BIOCLIMATIC NICHE MODELLING PROJECTS A POTENTIAL SHIFT IN DISTRIBUTION AND ABUNDANCE OF QUEENSLAND FRUIT FLY *BACTROCERA TRYONI* IN AUSTRALIA

Marja Simpson[1], Bernard C Dominiak[2]*, Ian J McGowen[1], Jason J Crean[1], and Tim J F Sides[1]
[1] *NSW Department of Primary Industries, Locked Bag 6006, Orange, New South Wales, 2800, Australia*
[2] *NSW Department of Primary Industries, 161 Kite Street, Orange, New South Wales, 2800, Australia*
* email: bernie.dominiak@dpi.nsw.gov.au

Keywords: Species distribution modelling, CLIMEX, climate change, horticulture industry, export

Summary

Queensland fruit fly (Qfly) is a native Australian species originally endemic to Queensland and coastal northern New South Wales. Horticultural production of imported hosts has contributed to Qfly spreading to all eastern Australian states. Market access for horticultural production was protected by the creation of pest-free areas such as the Fruit Fly Exclusion Zone (FFEZ) and Greater Sunraysia Pest Free Area (GSPFA) to assist trade from south eastern Australia. These zones had hot, dry summers and cold winters which were less likely to support Qfly establishment and persistence. Eradication was therefore more likely. In recent years, the FFEZ and GSPFA experienced an increase in Qfly outbreaks during the growing season, which may be attributed to an increased summer rainfall and warmer winters. This is an observed change in Australia's climate since the year 2000. Such climatic conditions enhance the suitability of southern Australian regions for Qfly establishment and proliferation. To assess this, the potential current and future distribution and abundance of Qfly was modelled using two global climate models and two emission scenarios. Results indicated that climate change is likely to cause a southern and coastal shift in the climatic suitability and support an increase in abundance. Horticultural production areas that are currently modelled as marginal for Qfly infestation were projected to become suitable by 2030, with areas that are currently unsuitable projected to become marginal. This change will place horticultural production areas under increasing pressure from Qfly. This change will place new challenges on area wide management and require the development of alternative control measures.

INTRODUCTION

Climate variability and change is one of the most significant threats to Australia's agricultural and horticultural production systems (Webb and Whetton 2010). Australia's climate has warmed since 1910 by 1°C (CSIRO and BOM 2016). Across Australia, a change in seasonal rainfall has been observed since 2000 with an increase in summer rainfall and a decline in winter rainfall (CSIRO and BOM 2016). From this climate change, a potential shift in the geographical distribution of pests, weeds and diseases is projected to occur (Bale *et al.* 2002; Bebber 2015). Additionally, an increase in temperatures due to climate change could result in longer periods of pest activity and greater abundance of pest species (Trnka *et al.* 2007). Evidence that species have already responded to climate change by shifting their geographical range has been found for a range of taxonomic groups (Parmesan *et al.* 1999; Hickling *et al.* 2006, Battisti and Larsson 2015). Various studies have been conducted using bioclimatic niche modelling tools to assess the potential shift in the geographical distribution and phenology of agricultural pests and their natural enemies. These pests include insects, weeds and pathogens (Stephens *et al.* 2007; Taylor and Kumar 2013; Bebber 2015; Ge *et al.* 2015; Furlong *et al.* 2017).

Queensland fruit fly (Qfly) (*Bactrocera tryoni* Froggatt) (Diptera: Tephritidae) is one of Australia's worst horticultural pest because it infests many horticultural crops, making produce unmarketable (Clarke *et al.* 2011). More than 100 fruit and vegetables species are suitable hosts, including major horticultural crops (Hancock *et al.* 2000). Qfly is native to Australia and its natural ecological distribution ranges from tropical and subtropical Queensland to coastal New South Wales (NSW) (Dominiak and Daniels 2012). However, horticultural production of suitable hosts and the long distance movements of infested produce (Dominiak and Coombes 2009) have contributed to a changed Qfly distribution. Population expansion has been driven by increased temperatures, moisture availability and humidity (Yonow *et al.* 2004). Additionally, urban environments provide host sources (Raghu *et al.* 2000) and populations tend to increase in these areas due to the increased temperature and humidity compared to rural environments (Dominiak *et al.* 2006). Permanent Qfly populations are now established across all of eastern Australia, extending westerly into inland Queensland, southerly into NSW and Victoria, and north-westerly towards Alice Springs and Darwin (Clarke *et al.* 2011; Dominiak and Mapson 2017). South Australia is under threat from Qfly incursions from the eastern states. South Australia has experienced sporadic Qfly outbreaks, but remains Qfly free following eradication programs (Maelzer 1990a,b; PIRSA 2015). The South Australian state government spends $5AU million annually on prevention, detection and eradication (PIRSA 2015). Western Australia experienced Qfly outbreaks in 1989, 1995, 2011 and 2015; these outbreaks were successfully eradicated (DAFWA 2015; Dominiak and Mapson 2017). Tasmania remains Qfly free because the climate is currently unsuitable for the species to overwinter and thus it is unable to establish permanent populations (Holz *et al.* 2010). Based on this climate, Tasmania has national and international recognition for Area Freedom from fruit flies (Holz *et al.* 2010). This status provides preferential access to international markets, where stringent regulations are in place, and adds approximately $90AU million annually to Tasmania's export income from horticultural industries (DPIPWE 2015).

The horticulture industry is an important part of Australia's economy and was the third largest agricultural industry, with a gross value of $8.7AU billion in 2013-14 (ABS 2015). State and federal governments have established protection zones such as the Fruit Fly Exclusion Zone (FFEZ) and Greater Sunraysia Pest Free Area (GSPFA) to minimise the incursion of Qfly and subsequent 'outbreaks'. The management of the GSPFA is consistent with International Standards for Phytosanitary Measures (ISPM) 26 (White *et al.* 2011) but has experienced an increase in outbreaks over the last five years (NSW DPI Plant Biosecurity 2015). This led the Victorian and NSW governments to temporarily suspend area freedom status for export markets in April 2014 (DEDJTR 2015). Warm to hot summer temperatures and high summer rainfall during these years (Webb 2012; White and Fox-Hughes 2013) were likely to have contributed to these outbreaks. Milder winters enable Qfly to persist throughout the year which can lead to multiple generations. Increased generations can lead to large populations if not quickly controlled (Harvey *et al.* 2010). An increase in lifestyle farms has also been identified as a biosecurity risk that can contribute to outbreaks because smaller scale farms commonly grow many host species.

The geographical distribution and abundance of Qfly in relation to current and future climate projections has been previously investigated in Australia (Yonow and Sutherst 1998; Sutherst *et al.* 2000; Yonow *et al.* 2004; Dominiak *et al.* 2006) and Tasmania (Holz *et al.* 2010). Additionally, a modelling study established that irrigation increased the suitability of areas such as the FFEZ for Qfly that were otherwise marginal under natural rainfall conditions (Yonow and Sutherst 1998). In a subsequent study, three incremental temperature scenarios of increases of 0.5°C, 1.0°C and 2.0°C showed that the costs of Qfly control and the risk of failure to maintain area freedom would intensify with temperature increase (Sutherst *et al.* 2000).
Since these earlier studies, the use of multiple global climate models (GCMs) and emission scenarios for species distribution modelling has been identified as important; variation between the models impacts the resulting projected distributions (Beaumont *et al.* 2008; Buisson *et al.* 2010). GCMs and emission scenarios are simulations of future climates that include a wide range of climatic variables. Further, ecosystems are not characterised by constant temperature increases as was the case before GCMs. The use of GCMs in conjunction with emission scenarios over modelling with constant incremental temperature changes is seen to produce more robust results (Mika *et al.* 2008). This is because GCMs include a range of climatic variables and topography simulated both spatially and temporally at a regional scale (Kriticos *et al.* 2012).

Many studies have modelled the potential distribution of pests based on climatic factors alone. Climatic requirements of a species must be met in the first instance for its persistence at a particular location. However, there are many ecological processes that influence a species' distribution and abundance (Kearney and Porter 2009). Therefore, the bioclimatic niche of a species is important and should be integrated into the modelling process, particularly when management options are being considered (Baker *et al.* 2000; Guisan and Thuiller 2005; McDonald *et al.* 2009; Li *et al.* 2012; Furlong *et al.* 2017). The bioclimatic niche is the potential species distribution that includes climatic, topographic, land use, soil factors and the presence of hosts. A species can have a large potential bioclimatic niche but may only be considered a problem pest for particular production systems or regions. These production areas can be defined as damage niche areas (McDonald *et al.* 2009). Therefore, damage niche areas are more appropriate than broader bioclimatic niche areas for developing specific pest management strategies (Davis *et al.* 2015).

