

# A robust impact assessment that informs actionable climate change adaptation: future sunburn browning risk in apple

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Received: 18 October 2015 / Revised: 21 October 2016 / Accepted: 22 October 2016 / Published online: 14 November 2016  
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**Abstract** Climate change impact assessments are predominantly undertaken for the purpose of informing future adaptation decisions. Often, the complexity of the methodology hinders the actionable outcomes. The approach used here illustrates the importance of considering uncertainty in future climate projections, at the same time providing robust and simple to interpret information for decision-makers. By quantifying current and future exposure of Royal Gala apple to damaging temperature extremes across ten important pome fruit-growing locations in Australia, differences in impact to ripening fruit are highlighted, with, by the end of the twenty-first century, some locations maintaining no sunburn browning risk, while others potentially experiencing the risk for the majority of the January ripening period. Installation of over-tree netting can reduce the impact of sunburn browning. The benefits from employing this management option varied across the ten study locations. The two approaches explored to assist decision-makers assess this information (a) using sunburn browning risk analogues and (b) through identifying hypothetical sunburn browning risk thresholds, resulted in varying recommendations for introducing over-tree netting. These recommendations were location and future time period dependent with some sites showing no benefit for sunburn protection from nets even by the end of the twenty-first century and others already deriving benefits from employing this

adaptation option. Potential best and worst cases of sunburn browning risk and its potential reduction through introduction of over-tree nets were explored. The range of results presented highlights the importance of addressing uncertainty in climate projections that result from different global climate models and possible future emission pathways.

**Keywords** Extreme temperature · Sunburn browning · Netting · Horticulture · Pome fruit · Climate projections

## Introduction

The purpose for undertaking most climate change impact assessments should be to inform adaptation decisions or prompt action for greenhouse gas mitigation. Many impact assessments, however, are not solution-focused nor do they respond to end-user perspectives (Kiem and Austin 2013). In presenting their results to end-users and decision-makers, the science community often focuses on exploring and explaining subjects, such as uncertainties in climate projections, which can over-complicate the advice. Here, an approach is outlined that aimed to provide robust yet simple results to enable actionable decisions while also including the uncertainty in future climate projections.

An increase in the occurrence of extreme heat events has been observed historically in Australia (Alexander et al. 2007; Trewin and Smalley 2013). The apple industry, which had a 2014–2015 gross value of \$AU550 million (ABS 2016), is particularly vulnerable to these extreme heat events as high air temperatures and solar radiation exposure cause ‘sunburn browning’, a brown spot on the sun-exposed side of the fruit, with affected fruit unmarketable (Schrader et al. 2003a, b; Thomson et al. 2014; Racsko and Schrader 2012). For example, a heat wave event in January 2009 in south-east Australia

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resulted in large yield losses due to sun damage, approximated at between 30 and 70% of the crop (Thomson et al. 2014). Under anthropogenic climate change, increases in the intensity, frequency, duration and spatial extent of extreme temperatures in Australia are expected (Alexander and Arblaster 2009; CSIRO and BoM 2015; IPCC 2012) potentially increasing the risk of sunburn damage.

Given this potential risk, many fruit-growing districts in Australia will likely need to implement adaptation strategies to minimise potential sun damage (Thomson et al. 2014). One adaptation option is to use over-tree netting to protect fruit from extreme conditions (Fig. 1, left). In a recent study, Darbyshire et al. (2015) determined minimum air temperature thresholds that can result in sun damage of ‘Royal Gala’ apple in non-netted and netted orchards. Their assessment employed thermocouple sensors under the fruit skin (Fig. 1, right) in combination with air temperature sensors. They identified air temperature thresholds of 34.1 and 37.9 °C that correlate to minimum FST thresholds that can cause sunburn browning in netted and non-netted orchards, respectively. To evaluate the use of over-tree netting as an adaptation strategy to reduce the risk of sun damage, this climate change impact study presents a method that minimised the potential number of descriptive climate projections to produce results aimed at informing adaptive actions. This was evaluated considering the frequency of exceedance of threshold air temperatures now and in future periods for non-netted and netted orchards. Current (centred on 1995) and projected threshold exceedance centred on 2030 and 2050, aligning with orchardists’ shorter and mid-term planning frameworks, respectively, was evaluated. In addition, a period centred on 2090 was assessed to align with long-term strategic planning.

To address the demand for regionally relevant climate change information (Kiem and Austin 2013), ten locations important for pome fruit production in Australia, covering a broad geographical extent and corresponding range of underlying climates, were assessed. One significant advantage to studying multiple locations in an impact assessment is that areas that experience similar climatic conditions, but which may be separated in space or time (i.e. with past or future climates), can be identified, i.e. climate analogues (Whetton et al. 2013). This can be helpful when considering adaptation strategies to a changing

climate (Hallegatte et al. 2007; Webb et al. 2013), a technique that will be demonstrated in this study.

For adaptation actions to be effective, comprehensive and plausible representation of the future climate is required to inform the projection results. The recently published Australian climate change projections are based on the full body of knowledge of the climate system and the most up to date perspective on how the current climate may change under enhanced greenhouse gas concentrations (CSIRO and BoM 2015). These projections of the future climate were informed by 40 Coupled Model Intercomparison Project 5 (CMIP5) (Meehl and Bony 2011) global climate models (GCMs), simulating the climate response to a range of plausible scenarios of how greenhouse gases and aerosols may change throughout the twenty-first century (Van Vuuren et al. 2011), termed Representative Concentration Pathways (RCPs).

