



Final Report

Understanding apple and pear production systems in a changing climate

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The Department of Agriculture and Fisheries (DAF)

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Summary

The objective of this project was to reduce the vulnerability of the Australian apple and pear industry to climate change by: investigating the potential impacts of a changing climate on winter chill, flowering, fruit sunburn and yield; exploring the effects of adaptation such as netting and dormancy-breaking products; and developing and extending appropriate adaptive responses to industry. The project used a broad range of research and technology transfer activities encompassing field observational data collection, controlled environment experimentation, biophysical modelling, website development, communication and extension.

Australia has undergone a consistent warming trend since 1910, however, analysis of historical climates undertaken in this project indicated that the experience of climate change has been different in each pome fruit growing region. For example, milder pome fruit growing regions of Australia have experienced a decline in annual winter chill accumulation since 1968, while the colder regions of Huonville and Orange have not changed. In modelling studies of future climate scenarios, warmer locations were projected to experience a reduction in winter chill of more than 20% by 2050, with a decline of less than 10 to 14% projected for the coldest production areas over the same period.

Flowering observations from 2012 to 2015 indicated that low winter chill in Manjimup was associated with greater variability in flowering dates between seasons, cultivars and individual trees, and irregular and protracted flowering across most apple cultivars, relative to Applethorpe and Shepparton. The variable pattern of flowering observed in Manjimup was likely the result of mild winter conditions and inadequate chilling for some cultivars. Use of climate analogues and modelling analyses suggest that milder winter growing regions of Australia are likely to experience symptoms of inadequate chilling with increasing frequency in future years.

Projections from the chill-overlap model for timing of full bloom in 'Cripps Pink' apple in 2030 and 2050 projected an earlier full bloom date on average at high chill locations in 2050, and a later full bloom date at the milder winter locations by 2030, with flowering dates delayed by more than a week in 2050. Trials with dormancy-breaking sprays demonstrated that they are likely to be a viable adaptation tool for some cultivars in lower winter chill years, but matching cultivars with climate is the preferred adaptation option.

Results from the climate modelling showed that by 2030, all pome fruit growing regions will experience an increase in the average number of extreme heat days during the summer growing season. Netting will reduce the risk of sunburn damage, as air temperature thresholds for damage of fruit under netting were shown to be higher than thresholds for fruit without netting. Findings from the Western Australian netting demonstration site showed little difference in air temperature conditions, winter chill or flowering dates under the white netted, black netted and non-netted orchard blocks. Black and white netting were equally effective in reducing fruit surface temperatures over the late summer period, compared with the no net apples.

The project highlighted the need for detailed information to enable growers to match apple and pear cultivars with suitable growing climates, including matching chilling requirements with winter chill and heat tolerance with summer temperatures. Comprehensive guidelines on orchard practices for managing extreme heat (including tree canopy structure, use of evaporative cooling, netting types, plant growth regulators and stress reduction chemicals) are also recommended.

It is clear from the project outcomes that climate change will add significant variability into the pome fruit production system with respect to flowering and fruit quality. Australian growers are used to dealing with some level of climate variability and it seems likely that impacts on flowering and fruit quality will be within the range of grower experience up to around 2030, but that by 2050 growers will be operating outside of current experience. This will present challenges for the Australian industry in the consistency of supply and in maintenance of the uniform orchard blocks.

A series of recommendations were developed, along with a list of significant research gaps, to assist the Australian apple and pear industry reduce the risks associated with climate variability and climate change.

Keywords

Climate change scenarios; climate change impact; climate change adaptation; dormancy; winter chill; flowering; extreme heat; sunburn browning; netting

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Introduction

Australia's climate has warmed since 1910, and is likely to continue warming with more hot days and fewer cold days expected in the future (State of the climate, 2016). Research has broadly identified a range of potential impacts of climate change on the productivity and profitability of the Australian apple and pear industry including inadequate winter chilling, increased fruit sunburn and changes to the upper limit of pome fruit productivity (Darbyshire et al., 2013b; Putland et al., 2011). However, the nature and timing of these potential impacts in different growing regions across Australia remains unclear. Understanding climate change impacts is essential for the timely implementation of appropriate adaptation strategies (Cobon et al., 2009).

Future changes in climate are predicted to result in reduced winter chilling in many apple and pear growing regions of Australia (Darbyshire et al., 2013b; Hennessy et al., 1995). It is not yet clear what the impact of this will be on the timing and quality of bud dormancy release and flowering in commercial pome fruit cultivars, and therefore the potential impacts on productivity. Advancement in flowering with increased historical temperature has been observed in temperate fruit trees globally (Legave et al., 2013); however, effects of recent warming on flowering in Australian pome trees are less obvious (Darbyshire et al., 2013a). Options for adaptation to lower winter chill include appropriate cultivar selection and the use of plant growth regulators; however, current understanding around cultivar chilling requirements and the use of dormancy-breaking sprays to compensate for a lack of winter chill is poor.

The risk of fruit sunburn damage is likely to increase under future climates and associated rising summer temperatures. Predictions regarding changes to sun damage risk and evaluation of adaptation options are therefore important for future planning. In Australia, apple growers currently estimate typical losses to vary from 6 to 30%, depending on season and fruit cultivar (Lolicato, 2011).

Netting has been identified as a potential climate change adaptation strategy to reduce fruit exposure to solar radiation and hence reduce sunburn damage, while also providing protection from hail events. Practical questions remain on the use of hail netting, particularly in warm growing regions, including the effect of different types of netting (weave density and colour) on temperature, fruit quality and yield. The effectiveness of netting as an adaptation strategy to reduce the risk of sunburn browning under predicted climate change is also unknown.

Project objectives

The broad objective was to reduce the vulnerability of the Australian apple and pear industry to climate change through, 1) investigation of the overarching research question '*What are the potential impacts of a changing climate on apple and pear production in Australia and how can the industry adapt to minimize the risks?*' and, 2) developing and extending appropriate adaptive responses to industry.

Specific objectives for the **research** component of the project were to:

1. Develop climate change scenarios for pome fruit growing regions of Australia in 2030 and 2050, including the likely impact of climate change on winter chill and extreme heat.
2. Understand how changes in autumn, winter and spring temperatures might impact the timing and quality of flowering in cultivars of apple and pear.

3. Identify adaptations to manage any negative effects of climate change on flowering.
4. Understand how changes in the frequency of extreme heat days might impact on the incidence of sunburn in pome fruit and the effectiveness of netting as an adaptation strategy.
5. Understand how different colours of netting impact on the orchard environment, fruit yield and quality.
6. Understand how the changing climate might impact the yield potential of apples.