This study assesses the potential current and future bioclimatic niche and abundance of Qfly for Australia and damage niche areas. The aim is to identify horticultural production regions that are and will be at risk from Qfly. The results of this study can be used to support the horticultural industry to adapt to climate change through the development of long-term control, management and surveillance options for Qfly.

MATERIALS AND METHODS

Climatic data and scenarios

The climatic data set, CliMond CM10_1975H_V1.2 (Kriticos *et al.* 2012), was used to model the current climate. This is a gridded dataset of monthly averages for 1961-1990 at a ten-minute (approximately 18 kilometres) resolution. CliMond climate data at the same resolution were used for future climate projections for 2030 (2016-2045), 2050 (2036-2065), 2070 (2056-2085) and 2080 (2070-2099). These data sets include the required variables for the CLIMEX software including: monthly averages for minimum and maximum temperatures, precipitation and relative humidity at 09:00h and 15:00h. Future projections for each of these periods were generated using the A1B and A2 emission scenarios for future global emissions of greenhouse gases and sulphate aerosols, also referred to as SRES scenarios, and two GCMs, CSIRO-MK 3.0 and MIROC-H (Kriticos *et al.* 2012). The SRES scenarios have since been replaced by representative concentration pathways, but it is still appropriate to use the former because they provide a similar pattern of change, particularly out to 2050 (Peters *et al.* 2013).

The bioclimatic niche area for Qfly is driven by temperature and moisture availability. The two GCMs selected project temperature increases by the end of this century of 4.31°C rise under the MIROC-H and 2.11 °C under the CSIRO-MK 3.0 model (Kriticos *et al.* 2012). Annual average rainfall is projected to decrease, 14% under the CSIRO-MK 3.0 model and 1% under the MIROC-H model (Chiew *et al.* 2009). Across the models in the Coupled Model Intercomparison Project 3 (CMIP3) the CSIRO-MK 3.0 and MIROC-H model performed well in reproducing observed patterns of seasonal average climate over Australia (Hennessy and Colman 2007). In 2013, the IPCC's fifth assessment report (AR5) was released with the Model Intercomparison Project Phase 5 (CMIP5). The IPCC notes, that between the two datasets, there is an overall consistency with some differences that are attributed to the change in emission scenarios. There is confidence in GCMs, particularly for global and regional temperature projections. However, there are uncertainties coming from future emissions scenarios, the range of GCMs, the representation of precipitation mechanisms at local to regional scales, and natural climate variability (Ziter *et al.* 2012). The two emission scenarios used here represent the middle (A1B) and upper (A2) range (Harris *et al.* 2014). ArcGIS™ version 10.3.1 was used for generating maps and area calculations of the bioclimatic niche classifications.

Bioclimatic niche modelling process

CLIMEX version 4.0.2 (Hearne Scientific Software Pty Ltd) (Kriticos *et al.* 2015) was used for the Qfly bioclimatic niche modelling. This software is a semi-mechanistic niche model. The software uses multiple species' specific input parameters such as field phenological observations, including physiological tolerances of growth and survival, development rates and geographical occurrence records to estimate the response of a species to climatic variables and its potential occurrence at a particular location. Thus, a species specific bioclimatic niche model is built rather than linking species occurrence records with spatial environmental data as is the case for correlative distribution modelling (Webber *et al.* 2011). The Qfly parameter values (Table 1) are based on key physiological and population growth requirements for Qfly that were sourced from empirical studies (Meats 1984; O'Loughlin *et al.* 1984; Muthuthantri *et al.* 2010). These studies were used previously by Yonow and Sutherst (1998). The derivation of these parameters was described by Kriticos *et al.* (2015) and was based on the assumption that a species' persistence in a particular location was primarily based on climatic variables.

An ecoclimatic index (EI) was calculated to model the potential bioclimatic niche of Qfly. CLIMEX calculates an EI value as an annual overall index. EI describes the climatic suitability of a given location to support a permanent population of a particular species (Kriticos *et al.* 2015). The scale of the EI value ranges from zero (unsuitable to support a permanent population) to 100 (a "perfect" climate year). The abundance of Qfly was calculated through estimation of the number of generations per year in CLIMEX. It is recognised that three to five generations per year are challenging to manage due to the high Qfly numbers produced by the end of the third or fifth generation respectively (Meats 1981). CLIMEX software calculates the number of degree-days above the lower temperature threshold (DV0) required for completing a generation a year under the assumption that moisture availability is adequate (Kriticos *et al.* 2015). Based on a degree-day development model used in the fruit fly Code of Practice and is used as the basis for managing area freedom, domestic and international market access (Anonymous, 1996), the generation time in CLIMEX was set to 380 degree-days above the threshold of 12°C. Occurrence records for Qfly from 1998-2014 were retrieved from the Australian Plant Pest Database (https://appd.ala.org.au/appd-hub/index) to validate the modelled current distribution.

Irrigation scenario

An irrigation scenario was established by representing a commercial orchard environment where top-up irrigation supplemented rainfall. This was included as a land use type that influences the occurrence of Qfly and thus its bioclimatic niche. The irrigation scenario was set to alleviate any water deficit and achieve a suitable soil moisture level for production. Top up was set to 3.6mm/day (equating to 25.2mm per week) from November to April. If the rainfall during a week was less then 25mm, the program would make up the deficit to

Table 1: CLIMEX parameter values for Queensland fruit fly distribution and abundance (Yonow and Sutherst 1998).

Index	CLIMEX parameters	Value
Temperature	DV0 = lower threshold	12°C
	DV1 = lower optimum temperature	25°C
	DV2 = upper optimum temperature	33°C
	DV3 = upper threshold	36°C
Moisture	SM0 = lower soil moisture threshold	0.1
	SM1 = lower optimum soil moisture	0.5
	SM2 = upper optimum soil moisture	1.75
	SM3 = upper soil moisture threshold	2
Heat stress	TTHS = temperature threshold	36°C
	THHS = stress accumulation rate	0.005
Cold stress	TTCS = temperature threshold	2°C
	THCS = stress accumulation rate	0.1
	DTCS = degree-day threshold (stress accumulates if the weekly number of degree-days above 36°C exceeds this value	20°C
	DHCS = stress accumulation rate	0.00025
Dry stress	SMDS = soil moisture dry stress threshold	0.1
	HDS = stress accumulation rate	0.005
Wet stress	SMWS = soil moisture wet stress threshold	2
	HWS = stress accumulation rate	0.002
Degree-days	PDD = Degree-days per generation	380

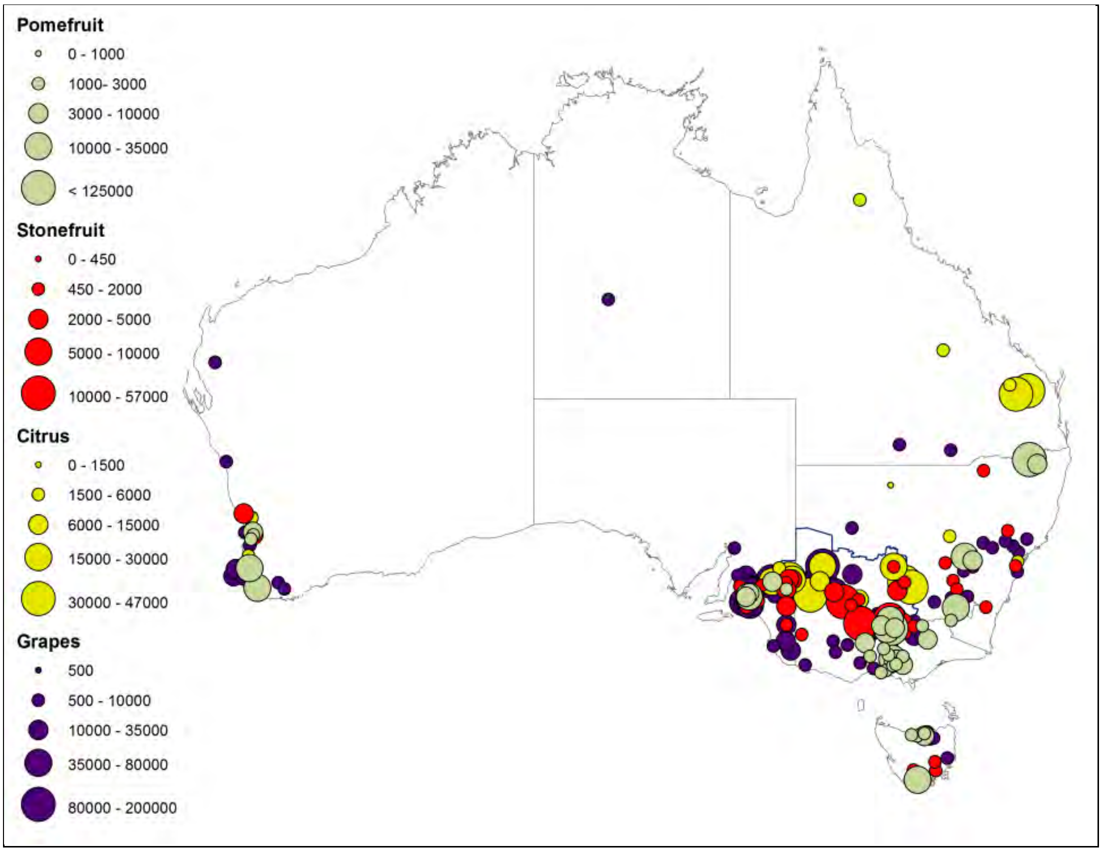


Figure 1: Production of horticultural commodities from 2010-11 in tonnes (Source: ABS 2015).