The use of over-tree netting as a climate adaptation option for Royal Gala apple was used as an example to demonstrate a method that simplifies complex climate projection information in a manner that promotes climate adaptation uptake while retaining scientific robustness. Evaluating the potential benefit of installing netting to reduce apple sunburn risk is a useful case study as financial loss can be significant from extreme heat events and netting is a clear implementable management option. The method used best-case and worse-case climate scenarios for several future time periods to evaluate future sunburn browning risk with and without the adaptation option of installing netting. This was applied Australian wide to ten growing districts to evaluate the adaptation option under future climates and across various site climate conditions. The results were interpreted using several different approaches, including climate analogues and considering different levels of grower risk aversion.

## Materials and methods

### Locations and regions assessed in the study

Climate data were selected from ten locations that represent the main commercial apple-growing regions in Australia. These were Applethorpe in Queensland, Donnybrook and Manjimup



**Fig. 1** A netted ‘Royal Gala’ apple orchard in Shepparton, Victoria (*left*), Royal Gala apples with evidence of sunburn browning damage (*centre*) and a thermocouple sensor placed under the fruit skin of a Royal Gala apple to measure fruit surface temperature (*right*)

in Western Australia, Lenswood in South Australia, Batlow and Young in New South Wales, Tatura and the Yarra Valley in Victoria and Spreyton and Huonville in Tasmania (Fig. 2). These locations were in two broad regions identified in a study by CSIRO and BoM (2015) based on their climate change response, denoted as either the Central Slopes or Southern Australia.

Recent climate projections for Australia were regionalised according to logical groupings of recent-past climatic conditions, biophysical factors and expected broad patterns of climate change (CSIRO and BoM 2015). The ten study locations are contained in two of these regions: Central Slopes and Southern Australia (Fig. 2). Temperature projection results from these two regions were used to inform selection of GCMs for this assessment.

### Projection methods

Analyses were conducted using daily maximum temperature (Tmax) for January, when most sun damage is incurred for Royal Gala apple, following Darbyshire et al. (2015). It was important to set the context in this climate change impact assessment by including historical risk, therefore allowing the change in risk to be investigated. In this study, historical risk was analysed using a 30-year baseline period centred on 1995 (1981–2010) using gridded (0.05° by 0.05°) daily January Tmax data obtained from the Australian Water Availability Project (AWAP) (Jones et al. 2009). Henceforth, this 30-year historical range is referred to as 1995.

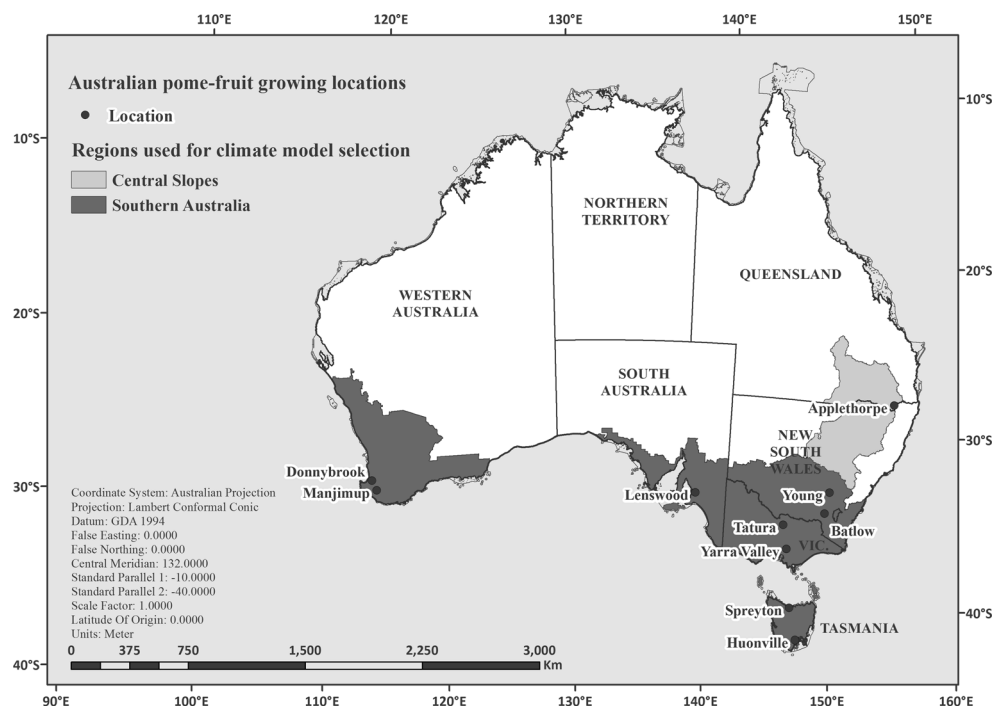
Future daily Tmax conditions were assessed in the study, with the aim to capture the range of climate projections resulting from the future range of RCPs and corresponding range of CMIP5 GCM output. To achieve this, a subset of RCPs and GCMs were identified and combined to create ‘best-case’ and ‘worse-case’ future climate scenarios. The selection of RCPs, GCMs and the method used to include day-to-day natural variability is detailed below:

### Emission pathways

Two RCPs (Moss et al. 2010; Van Vuuren et al. 2011) were selected to include the likely future range in emissions.