The **development** and **extension** components of the project were targeted at the Australian apple and pear industry. Target groups were apple and pear growers, industry consultants, Apple and Pear Australia Limited (APAL) and temperate fruit tree researchers. Specific objectives of this component were to:

1. Facilitate greater understanding of how the climate is likely to change by 2030 and 2050 in apple and pear growing regions of Australia, how this might impact on apple and pear production, and potential adaptation strategies to reduce the associated risks.
2. Increase knowledge and skills to enable informed decision-making around climate change adaptation, and orchard investment and planning, based on scientific evidence.
3. Build a connected and collaborative approach between research partners, funding bodies, industry and growers around managing and adapting to climate change.

General methodology

The objectives were investigated through a broad range of research and technology transfer activities encompassing field observational data collection, controlled environment experimentation, biophysical modelling, website development, written and oral communication and extension. The project combined research of immediate adaptive responses to current climate risks, with long-term climate change impacts and adaptation. The general methodological approach and associated activities undertaken for each of the stated project objectives are described in this section. Details of specific methods are given in the appropriate appendices, as indicated in the text.

Research methodology

The approach was to validate and refine models of flowering time, fruit surface temperature and yield potential, and use them in conjunction with regional climate projections to model the effects of the changing climate on apple and pear production systems, and the effectiveness of specific adaptation strategies. Climate analogues were also investigated as an alternative approach to understanding climate change impacts and adaptation.

1. Develop climate change scenarios for pome fruit growing regions of Australia in 2030 and 2050, including the likely impact of climate change on winter chill and extreme heat

Future climate scenarios were constructed for two representative concentration pathways (RCPs), RCP4.5 (minimum to medium case scenario) and RCP8.5 (worst case scenario), to represent a plausible range of future climates (Appendix 1). RCPs are greenhouse gas concentration trajectories adopted by the *Intergovernmental Panel on Climate Change* in its fifth Assessment Report in 2014 (a detailed description of these is given in Appendix 1). Scenarios were developed for 2030 and 2050 to support the mid to long-term orchard decision-making process. Trees planted in 2017 will be in their 13th leaf in 2030, the height of production, and therefore planting decisions made now will impact orchard profitability in 2030. Climate projections were not made beyond 2050 due the high degree of climate uncertainty associated with long-term projections.

Climate scenarios were expressed in terms of relevant horticultural metrics (chill portions and number of sunburn browning risk days) rather than simply as mean temperature changes, to enable better understanding of how warming temperatures might impact pome fruit production.

Winter chill was calculated in chill portions using the Dynamic Model (Erez et al., 1990; Fishman et al., 1987). This is the current 'best-practice' model and has been shown to perform better than other models for calculating winter chill, particularly in mild winter climates such as Australia (Luedeling et al., 2011).

2. Understand how changes in winter and spring temperatures might impact the timing and quality of flowering in cultivars of apple and pear

Detailed baseline data sets for temperature, bud burst and flowering were collected from three climatically distinct pome fruit growing regions of Australia (Applethorpe, Queensland; Manjimup, Western Australia; Shepparton, Victoria, Figure 1) for apple and pear cultivars and their pollinisers from 2012 to 2015. Phenology observation and collection methodology was standardised across locations making this dataset unique in Australia.

The data set was used to assess the variation in bud burst and flowering time across locations, seasons

and cultivars (Appendix 2), and to validate a phenology model (chill overlap model (Darbyshire et al., 2016)) for prediction of flowering time in apple now and under future climates (Appendix 1).

Climate analogue analysis involves a detailed comparison between locations, where the current climate of one location is similar to the projected future climate of the location of interest. This approach was investigated using Stanthorpe as a case study, to predict impacts of climate change on pome fruit flowering in Stanthorpe and to identify possible methods for adaptation (Appendix 3).

3. Identify adaptations to manage any negative effects of climate change on flowering

Forced bud experiments using controlled environment conditions were undertaken to determine cultivar chilling requirements, for use by industry in selection of suitable cultivars for different winter chill climates. Methods for collecting bud burst and flowering records were developed for growers to use for assessing cultivar performance in their local climate (Treeby et al., 2017a).

A one-year trial was conducted in three locations (Applethorpe, Queensland; Manjimup, Western Australia; Huonville, Tasmania) to determine the efficacy of using dormancy-breaking sprays in Gala as an adaptation to low winter chill years (Appendix 4).

Potential adaptations were also identified through the capture of grower experiences at national grower workshops and industry conferences.

4. Understand how changes in the frequency of extreme heat days might impact on the incidence of sunburn in pome fruit and the effectiveness of netting as an adaptation strategy

Two methodological approaches were taken using weather and fruit surface temperature data collected from two adjacent 'Royal Gala' sites in Shepparton, Victoria, one netted and one non-netted site. The first approach was to determine minimum air temperature thresholds for 'Royal Gala' apples grown with and without net, with potential to lead to sunburn damage under current climates (Appendix 5). Once established, these minimum air temperature thresholds were used to investigate the frequency of days exceeding these threshold air temperatures in current and future climates. The future sunburn risk and the effectiveness of netting in reducing this risk, was determined for growing locations around Australia for 2030 and 2050 (Appendix 1 and 7).

The second approach was to validate the thermodynamic Smart-Sinclair model for prediction of fruit surface temperature (Appendix 6).

5. Understand how different colours of netting impact on the orchard environment, fruit yield and quality

A netting demonstration site was established over a block of 'Cripps Pink' trees in Manjimup, Western Australia to expand on results from existing studies on the effects of netting on air temperature, relative humidity, wind and solar radiation (Darbyshire et al., 2015; Middleton et al., 2002) and to compare the effects of black and white net on the orchard environment, flowering, fruit yield and quality (Appendix 8).

6. Understand how the changing climate might impact the yield potential of apples

An apple physiological model, MaluSim (Lakso et al., 1990), was used to understand the effects of predicted climate change on net carbon exchange of apples and the upper limit of apple production (yield

potential). The model was evaluated for 'Royal Gala' with regard to prediction of apple yield under current Australian conditions in netted and non-netted orchard sites, and yield was predicted under warmer future climate conditions (Appendix 9).

Development and extension methodology

Extension and research activities were coordinated and conducted side-by-side to encourage the flow of information between growers, industry representatives, extension officers and researchers throughout the project, with industry feedback continuously informing the research.

The technology transfer activities undertaken as part of the extension component are outlined under each of the following objectives.