25.2mm. This amount of top-up irrigation was used in a previous modelling study on Qfly (Sutherst *et al.* 2000). The top-up irrigation was based on a study by Meats (1981) that suggests that monthly rainfall of 48mm could lead to high population densities.

Damage niche areas
The spatial distribution of potential host sites around Australia were identified using production data from 2010-11 for citrus, grapes, stone and pome fruit from the Australian Bureau of Statistics, at a local government area level (ABS 2015) (Figure 1). These are high value commodities to the horticulture industry (ABARES 2015; ABS 2015) and are an indication of host availability at a landscape scale. The production data was used to identify potential damage niche areas and a polygon vector file was created. This vector file was integrated with the EI and abundance outputs derived from CLIMEX in ArcGIS™ version 10.6.1. Therefore, these areas that were most at risk of potential damage where effort into pest management should be prioritised.

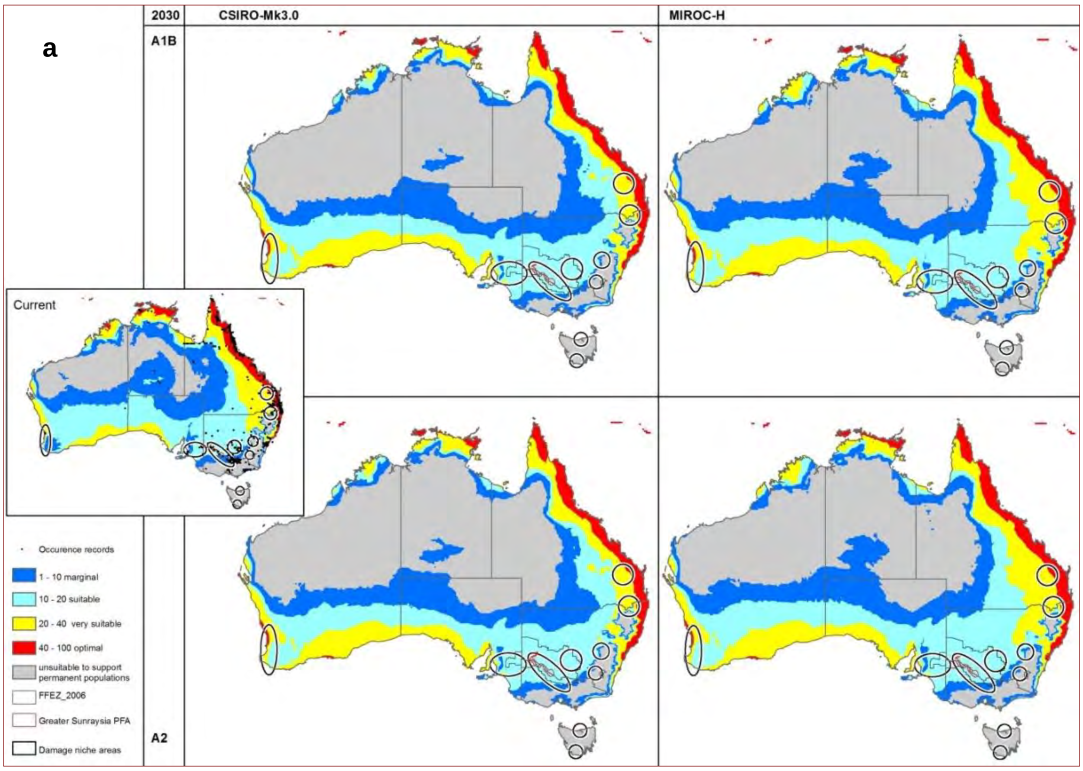
RESULTS

Changes in bioclimatic niche area
The modelling indicated that the bioclimatic niche for Qfly to establish permanent populations was widespread throughout Australia. Our modelling used the baseline climate period to represent current climate conditions, with top-up irrigation. Occurrence records were consistent with the modelled niche area (Figure 2). Much of Queensland was modelled as optimal to marginal, with a small area in central Queensland being unsuitable due to potential heat stress (Figure 2a). In NSW, top-up irrigation made a large part of the inland suitable. The high-value horticultural production areas such as the GSPFA and the former FFEZ (Figure 2a) were modelled as suitable and the more elevated areas were marginal. Other higher elevation areas, such as the Orange region in the central tablelands of NSW, were modelled as unsuitable due to cold stress in winter (Figure 5). The north-west of Victoria, which includes part of the GSPFA and former FFEZ, was modelled as suitable to marginal. In contrast, the southern part of Victoria was modelled as unsuitable with a thin strip along the south-west coast showing as marginal.

In South Australia, the climatic suitability ranged from marginal in the north (due to heat stress) to suitable and were very suitable throughout the centre and far south. A large part of Western Australia showed suitability ranging from marginal in the central areas of the state to suitable and very suitable. Small regions in the north and along the south west of the coast of Western Australia were predicted to be optimal. Much of the Northern Territory was marginal, with very suitable to optimal conditions in north of that state. Tasmania was modelled as unsuitable with a small area in the north-east being marginal (Figure 2a).

The potential projected bioclimatic niche for Qfly was modelled using two GCMs and two emission scenarios for four future time periods. The output showed a similar overall spatial pattern with the major difference being observed between climate models and minor differences between the emission scenarios (Figure 2a, 3, 5, 6). Australia-wide, the CSIRO-Mk 3.0 model projected a greater increase in areas unsuitable for Qfly than the MIROC-H model (Figure 6a). The output indicated that most of the unsuitable area was projected to occur in inland Australia. The unsuitable area in Australia's south eastern mainland and Tasmania were predicted to decrease (Figure 2a, 3). The areas of the other four classifications were projected to decrease Australia-wide, with the CSIRO-Mk 3.0 model projecting larger declines than the MIROC-H model (Figure 6a). Southern Australia's suitability for Qfly, including most of the areas, will potentially increase and areas that are currently marginal will become suitable to optimal (Figure 2a, 3). The area calculation for the damage niche areas revealed a decrease in unsuitable area and increase in suitable, very suitable and optimal areas (Figure 6b). The high-value horticulture region in NSW and Victoria (Figure 1) managed as the GSPFA was currently classed as suitable with the southern part being marginal. By 2030, this whole area was projected to be in the suitable category. The marginal areas were also projected to become suitable by 2030 for the horticultural production areas in South Australia and Western Australia. The results for north-eastern Tasmania predicted that this area potentially would become marginal to suitable by 2080 (Figure 2a, 3).

Changes in abundance
Overall, there is a similar spatial pattern in the projections for Qfly abundance from both models and the emissions scenarios. The abundance was modelled under the assumption that moisture was not a limiting factor. Therefore, some areas are modelled to have the potential for high numbers of generations despite the EI being unsuitable. There was a reduction in areas where there will be zero to seven generations per year (Figure 2b, 4, 7). The size of the area, where eight to 16 generations per year can potentially develop, was projected to increase. The major differences were between the two GCMs rather than the emissions scenarios (Figure 7). The CSIRO-Mk3.0 model projected a greater increase in the area where eight to 16 generations per year can develop. Areas where only zero to two generations per year can develop were projected to be smaller under the CSIRO-Mk 3.0 model than the MIROC-H model (Figure 7). Additionally, the output indicated that southern Australia would experience the greatest changes with more generations per year