1. RCP4.5: An intermediate pathway, which represents a future where carbon dioxide (CO<sub>2</sub>) emissions peak around 2040 and strong mitigation of emissions occurs in the latter half of the century, CO<sub>2</sub> concentrations reach 540 ppm by 2100. This scenario is similar to the Special Report on Emissions Scenarios (SRES) B1 scenario (Nakićenović and Swart 2000).
2. RCP8.5: A high pathway, which represents a future with little curbing of emissions, where the CO<sub>2</sub> concentration continues to rapidly rise, reaching 940 ppm by 2100. Current CO<sub>2</sub> concentration analysis indicates that we are tracking along this trajectory (Peters et al. 2012). This pathway is similar to the SRES A1FI scenario (Rogelj et al. 2012).

**Fig. 2** Australian pome fruit-growing locations (black dot) are shown in context of Australian states (capital letters; Victoria abbreviated to Vic.). The regions defined in CSIRO and BoM (2015) used for model selection in this study are Southern Australia (dark grey) and Central Slopes (light grey)



### Selecting GCMs

The 40 GCMs available from the CMIP5 were investigated to select GCMs that best defined the projected range in  $T_{max}$  for the two regions (Fig. 2). These were selected by analysing summer (harvest season)  $T_{max}$  projections for all 40 GCMs over three time periods: 2030 (2016–2045), 2050 (2036–2065) and 2090 (2075–2104) (henceforth referred to as 2030, 2050 and 2090) and the two identified RCPs (40 GCMs for RCP8.5 and 38 GCMs for RCP4.5) using the Australian Climate Futures approach (Clarke et al. 2011; Whetton et al. 2012). For each region, this approach categorised and then ranked projected increases in summer  $T_{max}$  GCM output using a multivariate ordering technique (Kokic et al. 2002). After ranking, only 26 GCMs of the 40 were considered for inclusion in the assessment as the remaining 14 have been found to perform poorly across a number of metrics for Southern Australia (Moise et al. 2015).

This assessment found that two GCMs, CanESM2 and MIROC5, best described the range in projected summer  $T_{max}$  increases for both the Southern Australian and Central Slopes regions (Table 1). Across both regions, the CanESM2 model was consistently warmer than the ensemble mean, while the MIROC5 model was consistently cooler than the mean. While these GCMs were not always the absolute least or most warming for each time period and RCP in the defined regions, across the range of future scenarios being considered, they represented the range well.

Using these selections of RCPs and GCMs, best-case and worst-case future scenarios were constructed to capture the range of climate projection uncertainty. The best-case scenario was constructed using MIROC5 forced by RCP4.5, and the worse-case scenario was similarly constructed using CanESM2 and RCP8.5. As such, reliance on using GCM names and emission pathway terminology was removed.

### Representing natural variability in the projected $T_{max}$ time series

To create future daily  $T_{max}$  time series, projected average monthly January  $T_{max}$  change values centred on 2030, 2050 and 2090 for the best-case and worst-case scenarios were added to the AWAP observed January daily  $T_{max}$  time series (1981 to 2010). To capture the most reliable estimate of location-specific natural climate variability, the baseline  $T_{max}$  time series was contrived to extend for the longest possible period, 30 years, while remaining centred on 1995 (CSIRO and BoM 2015). In this way, the influence of decadal shifts that may skew the ‘normal’ climatology, such as the Australian Millennium drought (Dijk et al. 2013), was minimised. By using this approach, the future variability in each scenario was the same as the underlying natural baseline temperature variability.

### Assessment of sunburn browning risk

For all locations, the 10th, 50th and 90th percentile of a 30-year time series of the number of days in January that  $T_{max}$  exceeded 34.1 °C (sunburn browning non-netted) and 37.9 °C (sunburn browning netted) (Darbyshire et al. 2015) were generated using the baseline (1995) period and each of the future periods (2030, 2050 and 2090).

The entire plausible range of days exceeding the threshold, or *sunburn browning risk* (days), for each future time period, was captured by incorporating results across the best-case and worst-case scenarios.

The potential benefit of netting, measured as a reduction in the number of sunburn browning risk days, was evaluated. To interpret this reduction in terms of benefit of netting, two risk cases were identified:

1. Risk-sensitive: Netting was introduced if the *maximum* (90th percentile) number of days in a 30-year period experiencing sunburn browning risk was greater than 20% of days in the month (i.e. 6 days).
2. Risk-tolerant: Netting was introduced if the *median* (50th percentile) number of days in a 30-year period experiencing sunburn browning risk was greater than 20% of days in the month (i.e. 6 days).

### Use of ‘sunburn browning risk’ analogues

An alternative method to assist decision-makers regarding the timing of introduction of over-tree nets is to identify a location where the threshold was already exceeded, i.e. where over-tree netting is already employed to minimise sunburn browning risk. Decision-makers will decide to introduce over-tree nets once the climate becomes similar, or analogous, to the identified location. To assist with using this approach, sunburn browning risk analogues were identified across the ten study locations for 2030, 2050 and 2090.

To define sunburn browning risk analogues, sunburn browning risk was categorised and colour coded as in Table 2.

## Results

Historical (1981–2010) daily January  $T_{max}$  ranges for the ten study locations indicated that Spreyton and Huonville were the coolest locations, with the warmest locations being Donnybrook and Young (Fig. 3; also see Fig. 2 map). Exceedance of non-netted (34.1 °C) and netted (37.9 °C) sunburn browning air thresholds for the period 1981–2010 occurred where the boxplot crossed the indicative lines.