1. Facilitate greater understanding of how the climate is likely to change by 2030 and 2050 in apple and pear growing regions of Australia, how this might impact on apple and pear production, and potential adaptation strategies to reduce the associated risks.

Multiple activities were undertaken to provide information to, and obtain feedback from, the apple and pear industry. A review of available climate change information relevant to Australian apple and pear growers was conducted at the project start, to identify information needs. A grower survey was performed to gain insight into grower attitudes and knowledge in regards to climate change and its impacts.

Communication and extension was undertaken throughout the project and included two years of national grower workshops (Appendix 10), regular publications in industry magazines and websites, presentations at industry conferences, field days and seminars, dedicated project web pages (APAL and Horticulture Industry Network (HIN)) and general media items.

Climate change information specific to Australia's apple and pear industry was published in a series of three grower publications at the conclusion of the project to communicate key project findings as well as important climate change information for the industry generally (Treeby et al., 2017a; Treeby et al., 2017b; White et al., 2017).

2. Increase knowledge and skills to enable informed decision making around climate change adaptation and orchard investment and planning based on scientific evidence

The grower publications and winter chill website were designed to provide practical information to growers for use in every day decision making and for long-term strategic planning.

3. Build a connected and collaborative approach between research partners, funders, industry and growers around managing and adapting to climate change

Relationships between stakeholders were established, maintained and developed through:

- Regular project teleconferences and face-to-face meetings.
- Close links with the University of Melbourne project '*Crossing the threshold: adaptation tipping points for Australian fruit trees*' undertaken within the Primary Industries Climate

Challenges Centre (PICCC)¹.

- Meetings with APAL staff at the head office in Melbourne, at conferences or via phone hook-up.
- Informal links with other apple and pear industry research programs such as the PIPS program, as well as with researchers and industry representatives from other horticultural industries, for example cherries and almonds.
- Establishment of the netting demonstration site in Western Australia.
- Data collection trials conducted on grower properties which provided avenues for informal engagement growers.
- Involvement and participation in industry conferences and events.
- Organisation and participation in national grower workshops.
- Involvement with the Climate Change Research Strategy for Primary Industries (CCRSPI).
- Involvement of post-graduate students and work experience students in project activities.



Figure 1. Research sites were located in Applethorpe (Qld), Shepparton (Vic), Manjimup (WA) and Huonville (Tas). Orange (NSW) and Mt Barker (SA) were included in the climate data analysis.

¹ <http://www.piccc.org.au/research/project/440>

Outputs

Grower publications

- Treeby, J., Goodwin, I., MurphyWhite, S., Darbyshire, R., White, N., McClymont, L., Richards, S., Measham, P., Bound, S. and Parkes, H. 2017. Winter chill and flowering – what is there to know? Department of Agriculture and Fisheries, Queensland.
- Treeby, J., Goodwin, I., MurphyWhite, S., Darbyshire, R., White, N., McClymont, L., Richards, S., Webb, L., Erwin, T. and Parkes, H. 2017. Netting for heat – what is there to know? Department of Agriculture and Fisheries, Queensland.
- White, N. Parkes, H. and Treeby, J. 2017. Future climates in pome fruit orchards – what is there to know? Department of Agriculture and Fisheries, Queensland.

Grower workshops

- Heidi Parkes, Jenny Treeby and Ian Goodwin presented “climate change impacts and adaptation research for the pome fruit industry” at Fruit Grower Victoria’s end of season review, Mooroopna, Vic, 12 May 2014. <http://www.hin.com.au/associations/fruit-growers/fgv-end-of-season-review>
<http://www.hin.com.au/resources/extreme-heat-powerpoint-may-2014>
<http://www.hin.com.au/resources/apples-and-pears-in-a-changing-climate-powerpoint-may2014>
- Heidi Parkes, Neil White and Clinton McGrath presented an “apple climate change workshop” at Applethorpe Research Facility, Qld, 23 July 2014.
- Heidi Parkes and Susie MurphyWhite presented “apples and pears in a changing climate” at an orchard walk in Manjimup, WA, 1 October 2014. <http://www.hin.com.au/associations/apples-and-pears/pit-stop-wa-for-the-national-roadshow>
- Heidi Parkes presented a “winter chill and flowering” workshop for the Perth Hills Orchard Improvement Group at Applethorpe Research Facility, Qld, 31 July 2015.
- Clinton McGrath, Heidi Parkes and Neil White presented a climate change risk management matrix workshop in Thulimbah, Qld, 5 August 2015.
- Heidi Parkes, Rebecca Darbyshire and Jenny Treeby presented a “winter chilling and climate adaptation workshop” in Bilpin, NSW, 16 September 2015.

Websites and tools

- White, N. and Parkes, H. 2017. Winter chill and growing degree day website: an interactive tool to calculate and interpret local chill and growing degree day accumulation. <https://hort-science.shinyapps.io/ChillCalculator/>

Technical working group meetings

- Queensland technical working group meeting, facilitated by Clinton McGrath, Applethorpe Research Facility, Qld, 20 August 2013.
- South Australian technical working group meeting, facilitated by Jenny Treeby and Paul James (Lenswood Co-op), Lenswood, SA, April 2013.

Victorian technical working group meeting, facilitated by Jenny Treeby and Michael Crisera (Fruit Growers Victoria), Shepparton, Vic, October 2013.

Industry surveys

A nation-wide survey of apple and pear growers was developed and coordinated by Jenny Treeby (based on input from DEDJTR's Service Innovations branch) to ascertain growers' attitudes, perceptions and knowledge of climate change. 2013. <https://www.surveymonkey.com/s/QTG7QKH>

A nation-wide survey of apple and pear growers was developed and coordinated by Heidi Parkes, Jenny Treeby and Susie MurphyWhite to gauge grower understanding and perceptions of winter chill. 2015.

Industry articles

Calderon, M. 2014. Bud burst in 'Williams' Pears highly variable. *Australian Fruitgrower* 8(8): 32.

Darbyshire, R. and Parkes, H. 2014. What's the blooming difference? *Australian Fruitgrower* 8(10): 30.

Darbyshire, R. and Parkes, H. 2015. Get in the chill zone. *Australian Tree Crop* Winter edition pp. 14.

Darbyshire, R., Goodwin, I. and MurphyWhite, S. 2016. New understandings to better predict apple flowering- introducing the chill overlap model. *Australian Fruitgrower* June/July edition. <http://apal.org.au/australian-fruitgrower-june-july-2016/>

McClymont, L., Goodwin, I. and Sessions, W. 2013. Net benefits- the sun protection factor in 2050. *Australian Fruitgrower* 7(6): 28-31.