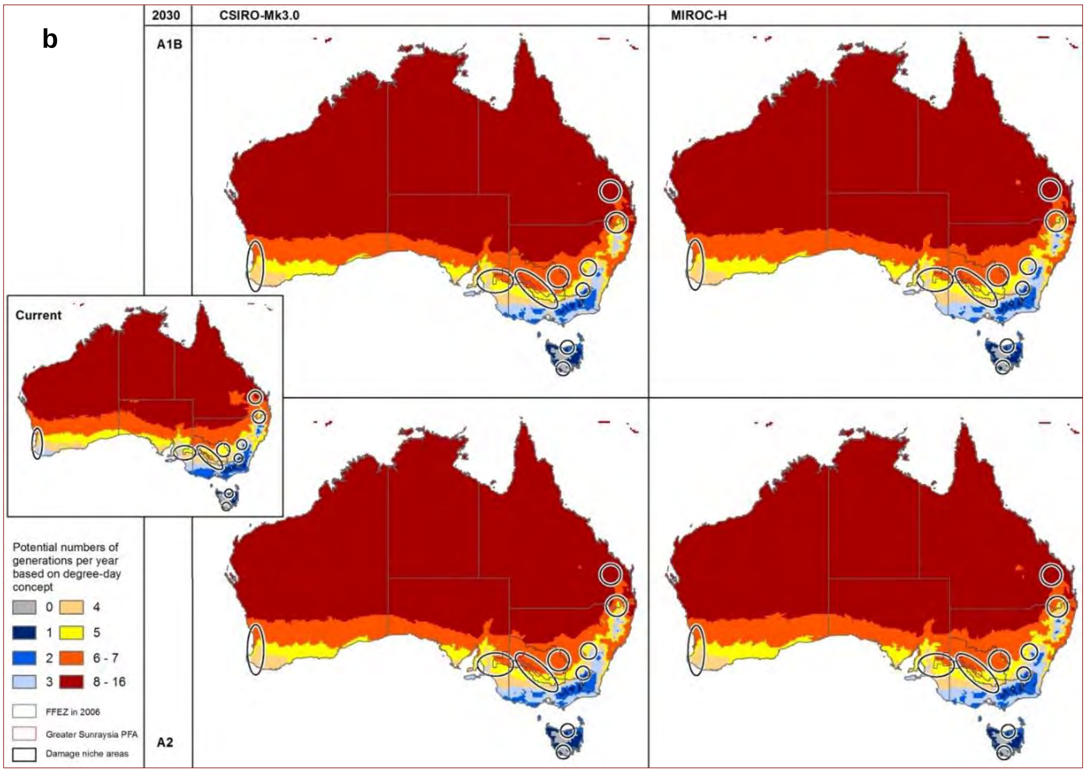


Figure 2: a) Comparison of climatic suitability (Ecoclimatic index EI) and b) Comparison of numbers of generations per year for Queensland fruit fly for the current (with occurrence records) and 2030 climate modelled in CLIMEX using two global climate models and two emission scenarios. The model included a top-up irrigation scenario to represent an orchard environment.

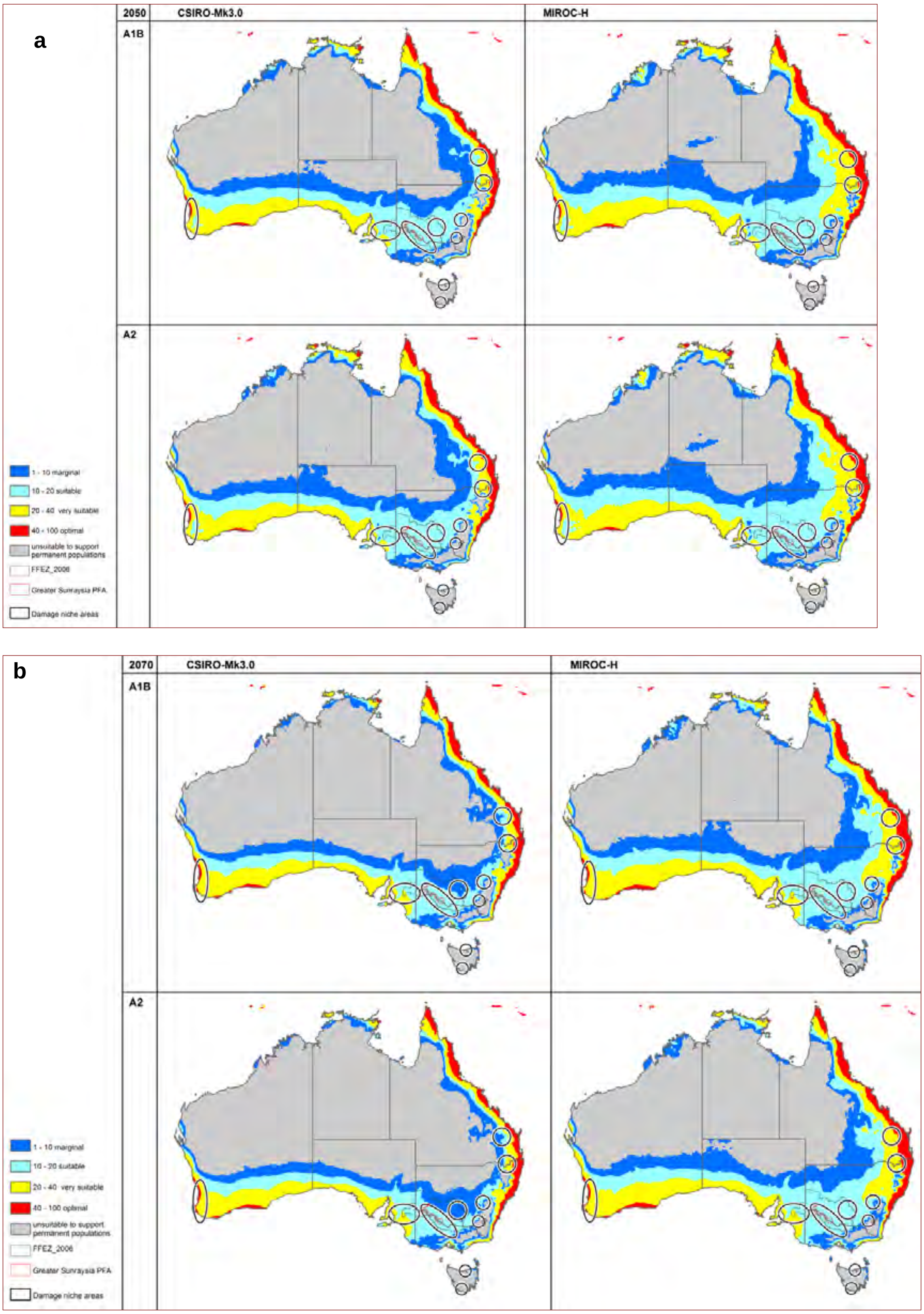


Figure 3: Comparison of climatic suitability (Ecoclimatic index EI) for Queensland fruit fly in (a) 2050, (b) 2070 modelled in CLIMEX using two global climate models and two emission scenarios. The model included a top-up irrigation scenario to represent an orchard environment.