**Table 1** Projected change in summer Tmax (°C) for Southern Australia and Central Slopes regions (see Fig. 2) for 20-year periods centred on 2030, 2050 and 2090, relative to the the 20-year period centred on 1995, under RCP4.5 and RCP8.5 for CanESM2 and MIROC5 CMIP5 GCMs, compared to the ensemble mean and standard deviation of 40 (RCP8.5) and 38 (RCP4.5) GCMs

	Southern Australia					Central Slopes				
	2030	2050		2090		2030	2050		2090	
	Both RCPs	RCP4.5	RCP8.5	RCP4.5	RCP8.5	Both RCPs	RCP4.5	RCP8.5	RCP4.5	RCP8.5
CanESM2	1.2	1.5	2.5	2.2	4.8	0.9	2.0	3.0	2.7	5.4
MIROC5	0.9	1.2	1.4	1.8	2.7	0.5	1.1	1.5	1.9	2.8
Mean	1.0	1.5	1.9	2.0	3.8	1.1	1.6	2.1	2.4	4.1
Standard deviation	0.3	0.4	0.4	0.5	0.9	0.5	0.7	0.7	0.7	0.9

**Current and projected sunburn browning risk**

The current (1995) and future (2030, 2050 and 2090) median (10th and 90th percentile in brackets) sunburn browning risk (days) for non-netted trees at the ten study locations is described in Table 3. To simplify the results, the range included both best-case and worse-case scenarios for each time period.

The median number of sunburn browning risk days for the 1995 period varied with location, from no damage at Spreyton, through to 3 days for Lenswood, 7 days for Donnybrook and 9 days for Young. The maximum exceedance in any 1 year through this period was 16 days recorded at Young (in the years 1988, 2003, 2006 and 2009).

For Tatura, a key growing district, median sunburn browning risk of approximately 9 days was projected by 2030. This could be up to 16 days in hottest years under a worst-case scenario, but in coolest years and best-case scenario, only 3 days would be expected to exceed the sunburn browning threshold temperature. In contrast under both best-case and worst-case scenarios and across the natural variability, Spreyton remained largely risk-free through to 2090 (Table 3).

To compare the sunburn browning risk between locations and for future time periods, instances with similar median sunburn browning risk were colour-coded in Table 3. These shadings indicate sunburn browning risk analogues. For example, the current sunburn browning risk at Young (median of 9 days per month) is expected at Tatura in 2030, while the

current risk at Tatura (6 days per month) is expected at Lenswood, Manjimup, Batlow and the Yarra Valley by 2090.

**Reduced sunburn browning risk through installation of over-tree nets**

Sunburn browning risk (days) with the installation of over-tree netting was evaluated (Table 4). With nets in place at Tatura, the maximum exposure for 2030 was halved to approximately 8 days for the hottest projected years and a worse-case projection scenario (16.3 days Table 3 vs. 8.4 days Table 4). By 2090 in Young, where up to 24.9 days of sunburn browning risk was experienced in the hottest years and under a worst-case scenario (no nets; Table 3), sunburn browning risk nearly halved to approximately 14 days with over-tree nets in place (Table 4), which is similar to current risk at Young, in the hottest years under a worst-case scenario, for non-netted trees (Table 3).

The reduction in sunburn browning risk (days) was calculated by measuring the average difference in exposure with and without over-tree nets. This is illustrated spatially separately for best-case and worst-case future scenarios for 2090 (Fig. 4). Tasmanian locations had little benefit from the installation of nets with Spreyton indicating 0-day benefit. Average exposure in Huonville was reduced by approximately 1 day under the best-case future scenario and up to 2 days under the worst case. For Manjimup, a more than 5-day (on average) improvement was realised through application of nets (worst case) or approximately 3 to 4 days (on average, best case). In currently hot areas, such as Young,

**Table 2** Sunburn browning risk (days) for the month (top) and proportion of days in the month (bottom)

≤ 1.6 days	1.7 to 3.1 days	3.2 to 6.2 days	6.3 to 9.3 days	9.4 to 15.5 days	≥ 15.6 days
≤ 5.0 %	5.1 to 10.0 %	10.1 to 20.0 %	20.1 to 30.0 %	30.1 to 50.0 %	≥ 50.1 %

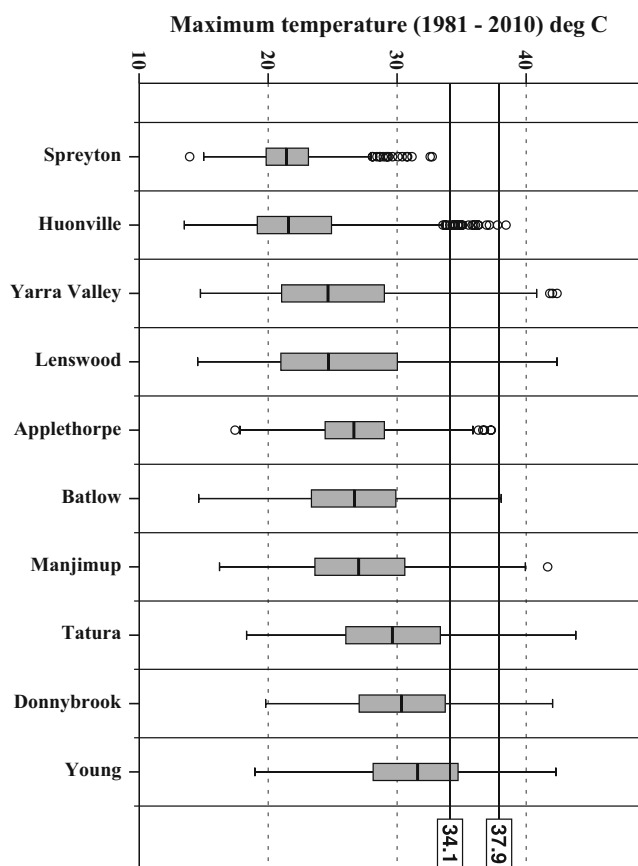
Colour shading corresponds to periods and locations having these sunburn browning risk levels

nets reduced sunburn browning risk by 8 to 9 days (on average, best to worst case).