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MurphyWhite, S., Prince, R. and Starkie, L. 2016. Black or white netting? Is there a difference? Or just a preference.... *VegetablesWA* Autumn: 71 - 73. <http://www.vegetableswa.com.au/wa-growers-magazine/>

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- Prince, R and MurphyWhite, S. 2015. Netting trial results in WA. *Australian Fruitgrower* 9(9): 26 - 29. <http://apal.org.au/netting-trial-results-in-wa/>
- Thomson, G., McClymont, L., Goodwin I. 2014. Sunburn protection Part 1: Adapt and limit apple sunburn during heatwaves. *Tree Fruit* November: 5–9.
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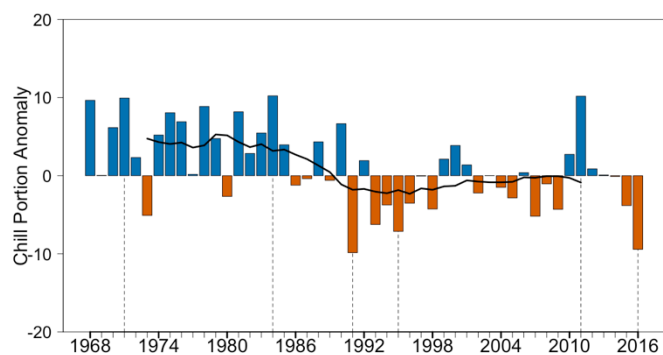
Outcomes

Historical climate trends and future scenarios

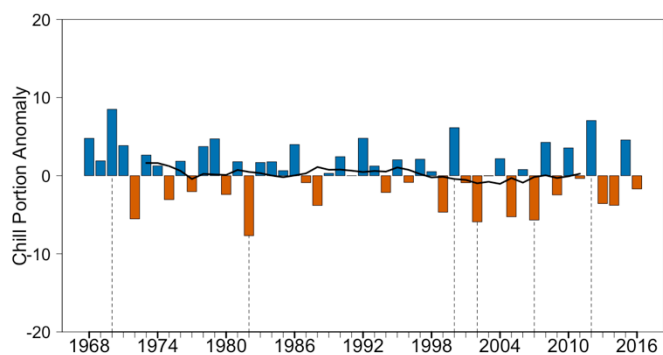
Historical trends in average temperatures, winter chill and heat days

(Appendix 1)

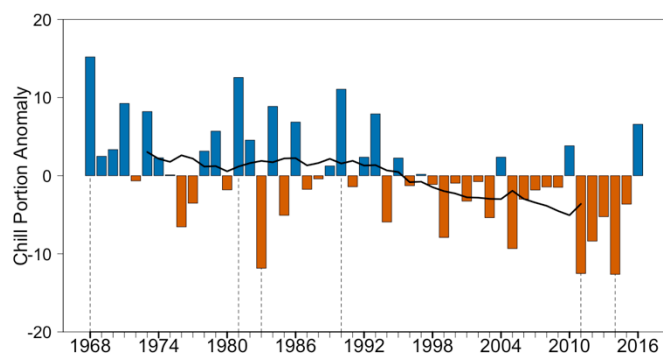
Australia has undergone a consistent warming trend since 1910 (State of the climate, 2016). In pome fruit growing regions across Australia this changing climate has been experienced in different ways at the local level. Changes in average minimum and maximum temperatures experienced in autumn/winter and spring/summer since 1968 differ between regions (appendix 1). The milder growing regions of Applethorpe, Manjimup and Mt Barker have experienced a decline in the number of chill portions over this period, while Shepparton has seen a small reduction in winter chill and the colder regions of Huonville and Orange have not changed (Figure 2). Increases in the number of extreme heat days have been experienced in Shepparton and Mt Barker, while the last seven years in Manjimup have been above the long-term average (Figure 3).