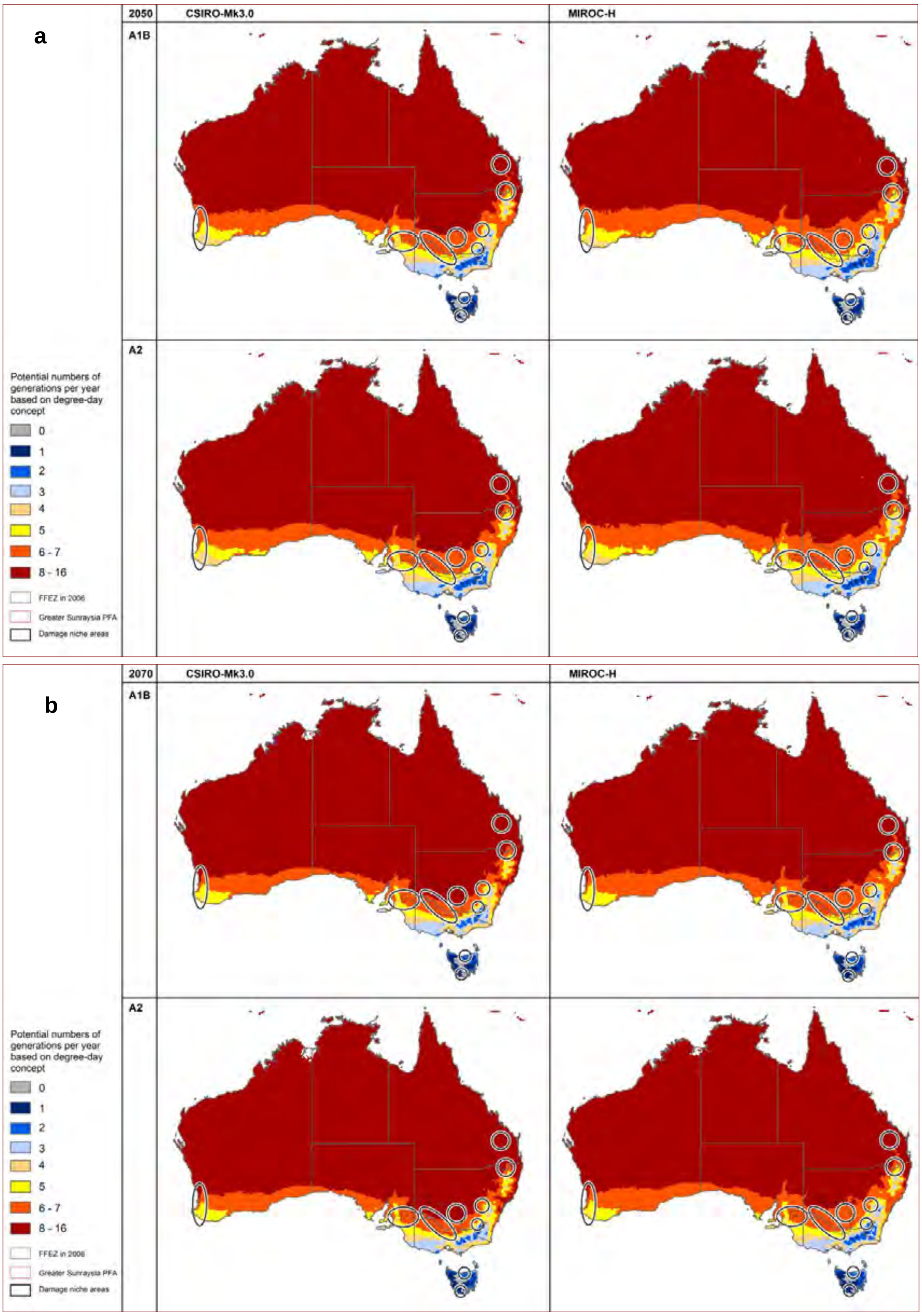


Figure 4: Comparison of numbers of generations per year for Queensland fruit fly in (a) 2050, (b) 2070 modelled in CLIMEX using two global climate models and two emission scenarios. The model included a top-up irrigation scenario to represent an orchard environment.

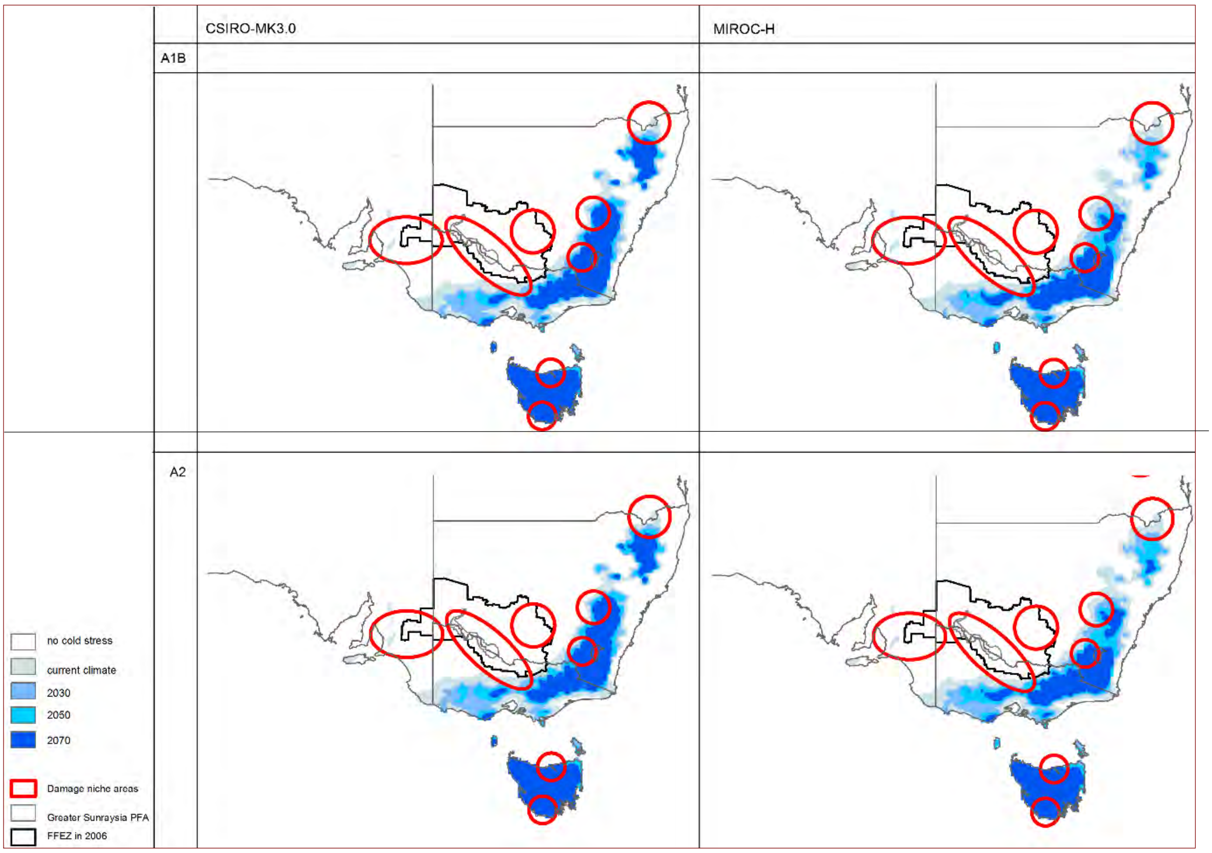


Figure 5: Areas of cold stress affecting Queensland fruit fly modelled for the current climate using the baseline climate data and future climate projections.

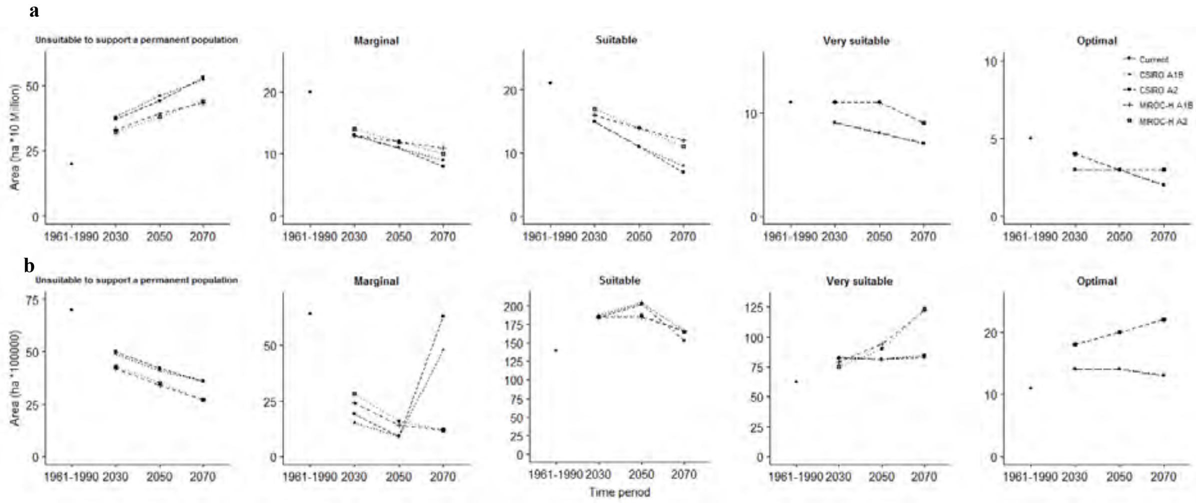


Figure 6: Australia-wide (a) and damage niche areas (b) climate projections for change in size of the bioclimatic niche area of Queensland fruit fly based on the Ecoclimatic Index (EI) classifications ('unsuitable area to support a permanent population'=EI of 0≤1, 'marginal'= EI of 1-10, 'suitable'=EI of 10-20, 'very suitable'=EI of 21-40, 'optimal'= EI of 40-100).