To evaluate potential decisions to install netting, the results were interpreted for two risk cases:

1. Risk-sensitive option (e.g. *maximum* sunburn browning risk (90th percentile) >6 days; Table 3).
2. Risk-tolerant option (e.g. *median* sunburn browning risk (50th percentile) >6 days; Table 3).

Depending on the risk case selected, nets were applied at different locations and different time periods as shown in Table 5. Under the risk-sensitive case, nets were applied at more locations and earlier. For example, it is only under the risk-sensitive case that nets were applied in Batlow. A further example at Manjimup indicated that nets would be installed in 2030 under the risk-sensitive case and not until 2090 under a risk-tolerant case. Installation of netting will be beneficial even for the historical period under either risk case in Young, Donnybrook and Tatura.



**Fig. 3** Boxplot showing daily January maximum temperature (°C) for 1981–2010 for the ten locations in the study (also see Fig. 2 map). The interquartile range (IQR) of the sample is indicated by the height of the box, the sample median (the *horizontal bar*) and 1.5 times IQR (the *whiskers*), with outliers (the ‘o’). Tmax thresholds (the *horizontal solid lines*) are given for sunburn risk (non-netted) 34.1 °C and sunburn risk (netted) 37.9 °C

## Discussion

The disconnect between defensible, credible and legitimate climate projection information and end-user requirements can act as a barrier to actionable climate adaptation recommendations (Kiem and Austin 2013). Indeed, inability to ever fully resolve uncertainty in climate projections should not restrict decision-relevant information being provided to inform end-users.

Presentation of context-specific best-case and worst-case outcomes can remove the barrier between the science and the end-user, with the decision-maker having robust information ready for decision implementation. In a critical first step to simplifying the outcomes of this study, two GCMs representative of the range of change were selected (Clarke et al. 2011; Whetton et al. 2012). Further to this, RCP4.5 and RCP8.5 (Van Vuuren et al. 2011) were used to represent the range of plausible future emission scenarios. While a lower option (RCP2.6) was available for modelling, this pathway was not considered achievable given current global emission policy settings (Meinshausen et al. 2009; Peters et al. 2012) and was therefore not assessed. Combining the projection information, scenarios for the best case, i.e. least-warming GCM/lowest emission pathway, and worst case, i.e. most-warming GCM/highest emission pathway, were identified and presented. This ensured that the full profile of climate projections was captured in a simplified manner without reducing the credibility of the results or the relevance of potential decision options. In doing so, a great deal of unnecessary complexity in calculation and presentation of data and results was avoided (Smith and Chandler 2010) and climate science terminology minimised. This approach could be applied to other impact analyses using temperature change or extended to studies where both temperature and rainfall are important, with for instance, best case identified as least-warming and wettest and worst case most-warming and driest future scenario.

Note that results need to be interpreted across the range of the best-case and worse-case scenarios. Employing only one GCM or RCP in an impact assessment can inadvertently lead to potentially flawed adaptation decisions. For example, at Applethorpe by 2090 and under the best-case scenario, a 1.5-day reduction to sunburn browning risk was achieved from over-tree netting, perhaps resulting in a decision not to install nets (see Fig. 4). Under the worst-case scenario, with nearly 6-day reduction to sunburn browning risk, nets could be considered useful (Fig. 4). Presenting the range of best-case and worst-case projections gives end-users the opportunity to make a better-informed decision by appreciating the range of likely options.

In this assessment, only some growing locations are at risk of sunburn browning under current and future climates. For example, for the Tasmanian locations of Huonville and Spreyton, sunburn browning risk remains minimal right through to the end of the century. However, for Young and

**Table 3** Median (10th to 90th percentile in brackets) sunburn browning risk (days) for ten Australian pome fruit-growing locations for 30-year periods centred on 1995, 2030, 2050 and 2090

Location	1995	2030	2050	2090
Spreyton	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.3)
Huonville	0.0 (0.0 to 2.0)	1.0 (0.0 to 2.7)	1.0 (0.0 to 2.9)	1.5 (0.0 to 3.2)
Yarra Valley	2.0 (0.0 to 7.7)	4.3 (0.6 to 9.2)	4.6 (0.6 to 9.5)	5.6 (1.3 to 10.5)
Lenswood	3.0 (1.0 to 7.0)	4.5 (1.6 to 9.4)	5.1 (1.8 to 10.2)	6.0 (2.8 to 10.7)
Applethorpe	0.0 (0.0 to 2.0)	0.3 (0.0 to 4.6)	1.0 (0.0 to 5.9)	3.0 (0.0 to 9.7)
Batlow	1.0 (0.0 to 4.0)	2.9 (0.0 to 7.7)	4.1 (0.0 to 9.5)	5.5 (0.3 to 12.6)
Manjimup	2.5 (0.0 to 5.0)	3.9 (0.1 to 7.2)	4.5 (1.1 to 7.7)	6.1 (2.1 to 9.5)
Tatura	6.0 (1.0 to 13.0)	9.4 (3.3 to 16.3)	10.4 (4.5 to 17.7)	13.0 (6.5 to 21.0)
Donnybrook	7.0 (3.0 to 11.0)	8.9 (3.2 to 13.9)	10.3 (4.1 to 15.4)	12.8 (7.1 to 18.4)
Young	9.0 (1.2 to 16.0)	13.3 (2.6 to 20.2)	15.4 (3.8 to 22.7)	17.8 (5.8 to 24.9)

Future sunburn browning risk incorporates potential best-case and worst-case results. Sunburn browning risk categories and colour coding defined in the [Materials and methods](#) section of this publication

Tatura, by mid-century, over a third of days in the harvest month could pose a sunburn browning threat.