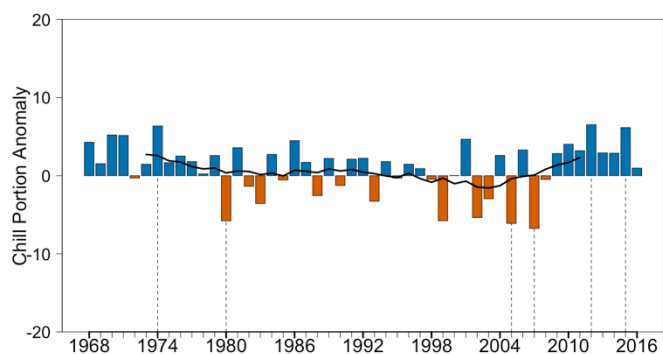
Applethorpe



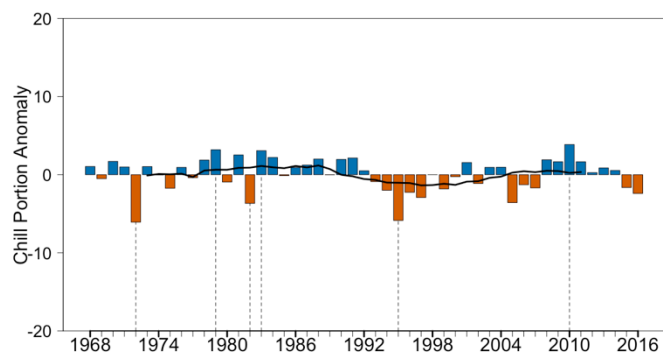
Shepparton



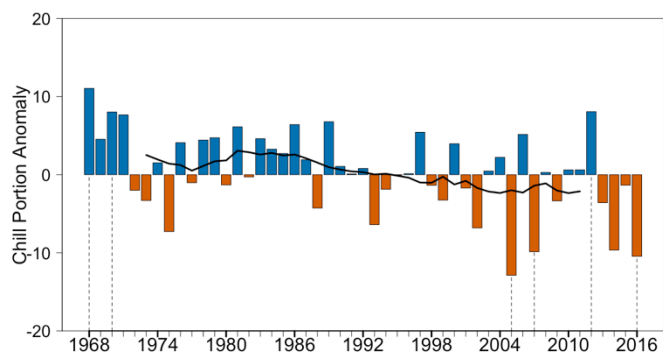
Manjimup



Huonville

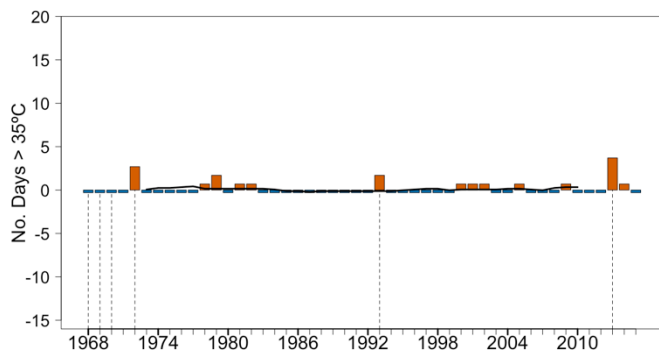


Orange

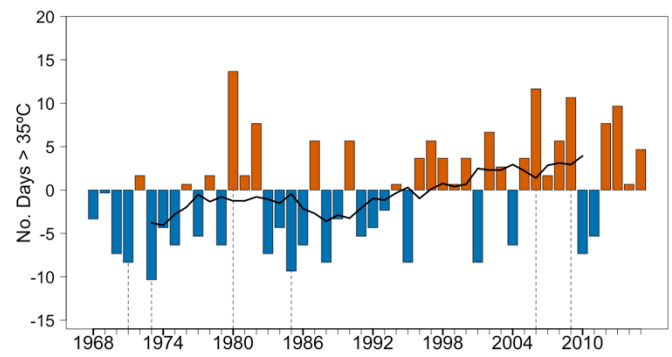


Mount Barker

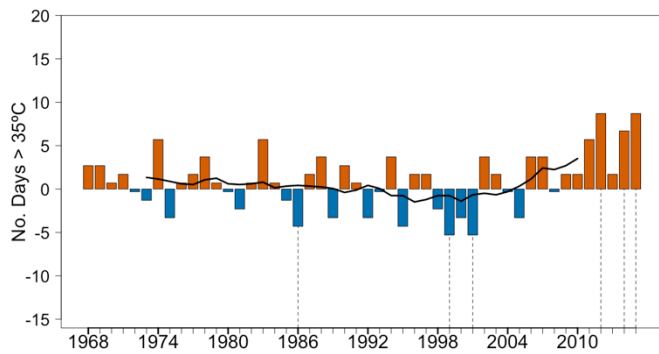
Figure 2. Annual anomaly in accumulation of chill portions (1 Mar to 31 Aug). Anomalies are the difference between the yearly value and a base period of 1981 to 2010. The black line is an 11-year moving average.



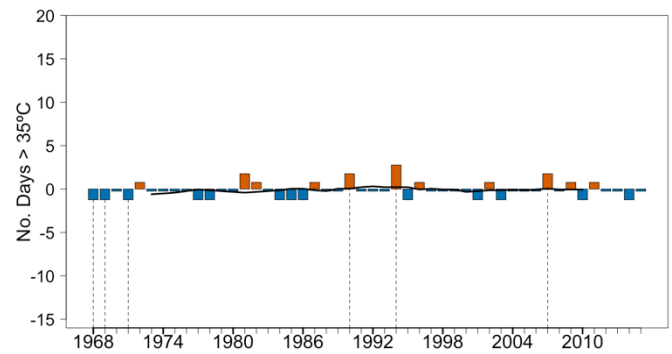
Applethorpe



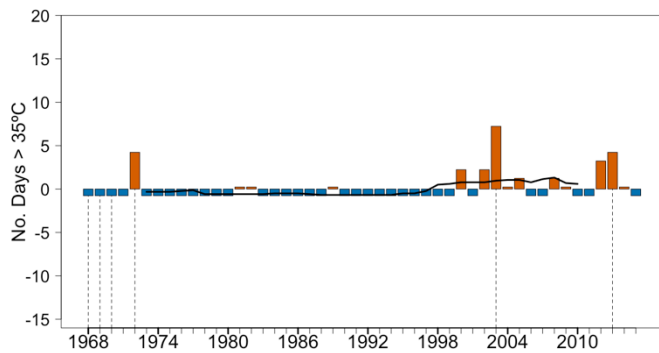
Shepparton



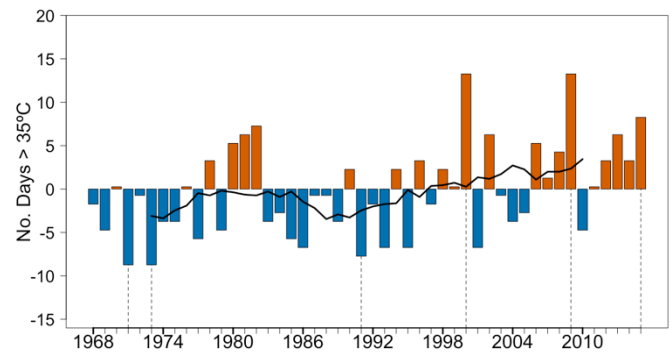
Manjimup



Huonville



Orange



Mount Barker

Figure 3. Annual anomaly in average number of days where maximum temperature exceeds 35° C. Anomalies are expressed as the difference between the yearly value and a base period of 1981 to 2010. The black line is an 11-year moving average.

Climate projections for average winter chill and heat days

(Appendix 1)

Climate projections were developed for minimum to medium (RCP4.5) and worst case (RCP8.5) scenarios for 2030 and 2050 for each of the pome fruit growing regions. Winter chill accumulation declined at all sites in 2030 and 2050 under both scenarios. The greatest declines were in the milder growing regions of Applethorpe and Manjimup (greater than 20% in 2050) and the smallest declines in Huonville and Orange (around 5% in 2030 and less than 15% in 2050) (Table 1).

By 2050, growers will be managing orchards under a different climatic environment. For example, in Applethorpe, a low chill year is currently around 60 chill portions. This will be a good year in 2050 and the worst years will be outside the existing range of experience.