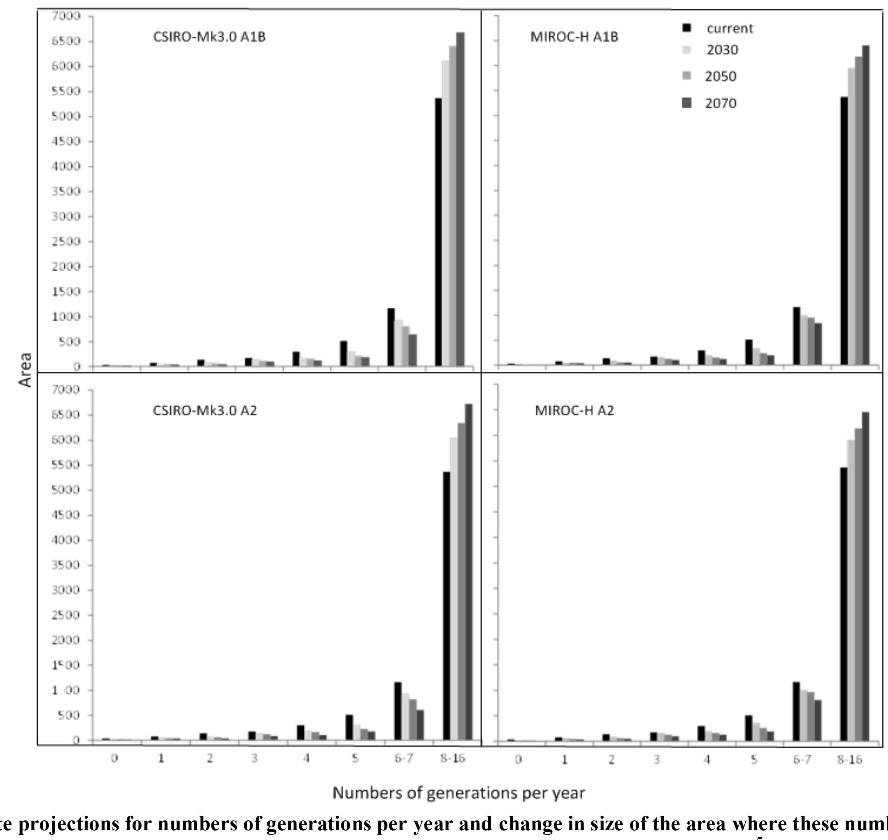


Figure 7: Climate projections for numbers of generations per year and change in size of the area where these numbers can potentially be completed annually for Queensland fruit fly. Area size is represented as hectares x 10^5.

(Figure 2b, 4). For example, four to five generations per year were projected to develop in areas that were modelled as suitable such as the former FFEZ and GSPFA under the baseline climate period (Figure 2b). However, by 2030 both GCMs suggested that six to seven generations per year can potentially develop for most of the GSPFA. Parts of Tasmania were projected to become potentially more suitable and develop up to two to three generations per year. This was similar to the current situation for the cool climate region near Orange in NSW (Figure 4).

Refined results

The Qfly host availability data were intersected with geographical distribution and abundance data to refine the bioclimatic niche results. Qfly host availability data was represented by tonnes of production of major horticultural commodities. The resulting output identified the damage niche areas that are and will be at risk of Qfly outbreaks. Major Qfly hosts that were mapped included citrus, grapes, stone and pome fruit (Figure 1). The bioclimatic niche maps and the area calculations of the EI classifications indicated that the suitability for Qfly will be shifting towards southern and coastal Australia with an increased number of potential generations per year. The results showed that this shift may potentially affect major horticultural production areas more seriously (Figures 2, 3, 6b).

DISCUSSION

Climate change projections indicated increases in temperatures Australia-wide over this century and a decline in winter rainfall across southern Australia, but changes to rainfall are uncertain (CSIRO and BOM 2016). The geographical distribution and abundance of Qfly was expected to change given projections of future climate change. Therefore, identifying the boundaries of the bioclimatic and damage niche and the likely abundance of Qfly is important to determine the effective management options for this pest.

Two GCMs and two emission scenarios were used to project the distribution and abundance of Qfly. The modelling showed both GCMs and emission scenarios projected a similar overall pattern. The major difference in results was between the two models, with only minor differences between the emission scenarios. The major differences between models were in the projections for the area sizes of the different suitability classifications. This highlighted the importance of using a set of representative models and emission scenarios for bioclimatic niche modelling because they demonstrate a range of plausible projections of future climates (Harris *et al.* 2014; Kriticos *et al.* 2012; Whetton *et al.* 2012). The bioclimatic niche area for Qfly was increasingly reduced for the CSIRO-Mk3.0 model compared to the MIROC-H model for 2030, 2050, 2070 and 2080. These were due to the CSIRO-Mk3.0 being a drier scenario compared to MIROC-H, which is a wetter projection (Chiew *et al.* 2009). Comparison between this study and two other studies on Qfly distribution, carried out nearly two decades ago (Yonow and Sutherst 1998; Sutherst *et al.* 2000), revealed differences in the modelling of the climatic suitability for Qfly. The major differences for the current Qfly climatic suitability can be seen in the spatial distribution of the optimal and very suitable areas which are currently smaller. This difference could be attributed to the different data sets, different time period being used and to differences in the climatic variables as part of using GCMs modelled. There were also differences between the studies for future climate projections. This can be largely attributed to the climatic data sets used. The present study used GCMs and emission scenarios for a range of future time periods, compared to the previous studies which modelled constant incremental temperature increases alone. A limitation of using constant temperature increases is that this assumes the same increase Australia-wide. GCMs incorporate interactions between the atmosphere, oceans, sea ice and land surface that allow for spatial variation in climatic variables (CSIRO and BOM 2016). Thus regional discretisation modelling outputs based on GCMs produce projections with a greater confidence. The major differences between the studies were in the projected extent of the very suitable and optimal areas. There was particular confidence in the temperature projections from GCMs and the use of a range of projections demonstrated the variation between the models. This accounted for the uncertainty in the climatic data but most importantly showed plausible scenarios that follow a similar pattern.

In southern Australia, Qfly distribution and abundance is temperature and moisture dependent. The projected increase in warming will reduce cold stress and extend the development season for Qfly. High value horticultural areas, such as the former FFEZ and GSPFA, were established because cold winters and hot dry summers allowed Qfly eradication. This climatic scenario allowed easy maintenance of the pest freedom status of these areas. Climate change will make these areas more suitable for Qfly. These predicted changes will put increased pressure on the horticultural industries in these areas to manage this pest, to maintain area freedom status and therefore maintain unrestricted trade. More of Victoria and South Australia will become favourable for Qfly survival. Currently, South Australia remains free of Qfly through an integrated program (Hall 2015). Climatic suitability within South Australia will shift southward with the very suitable area being projected to increase between 2030 to 2080. If South Australia is to maintain its Qfly free status, then current border controls will have to be maintained or increased to prevent Qfly from being carried into the state by vehicular traffic and other means (Florec *et al.* 2013; Dominiak and Coombes 2009). Currently, Tasmania remains Qfly free because of cold stress and being isolated from the mainland. However, climate projections predict that the north-east of Tasmania will become marginal to suitable by 2080. These results are similar to those from a previous study (Holz *et al.* 2010). Sultana *et al.* (2017) reported similar results for Qfly however they used different software (Maxent), a different climate database and different sources for Qfly occurrence data. In contrast to our work, Sultana *et al.* (2017) did not use emissions in their assessment. Sultana *et al.* (2019) reported similar threats to southern regions from other fruit fly species in Australia.

The distribution of Qfly is determined by climatic factors but is strongly influenced by land management and host availability. We used a top-up irrigation scenario in the CLIMEX model to better represent the extent of the bioclimatic niche area for Qfly. The irrigation scenario characterised a commercial orchard environment as tree fruit horticultural production in Australia is often reliant on supplementary irrigation. The climatic suitability was further refined by using host availability data. Host availability was identified from the selection of major horticultural production areas that grow suitable Qfly hosts in conjunction with the bioclimatic niche, the latter indicating the damage niche areas. Currently, these damage niche areas can be characterised as marginal to suitable. Some areas in south-eastern Australia and Tasmania were unsuitable for Qfly to establish permanent populations. The GSPFA was modelled as suitable. The development of four to five generations per year was possible if sufficient moisture is available in GSPFA. This is likely in irrigated crop environments. The GSPFA area freedom status was suspended during the 2013-14 growing season due to a high number of outbreaks. Our climate change projections for the GSPFA indicate that there will potentially be an increase in number of generations per year by 2030 to six to seven. This will translate into an increase in costs for control treatments. These costs will place further pressure on the cost of production, maintaining area freedom status and therefore profit margins. Sutherst *et al.* (2000) modelled the increase in treatment costs with increasing temperatures and concluded that Qfly posed a serious threat to horticultural industries, particularly in southern Australia in a warming climate.

One aspect of bioclimatic niche modelling is that the climatic stress parameters in the modelling software are fixed. This assumes that the current stress tolerances will continue to restrict the species in the future. However, the damage niche areas are situated in southern and coastal Australia where the climatic suitability for Qfly was projected to improve due to decreased cold stress. With projected temperature and summer rainfall increases, the stress tolerances for Qfly therefore remain valid. In spite of this, the modelling results from this study should be used as a guide because the spatial resolution of the climate data microclimate effects were not picked up. Therefore, future work could use fine-resolution, dynamically down-scaled climate data and increase the number of GCMs to account for differences in precipitation projections. The use of such data in CLIMEX will allow remodelling of the EI and abundance of Qfly for particular damage niche areas or locations that produce high value horticultural commodities at a regional and local scale. This will improve the resolution of the spatial distribution and abundance of Qfly in areas where some climatic variation can be obscured due to topography.