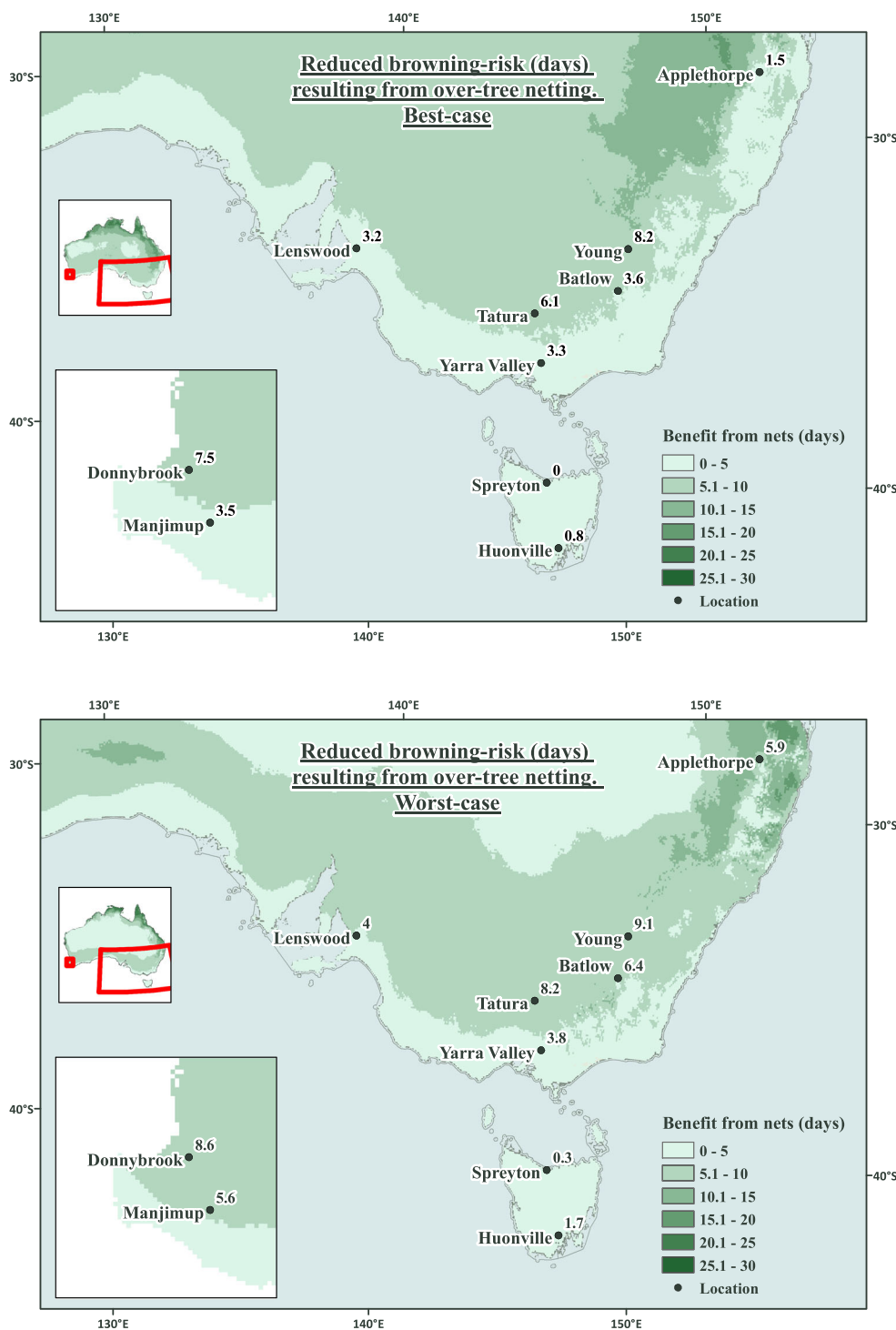
Over-tree netting is an effective option for reducing sunburn browning risk (Smit 2007; Smit et al. 2008; Solomakhin and Blanke 2010) and was found in this study to notably reduce sunburn browning risk for most growing districts. Adaptation planning to determine the time period in which nets could be introduced to reduce sunburn browning risk was explored. This can be informed by using analogues of current and future exposure to extreme heat events (Webb et al. 2013). For example, the exposure to damaging heat events currently experienced in Tatura is likely to be the same as that projected for Lenswood by 2050 or Batlow by 2090. The benefit of future investment in over-tree nets for Lenswood or Batlow can be informed by looking at current regional netting practises in Tatura.