Table 1. Average chill portions (1 Mar to 31 Aug) for 2030 and 2050 using a minimum to medium (RCP4.5) and worst (RCP8.5) case scenario. The average is of 30 years with the lowest and highest chill portions in brackets.

| Average chill portions | Present | 2030 | | 2050 | |
|------------------------|--------------|-------------|-------------|-------------|-------------|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 72 (62-83) | 63 (48-75) | 60 (44-73) | 56 (41-69) | 51 (36-65) |
| Shepparton | 84 (73-93) | 75 (63-85) | 74 (62-86) | 71 (58-81) | 67 (57-79) |
| Manjimup | 67 (55-82) | 57 (43-76) | 55 (42-75) | 50 (36-72) | 47 (33-68) |
| Huonville | 105 (94-113) | 98 (81-112) | 97 (78-110) | 93 (74-105) | 90 (71-104) |
| Orange | 100 (90-110) | 94 (85-104) | 93 (82-101) | 90 (81-99) | 87 (78-94) |
| Mount Barker | 84 (67-93) | 74 (55-88) | 73 (53-88) | 70 (53-84) | 65 (47-80) |

The climate projections for 2030 and 2050 show that all pome fruit regions across Australia can expect to experience an increase in the number of extreme heat days during the growing season, with the greatest impacts likely to be in regions such as Shepparton, with hot summer climates (data not shown). Impacts on the risk of sunburn browning in apples are described in the section 'Potential impact of an increased frequency in extreme heat events on the incidence of sunburn, and the effectiveness of netting as an adaptation strategy' on p34.

Impacts of warming autumn, winter and spring temperatures on flowering and options for adaptation

Understanding relationships between temperature and flowering

1. Variation in flowering of pome fruit trees across Australia

(Appendix 2)

Differences in the pattern of chill accumulation (Figure 4) were accompanied by variability in the timing and pattern of green tip and flowering between locations and between years (Figure 5). Green tip and full bloom dates were more variable between years, cultivars and individual trees in Manjimup compared with Applethorpe and Shepparton, and trees consistently displayed a more protracted pattern of flowering (Figure 5). Delayed and uneven flowering are symptoms of inadequate chill and it is likely that the observed patterns of bud burst and flowering in Manjimup were in response to the mild winter conditions experienced in that location in 2012 to 2014.

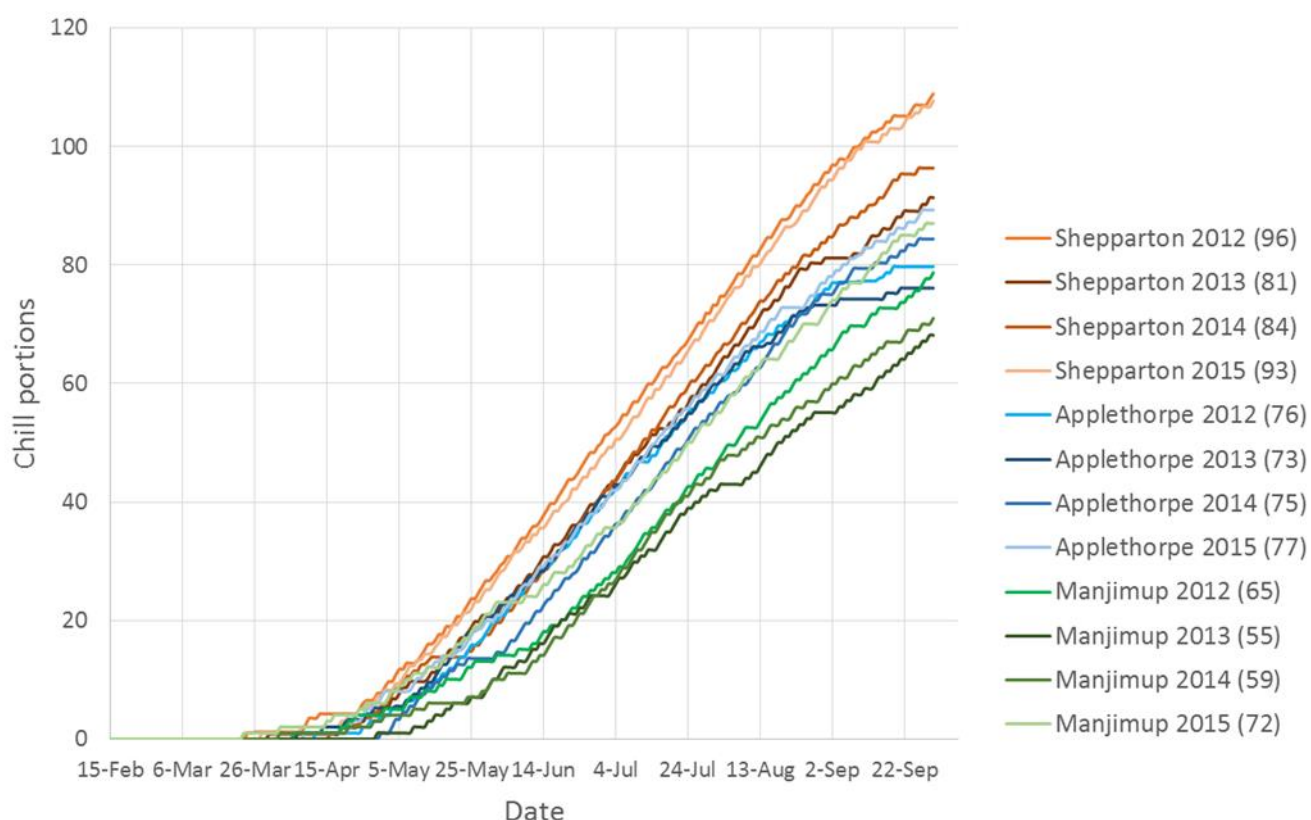
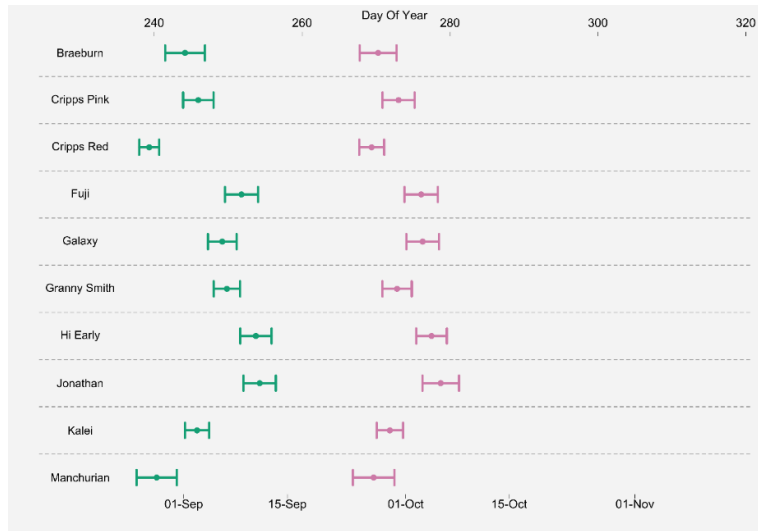


Figure 4. Chill accumulation in Shepparton, Applethorpe and Manjimup in 2012 to 2015. Number in brackets is the total chill portions received up to 31 Aug.