Overall, our modelling study casts doubt on the ecological sustainability of large regional pest free areas in Australia. It is likely that other adaptive management options will be developed. Other trade standards such as Areas of Low Pest Prevalence (ALPP) may be developed in the damage niche areas (Dominiak *et al.* 2015). Increasingly, there is a market access movement towards standards other than large pest free regions. These standards are likely to be managed using a systems approach for individual production units or area-wide management for groups of production units (Dominiak 2019; van Klinken *et al.* 2020). Such an approach would lower risks from outbreaks, particularly in urban and peri-urban areas.

ACKNOWLEDGEMENTS

The authors thank Aaron Simmons, Rebecca Darbyshire and journal reviewers for valuable comments and suggestions on this manuscript.

REFERENCES

ABARES. (2015). Agricultural commodities: September quarter 2015 Statistics. http://www.agriculture.gov.au/ag-farm-food/hort-policy/horticulture_fact_sheet#trade-statistics. Accessed 13 June 2016

ABS. (2015). Australian Bureau of Statistics. Value of Agricultural Commodities produced, Australia, year ended 30 June 2014.

Anonymous. (1996). Code of practice for management of Queensland fruit fly. Standing Committee on Agriculture and Resource Management, Department of Primary Industries, Canberra, Australia.

Baker, R.H.A., Sansford, C.E., Jarvis, C.H., Cannon, R.J.C., MacLeod, A. and Walters, K.F.A. (2000). The role of climatic mapping in predicting the potential geographical distribution of non-indigenous pests under current and future climates. *Agriculture, Ecosystems & Environment* **82**: 57-71.

Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., and Whittaker, J.B. (2002). Herbivory in global climate change research: direct effects of rising temperature on insect herbivores. *Global Change Biology* **8**: 1-16.

Battisti, A. and Larsson, S. (2015). Climate change and insect pest distribution range. In Climate Change and Insect Pests, ed. C Bjorkman, P Niemela, pp. 1–15. Wallingford, UK: CABI Int.

Beaumont, L.J., Hughes, L. and Pitman, A. (2008). Why is the choice of future climate scenarios for species distribution modelling important? *Ecological Letters* **11**: 1135-1146.

Bebber, D.P. (2015). Range-Expanding Pests and Pathogens in a Warming World. *Annual Review of Phytopathology* **53**: 335-356.

Buisson, L., Thuiller, W., Casajus, N., Lek, S. and Grenouillet, G. (2010). Uncertainty in ensemble forecasting of species distribution. *Global Change Biology* **16**: 1145-1157.

Chiew, F.H.S., Kirono, D.G.C., Kent, D. and Vaze, J. (2009). Assessment of rainfall simulations from global climate models and implications for climate change impact on runoff studies. 18th World IMACS / MODSIM Congress, Cairns, Australia 13-17: 3907-3913.

Clarke, A.R., Powell, K.S., Weldon, C.W. and Taylor, P.W. (2011). The ecology of *Bactrocera tryoni* (Diptera: Tephritidae): what do we know to assist pest management? *Annals of Applied Biology* **158**: 26-54.

CSIRO and BOM. (2016). State of the Climate 2016. Technical Report, CSIRO and Bureau of Meteorology, Commonwealth of Australia.

DAFWA. (2015). Department of Agriculture and Food, Western Australia. Queensland fruit fly detected in WA. https://www.agric.wa.gov.au/news/media-releases/queensland-fruit-fly-detected-wa. Accessed 6 April 2015

Davis, A.S., Schutte, B.J., Hager, A.G. and Young, B.G. (2015). Palmer Amaranth (*Amaranthus palmeri*) damage niche in Illinois soybean seed limited. *Weed Science* **63**: 658-668.

DEDJTR (Department of Economic Development, Jobs, Transport and Resources, Victoria). (2015). Greater Sunraysia PFA, http://agriculture.vic.gov.au/agriculture/pests-diseases-and-weeds/pest-insects-and-mites/queensland-fruit-fly/greater-sunraysia-pfa. (Accessed 3 March 2016).

Dominiak, B.C., Mavi, H.S. and Nicol, H.I. (2006). Effect of town microclimate on the Queensland fruit fly *Bactrocera tryoni*. *Australian Journal of Experimental Agriculture* **46**: 1239-1249.

Dominiak, B.C. and Coombes, N. (2009). Fruit carrying characteristics of travellers into a quarantine zone in New South Wales in 1999/2000. *Plant Protection Quarterly* **24**: 14-19.

Dominiak, B.C. and Daniels, D. (2012). Review of the past and present distribution of Mediterranean fruit fly (*Ceratitis capitata* Wiedemann) and Queensland fruit fly (*Bactrocera tryoni* Froggatt) in Australia. *Australian Journal of Entomology* **51**: 104-115.

Dominiak, B.C., Wiseman, B., Anderson, C., Walsh, B., McMahon, M. and Duthie, R. (2015). Definition of and management strategies for areas of low pest prevalence for Queensland fruit fly *Bactrocera tryoni* Froggatt. *Crop Protection* **72**: 41-46.

Dominiak, B.C. and Mapson, R. (2017). Revised distribution of *Bactrocera tryoni* in Eastern Australia and effect on possible incursions of Mediterranean fruit fly: Development of Australia's Eastern Trading Block. *Journal of Economic Entomology* **110**: 2459-2465.

Dominiak, B.C. (2019). Components of a systems approach for the management of Queensland fruit fly *Bactrocera tryoni* (Froggatt) in a post dimethoate fenthion era. *Crop Protection* **116**: 56-67.

DPIPWE (Department of Primary Industries, Parks, Water and Environment). (2015). Fruit fly. http://dpipwe.tas.gov.au/biosecurity/plant-biosecurity/pests-and-diseases/fruit-fly. Accessed 26 June 2016

Florec, V., Sadler, R.J., White, B. and Dominiak, B.C. (2013). Choosing the battles: The economics of area wide pest management for Queensland fruit fly. *Food Policy* **38**: 203-213.

Furlong, M.J., Zalucki, M.P., Shabbir, A. and Adamson, D.C. (2017). Biological control of diamondback moth in a climate of change. *Mysore Journal of Agricultural Science* **51**(A): 115-124.

Ge, X.Z., He, S.Y., Wang, T., Yan, W. and Zong, S.X. (2015). Potential Distribution Predicted for *Rhynchophorus ferrugineus* in China under Different Climate Warming Scenarios. *PLOS One* 10. doi: 10.1371/journal.pone.0140000

Guisan, A. and Thuiller, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecological Letters* **8**: 993-1009.

Hall, D. (2015). Fruit fly management - South Australia. Fact Sheet. http://www.pir.sa.gov.au/__data/assets/pdf_file/0006/258693/Fruit_Fly_Management_Fact_Sheet_V4.pdf. Accessed 27 June 2016.

Hancock, D.L., Hamacek, E.L., Lloyd, A.C. and Elson-Harris, M.M. (2000). The distribution and host plants of fruit flies (Diptera: Tephritidae) in Australia. Queensland Department of Primary Industries. ISSN 0727-6273.

Harris, R.M.B., Grose, M.R., Lee, G., Bindoff, N.L., Porfirio, L.L. and Fox-Hughes, P. (2014). Climate projections for ecologists. Wiley Interdisciplinary Reviews. *Climate Change* **5**: 621-637.

Harvey, S., Fisher, B., Larson, K. and Malcom, B. (2010). A benefit cost analysis on management strategies for Queensland fruit fly: methods and observations. AARES National Conference.

Hennessy, K.J. and Colman, R. (2007). in Global Climate Change Projections, Climate Change in Australia - Technical Report 2007 (eds Pearce KB et al). CSIRO.

Hickling, R., Roy, D.B., Hill, J.K., Fox, R. and Thomas, C.D. (2006). The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology* **12**: 450-455.

Holz, G.K., Grose, M.R., Bennett, J.C., Corney, S.P., White, C.J., Phelan, D., Potter, K., Kriticos, D.J., Rawnsley, R., Parsons, D., Lisson, S., Gaynor, S.M. and Bindoff, N.L. (2010). Climate futures for Tasmania: impacts on agriculture technical report. Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania.

Li, Z., Zalucki, M.P., Bao, H., Chen, H., Hu, Z., Zhang, D., Lin, Q., Yin, F., Wang, M. and Feng, X. (2012). Population dynamics and "outbreaks" of diamondback moth (Lepidoptera: Plutellidae) in Guandong Province, China: climate or failure of management? *Journal of Economic Entomology* **105**: 739-752.