An alternative approach for informing future adaptation planning decisions was presented using two hypothetical risk profiles: a risk-sensitive and a risk-tolerant. Using this approach, nets would be recommended to be installed at different locations at different times through the twenty-first century. While this example was informative, individual risk assessment will likely change with appetite for business risk, grower experience and financial position. A benefit-cost analysis would assist with this decision-making. An assessment of the economics of installing nets in the current climate in Europe, for example, showed that they were not economically beneficial (Iglesias and Alegre 2006). This would certainly apply in Tasmania where the cost of netting would exceed crop loss due to sunburn browning. For other locations, the benefit-cost ratio would vary and could be estimated both

**Table 4** As for Table 3, with over-tree nets in place

Location	1995	2030	2050	2090
Spreyton	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.0)
Huonville	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.5)	0.0 (0.0 to 1.0)	0.3 (0.0 to 1.3)
Yarra Valley	0.0 (0.0 to 1.9)	0.9 (0.0 to 3.5)	1.3 (0.0 to 4.2)	1.9 (0.0 to 6.1)
Lenswood	1.0 (0.0 to 2.9)	1.5 (0.0 to 4.5)	1.8 (0.3 to 5.2)	2.3 (0.3 to 5.7)
Applethorpe	0.0 (0.0 to 0.0)	0.0 (0.0 to 0.5)	0.0 (0.0 to 1.0)	0.0 (0.0 to 2.0)
Batlow	0.0 (0.0 to 0.0)	0.0 (0.0 to 1.0)	0.1 (0.0 to 2.5)	0.6 (0.0 to 4.0)
Manjimup	0.0 (0.0 to 2.0)	0.0 (0.0 to 2.5)	0.5 (0.0 to 3.0)	1.4 (0.0 to 4.3)
Tatura	2.0 (0.0 to 5.9)	2.8 (0.0 to 8.4)	3.6 (0.3 to 9.4)	5.6 (0.8 to 12.6)
Donnybrook	1.0 (0.0 to 3.0)	2.0 (0.0 to 5.0)	3.0 (0.0 to 5.7)	5.0 (1.0 to 8.2)
Young	2.0 (0.0 to 5.9)	3.9 (0.0 to 9.0)	5.4 (0.5 to 11.5)	7.8 (1.1 to 14.2)

**Fig. 4** The average reduction of sunburn browning risk days for 2090 resulting from using over-tree netting for best-case (*top*) and worst-case (*bottom*) scenarios



under current and future climates (not in the scope of this study).

In further support of over-tree netting for use as an adaptation measure, several additional benefits to reducing sunburn browning risk, such as reduced hail damage, irrigation requirement, incidence of bitter pit and apple scab, decay after cold storage and fruit fly damage, have been reported (do Amarante et al. 2011).

Negative effects of installing netting have been reported including poorer skin colour (pale blush and a more intense green background colour), higher soluble solid concentration (SSC) and increased starch. Interestingly, when tasting apple slices of undamaged and sunburned fruit, sunburned fruit were consistently rated higher than undamaged fruit due to their higher SSC and lower tartaric acid concentration (Racsko and Schrader 2012);



**Table 5** Decision not to install nets (X) or to install nets (✓) for a risk-sensitive case (maximum sunburn browning risk >6 days; Table 3) (left) and a risk-tolerant case (median sunburn browning risk >6 days; Table 3) (right)

Location	Risk-sensitive			Risk-tolerant		
	2030	2050	2090	2030	2050	2090
Spreyton	X	X	X	X	X	X
Huonville	X	X	X	X	X	X
Yarra Valley	✓	✓	✓	X	X	X
Lenswood	✓	✓	✓	X	X	✓
Applethorpe	X	X	✓	X	X	X
Batlow	✓	✓	✓	X	X	X
Manjimup	✓	✓	✓	X	X	✓
Tatura	✓	✓	✓	✓	✓	✓
Donnybrook	✓	✓	✓	✓	✓	✓
Young	✓	✓	✓	✓	✓	✓

therefore, processed (e.g. apple chips, apple pie, apple juice) or semi-processed (e.g. fresh cut slices) forms of apple may show future promise for marketing sunburnt fruit.

There are also community and social barriers and/or incentives that need to be considered when deciding to install nets. For example, in some regions in Australia (e.g. Yarra Valley), visual amenity of nets has restricted their introduction, whereas in other areas (NSW), government financial incentives exist for growers wishing to install netting (NSW Government 2015).

Other adaptation measures to reduce exposure to sunburn include evaporative cooling, fruit bagging or particle films (Gindaba and Wand 2006; Racsko and Schrader 2012). Over-tree evaporative cooling systems based on pulsing water applications can reduce sunburn, while also reducing tree transpiration and irrigation requirements (Green et al. 2012). However, access to water for this purpose needs to be considered (Evans 2004), especially for drought-prone areas like Australia. Many physiological and cultural management practises can also influence the extent of sunburn browning in apples: cultivar susceptibility, developmental stage of fruit, tree form and training system, row orientation in the orchard, growth vigour (rootstock, pruning) and water stress (Racsko and Schrader 2012). Acclimation, by previous exposure to high temperatures within the season, can also reduce the extent of sunburn damage (Racsko and Schrader 2012).

This study aimed at providing information to assist with climate adaptation. The approach indicated an increase in the number of days potentially suitable for the formation of sunburn browning damage. Use of a threshold assessment linearly massing ‘potential damage days’ or sunburn browning risk was appropriate for climate projection application and provided growers with clear information on potential changes in sunburn browning risk. Building a more complex model accounting for all additional aspects (UV, wind speed, humidity, colour, etc.) of

individual fruit incorporating canopy structure modelling could go part way to estimating damage at particular growing points. To our knowledge, such models have not been developed. Furthermore, combining these sorts of fine flux models (subdaily and very small spatial component) with climate projection data would be misrepresentative. Climate projection models are unable to accurately resolve variables such as wind speed through complex landscapes and still require work in predicting sequences of weather, such as heat waves.