Applethorpe



Shepparton



Manjimup

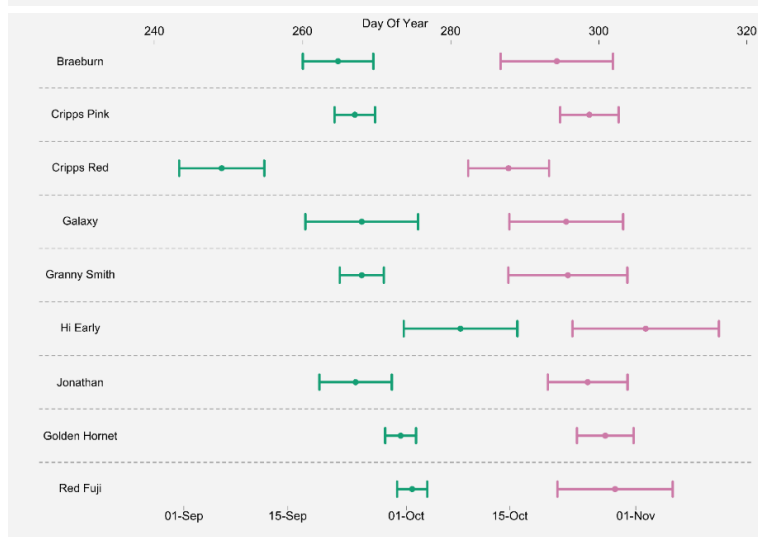


Figure 5. Green tip (green) and full bloom (pink) dates for apple cultivars in Applethorpe, Shepparton and Manjimup. Data is the average of observations from 2012 to 2015 with bars indicating the confidence interval.

2. Chilling requirements

A collection of apple chilling requirements in chill portions, chill units and chill hours were produced for the mild climatic region of Applethorpe, Queensland, Australia (Table 2).

The chilling requirements measured were higher across a number of cultivars when compared with previously published thresholds (Ghariani et al., 1994; Hauagge et al., 1991). For example, Darbyshire et al. (2016) estimated a chilling requirement of 34 chill portions for 'Cripps Pink', notably lower than the chilling requirement of 73 chill portions calculated here. Comparison of chilling requirements between studies is problematic due to the use of vastly different methodologies for threshold determination (Dennis, 2003). Research to understand the genetic basis of progression through the phases of dormancy is needed to enable accurate definition of cultivar chilling requirements (Cooke et al., 2012).

Regardless of these gaps in knowledge, the chilling requirements measured using the forced bud methodology can be used to put apple cultivars into groups with low ('Cripps Red', 'Manchurian' crab apple), medium ('RS103-110', 'Granny Smith', 'Cripps Pink', 'Kalei') and higher chilling requirements ('Galaxy', 'Fuji', 'Hi-Early'). These groupings provide practical benefit to industry by enabling growers to make more informed cultivar and pollinizer choices at planting, particularly when considering projected changes to future climate.

A draft manuscript titled 'chilling requirements of apple varieties grown in mild Australian winter conditions' details this work, and has been prepared for submission to the journal *HortScience*.

Table 2. Chilling requirements of apple cultivars and a crab apple polliniser cultivar measured in chill portions, chill units and chill hours.

| Cultivar | Year | Dynamic (CP) | mean±sd | CV(%) | Utah (CU) | mean±sd | CV(%) | Chill Hours (CH) | mean±sd | CV(%) |
|--------------|------|--------------|----------|-------|-----------|------------|-------|------------------|----------|-------|
| Cripps Red | 2014 | 54.9 | 57±2.9 | 5.1* | 947 | 976±40.3 | 4.1 | 694 | 662±44.5 | 6.7 |
| | 2015 | 59 | | | 1004 | | | 631 | | |
| Manchurian | 2014 | 58.5 | 61±3.6 | 5.9 | 1016 | 1031±21.6 | 2.1* | 748 | 724±33.2 | 4.6 |
| | 2015 | 63.6 | | | 1046.5 | | | 701 | | |
| RS103-110 | 2014 | 68.7 | 70.8±2.9 | 4.1 | 1207 | 1186±29.3 | 2.5 | 845 | 838±10.6 | 1.3* |
| | 2015 | 72.8 | | | 1165.5 | | | 830 | | |
| Granny Smith | 2014 | 72.9 | 72.8±0.1 | 0.1* | 1312 | 1239±103.6 | 8.4 | 875 | 852±31.8 | 3.7 |
| | 2015 | 72.8 | | | 1165.5 | | | 830 | | |
| Cripps Pink | 2014 | 72.9 | 73.3±0.6 | 0.9* | 1312 | 1242±99 | 8 | 875 | 856±27.6 | 3.2 |
| | 2015 | 73.8 | | | 1172 | | | 836 | | |
| Kalei | 2014 | 72.9 | 75.5±3.7 | 4.9 | 1305 | 1275±42.1 | 3.3 | 875 | 883±11.3 | 1.3* |
| | 2015 | 78.1 | | | 1245.5 | | | 891 | | |
| Galaxy | 2014 | 79.5 | 76.7±4 | 5.3* | 1429 | 1300±181.7 | 14 | 950 | 893±80.6 | 9 |
| | 2015 | 73.8 | | | 1172 | | | 836 | | |
| Fuji | 2014 | 76 | 77±1.5 | 1.9* | 1368 | 1307±86.6 | 6.6 | 924 | 908±23.3 | 2.6 |
| | 2015 | 78.1 | | | 1245.5 | | | 891 | | |
| Hi Early | 2014 | 76 | 77±1.5 | 1.9* | 1368 | 1307±86.6 | 6.6 | 924 | 908±23.3 | 2.6 |
| | 2015 | 78.1 | | | 1245.5 | | | 891 | | |

* lowest coefficient of variation, CV(%) across the three chill models

3. Modelling to predict the timing of flowering in apple under current climates

(Appendix 1)

The relationship between winter chill, heat and flowering was described mathematically in the chill-overlap model of flowering developed for almonds (Pope et al., 2014) (Figure 6). This model assumes that there is a minimum amount of chill and a minimum amount of heat required for flowering. The more chill that is received over and above the minimum chilling requirement, the lower the amount of heat that is needed. In this way, the timing of flowering is determined by the complex relationship between the amount of chill and heat that is received during dormancy.

The baseline flowering and temperature datasets collected as part of this project were used to successfully validate the chill-overlap model for 'Cripps Pink' apple (Darbyshire et al., 2016), enabling projections of climate change impacts on the timing of flowering to be made (Table 3).