Kearney, M. and Porter, W. (2009). Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. *Ecological Letters* **12**: 334-350.

Kriticos, D.J., Webber, B.L., Leriche, A., Ota, N., Macadam, I., Bathols, J. and Scott, J.K. (2012). CliMond: global high-resolution historical and future scenario climate surfaces for bioclimatic modelling. *Methods in Ecology and Evolution* **3**: 53-64.

Kriticos, D.J., Maywald, G.F., Yonow, T., Zurcher, E.J., Herrmann, N.I. and Sutherst, R.W. (2015). CLIMEX

Version 4: Exploring the effects of climate on plants, animals and diseases. CSIRO, Canberra.

Macfadyen, S., McDonald, G. and Hill, M.P. (2018). From species distribution to climate change adaption: knowledge gaps in managing invertebrate pests in broad-acre grain crops. *Agriculture, Ecosystems and Environment* **253**: 208-219.

Maelzer, D.A. (1990a). Fruit fly outbreaks in Adelaide, S.A., from 1948-49 to 1986-87. I. Demarcation, frequency and temporal patterns of outbreaks. *Australian Journal of Zoology* **38**: 439-452.

Maelzer, D.A. (1990b). Fruit fly outbreaks in Adelaide, S.A., from 1948-49 to 1986-87. II. The phenology of both pestilent species. *Australian Journal of Zoology* **38**: 555-572.

McDonald, A., Riha, S., DiTommaso, A. and DeGaetano, A. (2009). Climate change and the geography of weed damage: Analysis of US maize systems suggests the potential for significant range transformations. *Agriculture, Ecosystems & Environment* **130**: 131-140.

Meats, A. (1981). The bioclimatic potential of the Queensland fruit fly, *Dacus tryoni*, Australia. *Proceedings of the Ecological Society of Australia* **11**: 151-161.

Meats, A. (1984). Thermal constraints to successful development of the Queensland fruit fly in regimes of constant and fluctuating temperatures. *Entomologia Experimentalis et Applicata* **36**: 55-59.

Mika, A.M., Weiss, R.M., Olfert, O., Hallett, R.H. and Newman, J.A. (2008). Will climate change be beneficial or detrimental to the invasive swede midge in North America? Contrasting predictions using climate projections from different general circulation models. *Global Change Biology* **14**: 1721-1733

Muthunthantri, S., Maelzer, D., Zalucki, M.P. and Clarke, A.R. (2010). The seasonal phenology of *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae), in Queensland, Australia. *Australian Journal of Entomology* **49**: 221-233.

NSW DPI Plant Biosecurity. (2015). Order O-458 Plant Diseases (NSW Greater Sunraysia Pest Free Area and Fruit Fly Outbreak and Suspension Areas) Order (No3) 2015. http://gazette.legislation.nsw.gov.au/so/download.w3p?id=Gazette_2015_2015-94.pdf#page=2. (Accessed 3 March 2016)

O'Loughlin, G., East, R.A. and Meats, A. (1984). Survival, development rates and generation times of the Queensland fruit fly, *Dacus tryoni,* in a marginally favourable climate: experiments in Victoria. *Australian Journal of Zoology* **32**: 353-61.

Parmesan, C., Ryrholm, N., Stefanescu, C., Hill, J.K., Thomas, C.D., Descimon, H., Hentley, B., Kaila, L., Kullberg, J., Tammary, T., Tennent, W.J., Thomas, J.A. and Warren, M. (1999). Polewards shifts in geographic ranges of butterfly species associated with regional warming. *Nature* **399**: 579-583.

Peters, G.P., Andrew, R.M., Boden, T., Canadell, J.G., Ciais, P., Le Quere, C., Marland, G., Raupach, M.R. and Wilson, C. (2013). The challenge to keep global warming below 2°C. *Nature Climate Change* **3**: 4-6.

PIRSA. (2015). Department of Primary Industries & Regions South Australia. Fruit fly management – South Australia, Fact Sheet. http://pir.sa.gov.au/__data/assets/pdf_file/0006/258693/Fruit_Fly_Management_Fact_Sheet_V4.pdf. (Accessed 3 March 2016).

Raghu, S., Clarke, A.R., Drew, R.A.I. and Hulsman, K. (2000). Impact of habitat modifications on the distribution and abundance of fruit flies (Diptera: Tephritidae) in Southeast Queensland. *Population Ecology* **42**: 153-160.

Stephens, A.E.A., Kriticos, D.J. and Leriche, A. (2007). The current and future potential geographical distribution of the oriental fruit fly, *Bactrocera dorsalis* (Diptera : Tephritidae). *Bulletin of Entomological Research* **97**: 369-378.

Sultana, S., Baumgartner, J.B., Dominiak, B.C., Royer, J.E. and Beaumont, L.J. (2017). Potential impacts of climate change on habitat suitability for the Queensland fruit fly. *Scientific Reports* 7: 13025 DOI:10.1038/s41598-017-13307-1.

Sultana, S., Baumgartner, J.B., Dominiak, B.C., Royer, J.E. and Beaumont, L.J. (2019). Impacts of climate change on high priority fruit fly species in Australia. *bioRxiv doi.org*/10.1101/567321.

Sutherst, R.W., Collyer, B.S. and Yonow, T. (2000). The vulnerability of Australian horticulture to the Queensland fruit fly, *Bactrocera* (Dacus) *tryoni*, under climate change. *Australian Journal of Agricultural Research* **51**: 467-480.

Taylor, S. and Kumar, L. (2013). Potential distribution of an invasive species under climate change scenarios using CLIMEX and soil drainage: A case study of *Lantana camara* L. in Queensland, Australia. *Journal of Environmental Management* **114**: 414-422.

Trnka, M., Muška, F., Semerádová, D., Dubrovský, M., Kocmánková, E. and Žalud, Z. (2007). European Corn Borer life stage model: Regional estimates of pest development and spatial distribution under present and future climate. *Ecological Modeling* **207**: 61-84.

Van Klinken, R.D., Fiedler, K., Kingham, L., Collins, K. and Barbour, D. (2020). A risk framework for using systems approaches to manage horticultural biosecurity risks for market access. *Crop Protection* **129**: 104994

Webb, L. and Whetton, P.H. (2010). Horticulture. In: Stokes, C, Howden, M (eds) Adapting agriculture to climate change: preparing Australian agriculture, forestry and fisheries for the future. CSIRO Publishing, Melbourne, pp 119-136.

Webb, M.A. (2012). Seasonal climate summary southern hemisphere (summer 2011-12): a mature La Nina, strongly positive SAM and active MJO. *Australian Meteorological and Oceanographic Journal* **62**: 335-349.

Webber, B.L., Yates, C.J., Le Maitre, D.C., Scott, J.K., Kriticos, D.J., Ota, N., McNeil, A., Le Roux, J.J. and Midgley, G.F. (2011). Modelling horses for novel climate courses: insights from projecting potential distribution of native and alien Australian acacias with correlative and mechanistic models. *Diversity and Distribution* **17**: 978-1000.

Whetton, P., Hennessy, K., Clarke, J., McInnes, K. and Kent, D. (2012). Use of Representative Climate Futures in impact and adaptation assessment. *Climate Change* **115**: 433-442.

White, B., Sadler, R., Florec, V., Dominiak, B.C., More, K., Buetre, B. and Abougamous, H. (2011). Optimal Investment in R&D for Plant Biosecurity. Final report CRC70100. http://legacy.crcplantbiosecurity.com.au/sites/all/files/70100_final_report.pdf. Accessed 26 June 2016

White, C.J. and Fox-Hughes, P. (2013). Seasonal climate summary southern hemisphere (summer 2013-13): Australia's hottest summer on record and extreme east coast rainfall. *Australian Meteorological and Oceanographic Journal* **63**:443-436.

Yonow, T. and Sutherst, R.W. (1998). The geographical distribution of the Queensland fruit fly, *Bactrocera* (Dacus) *tryoni*, in relation to climate. *Australian Journal of Agricultural Research* **49**: 935-953.

Yonow, T., Zalucki, M.P., Sutherst, R.W., Dominiak, B.C., Maywald, G.F., Maelzer, D.A. and Kriticos, D.J. (2004). Modelling the population dynamics of the Queensland fruit fly, *Bactrocera* (Dacus) *tryoni*: a cohort-based approach incorporating the effects of weather. *Ecological Modelling* **173**: 9-30.

Ziter, C., Robinson, E.A. and Newman, J.A. (2012). Climate change and voltinism in Californian insect pest species: sensitivity to location, scenario and climate model choice. *Global Change Biology* **18**: 2771-2780.