Apples can respond to high-temperature stress, even at advanced stages of maturity, by synthesising heat shock proteins, which likely play an important role in protecting cellular biochemical processes during periods of stress (Ritenour et al. 2001). Theoretically, summer pruning and leaf thinning should be performed on cool overcast days when the forecast is for cloudy weather in following days to allow time for heat shock proteins to accumulate prior to exposure to direct solar radiation. However, the timing and duration of exposure required to encourage production of heat shock proteins are not fully understood. Slow, progressive exposure may allow their protective build-up (Ritenour et al. 2001; Wünsche et al. 2004; Zhang et al. 2003; Ma and Cheng 2004; Edreva 2005). Future strategies may make better practical use of this knowledge by preparing fruit for sun exposure (Wünsche et al. 2001; Ritenour et al. 2001).

There are other cultivars, not commercially grown in Australia, that are more susceptible to sunburn browning. For instance, ‘Cameo’ and ‘Honeycrisp’ were found to sustain damage at 46 °C (Schrader et al. 2003b), lower than that for Gala (47.8 °C, Schrader et al. 2001). Royal Gala was used in this assessment as production in Australia is high, with production in 2007/2008 the third highest behind Cripps Pink and Granny Smith (Australian Bureau of Statistics 2008).

Other forms of sunburn such as sunburn necrosis, a more severe level of damage, could also be considered using the framework outlined in this study. Identification of air threshold temperature for sunburn necrosis on Royal Gala apple under nets would need to be evaluated prior to such an analysis and highlights a topic for further study (Darbyshire et al. 2015). The nature of extreme heat events, often occurring from less than 1 day to a few days at most, requires use of special modelling techniques that are not available directly from GCM output. Projections from GCMs are commonly produced at a monthly timescale, with daily output unable to be directly interpreted. To overcome this, different techniques that can produce locally relevant, synthetic future daily data can be used. These methods include using weather generators, statistical downscaling, the change factor method or dynamical downscaling. There are pros and cons of these different approaches, and there is no one best method (CSIRO and BoM 2015; Wilby et al. 2009). In this analysis, the change factor method was used to generate a synthetic future daily temperature time series incorporating a local representation of natural variability uncertainty (Wilby et al. 2009). This method involved applying GCM-derived temperature changes to a higher spatial resolution

historical (or baseline) climatology, 0.05° spacing of longitude and latitude. The projected climatology (with an original spatial resolution of approx. 1.5° (or 150 km) therefore also takes on this finer resolution. In this way, a synthetic projected temperature climatology captures local topographical and coastal climate influences.

One of the limitations with the change factor method is that, although the resultant scenario incorporates the detail of the station records, as well as the average climate change of the specified GCM grid box, the scaled and the baseline scenarios only differ in terms of their respective means, maxima and minima; all other properties of the data, such as the range and distribution, remain unchanged (Wilby et al. 2004). In support of the method chosen, this should pose minimal effect, given that for most of the Australian region, mean temperature change is broadly similar in magnitude and direction to extreme temperature change (CSIRO and BoM 2015). However in the southern coastal regions, the increases in the annual and 1-in-20-year maximums are a little higher than for the means. This seems consistent with the effect of hot winds from the interior providing an even greater temperature contrast to those from across the ocean under the warmer climates, as examined by Watterson et al. (2008). In viewing the future exposure for locations in Southern Australia (Lenswood and Yarra Valley), this potential underestimate should be acknowledged. It should also be noted that the change factor method is not advised for producing future rainfall time series, where in some regions, for example, changes in extreme rainfall are projected to increase even if mean rainfall is projected to decrease (CSIRO and BoM 2015).

For this case study, projected changes to extreme temperature and the efficacy of over-tree netting in diminishing adverse effects were explored in some detail. In a broader assessment of climate change impacts on the Australian apple industry, it would be naïve to ignore changes to other climate variables given that these crops are affected directly and indirectly by many climatic factors. Projections for rainfall, evapotranspiration, drought, fire and wind are all of interest to the grower and have implications for future viability of orchards. The importance of these should not be underestimated in terms of the crop's vulnerability and also with regards to orchard operational practises, e.g. spraying in hot conditions. Finally, although often overlooked for agricultural workers, human health as impacted by exposure to extreme heat should also be considered (Kjellstrom et al. 2009).

## Conclusion

A methodology was outlined to provide action-oriented climate projection information. The adaptation decision to install over-tree netting to protect apples against sunburn was used as an example. The methodology simplified climate projection information to a range between best-case and worse-case scenarios. The results were presented in several ways to assist in decision-making including colour-coded analogues and a risk profile

approach. For Australia, heterogeneity in the benefit of over-tree netting was found geographically and into future time periods. The results highlight areas with little risk, and hence, no adaptation response is required through to areas at considerable risk and a significant benefit for the installation of netting. This approach, focussed on adaptation action founded on a robust scientific method, can be used as a template for a diverse range of impact studies to provide climate projection information that is easily transferrable into adaptation actions.

**Acknowledgements** We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP, the US Department of Energy's Programme for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organisation for Earth System Science Portals.

Craig Heady and Tim Bedin for work in preparation of the threshold exceedance database (CSIRO) and Penny Whetton (CSIRO) for her thorough review of the manuscript.

## Compliance with ethical standards

**Funding** Funding for this research was provided by the Australian Department of Agriculture and Water Resources.

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