson Viticultural pests and natural enemies under climate change. GWRDC Climate Change Workshop. Adelaide, October 2009.

MSc Thesis

Yi-Chun Yeh. 2013. The future of invertebrate pest control: mealybugs and their natural enemies in Australian vineyards. MSc thesis. Zoology Department, University of Melbourne.

Appendix 2: Intellectual Property:

None identified. The research outcomes have all been published and provided as a public benefit.

Appendix 3: References:

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