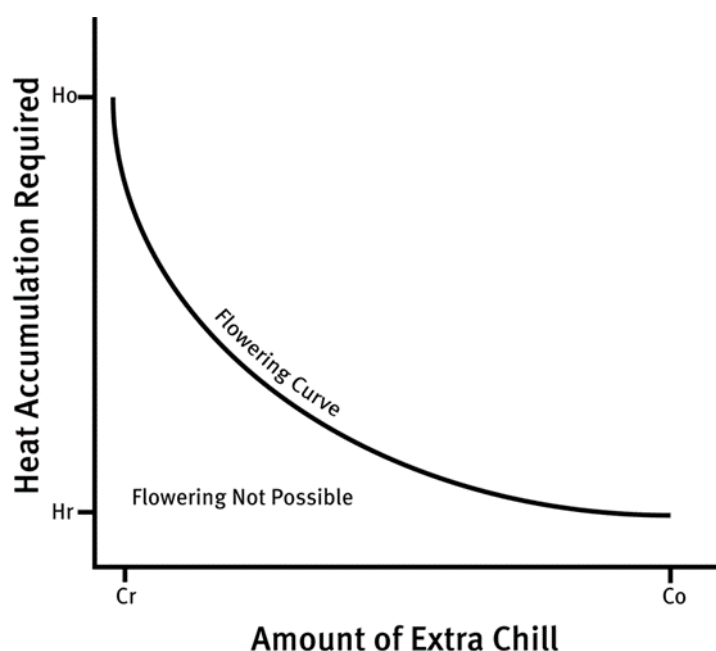


Figure 6. The Chill-Overlap Model for flowering in apple. C_r is minimum chill required for flowering, C_o is the maximum additional chill that will reduce the heat requirement. H_r is the heat required when C_o chill is accumulated, and H_o is the maximum possible heat requirement for flowering. (Redrawn from Darbyshire et al., 2016).

Potential impacts of warming temperatures on flowering

1. Modelling to predict changes in the timing of apple flowering under future climates

(Appendix 1)

The chill-overlap model for 'Cripps Pink' apple was used to predict changes in the timing of full bloom in growing regions across Australia in 2030 and 2050. In Orange, a high chill location, the average date of full bloom was advanced (earlier bloom) in 2050 by 4 to 5 days. The milder winter locations showed a delayed full bloom date in 2030 and 2050, with the greatest impact felt at Manjimup.

Changes in flowering time for 'Cripps Pink' in 2030 are likely to be within the current range of grower experience. However, by 2050 flowering times are predicted to be considerably later in milder winter regions. To determine how flowering time in other apple cultivars will be impacted by climate change, the chill-overlap model would require validation with flowering data from each cultivar.

Table 3. Average date of full bloom for 'Cripps Pink' apple in 2030 and 2050 using a minimum to medium (RCP4.5) and worst case scenario (RCP8.5) modelling approach.

| Average Predicted Full Bloom date | Present | 2030 | | 2050 | |
|-----------------------------------|---------|--------|--------|--------|--------|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 4 Oct | 7 Oct | 9 Oct | 12 Oct | 16 Oct |
| Shepparton | 30 Sep | 3 Oct | 3 Oct | 5 Oct | 6 Oct |
| Manjimup | 16 Oct | 22 Oct | 25 Oct | 30 Oct | 2 Nov |
| Huonville | 26 Sep | 27 Sep | 29 Sep | 29 Sep | 29 Sep |
| Orange | 2 Oct | 28 Sep | 28 Sep | 28 Sep | 27 Sep |
| Mount Barker | 1 Oct | 5 Oct | 4 Oct | 6 Oct | 8 Oct |

2. Using climate analogues

(Appendix 3)

The climate analogue analysis using Manjimup as an analogue for Stanthorpe in 2030 indicated that growers in the Stanthorpe region were likely to experience a more variable and protracted pattern of flowering across many apple cultivars by 2030 (Figure 7), but without any clear negative impact on productivity. Use of dormancy-breaking sprays was identified as a possible adaptation with no obvious requirement to shift to different cultivars or tree crop species at this stage.

Results from this case study indicated that the climate analogue approach can provide valuable information around potential climate change impacts and adaptation strategies for horticultural industries.

This finding comes with a note of caution however. Climate and plant physiology are complex systems, and the information gained from using climate analogues should be considered in a broad context, with care taken to the detail.



Figure 7. Variable bud burst and flowering in 'Cripps Pink', Manjimup, spring 2014.

Options for adaptation: management of flowering under future climates

1. Cultivar selection — matching cultivars with appropriate winter climates

Ideally, apple and pear cultivars should be matched with suitable growing climates, which in this case refers to selection of cultivars with chilling requirements that are comfortably below the minimum winter chill received in a particular location (Atkinson et al., 2013; Luedeling et al., 2015). However, there are multiple factors that influence cultivar choice (for example, market opportunities) and uncertainty around determination of cultivar chilling requirements make this somewhat difficult.

The collection of flowering time observations undertaken as part of this study indicated that more detailed monitoring and recording of green tip and flowering dates across the orchard would enable growers to identify cultivars that are performing well in the local climate, and those that are not getting enough chilling from season-to-season (providing early indication of cultivars that might be impacted by warmer winters in the future changing climate). These records could also be used to identify subtle shifts in the timing of flowering between cultivars and their pollinisers. New sensing technologies will enable simpler collection of large amounts of data in the future (Panda et al., 2010).

2. Dormancy-breaking sprays as an adaption to inadequate winter chill

(Appendix 4)

The dormancy-breaking sprays assessed in this 2015-16 study were able to advance flowering time and compact the flowering period in 'Gala' apple, with differences observed between products and sites (Figure 8). A more compact and uniform flowering period has been shown to have a number of benefits including improved management of flowering pests and chemical thinning practices (Bound et al., 2004; Theron, 2013).

Despite the compaction of flowering, there were no clear differences observed in fruit set, yield or variability of apple maturity in trees treated with dormancy-breaking sprays. More work is required to test the potential of these products to improve fruit quality and reduce the length of harvest. Advances in harvest timing were observed with the dormancy-breakers and generally reflected differences in flowering dates. The ability to manipulate harvest timing can be useful in situations where advantage can be taken of a high-price market window.

The results suggest that dormancy-breaking products are likely to be a viable adaptation tool for some cultivars in lower winter chill years, but the degree to which flowering can be managed with dormancy-breakers as the climate continues to warm, is yet to be determined.

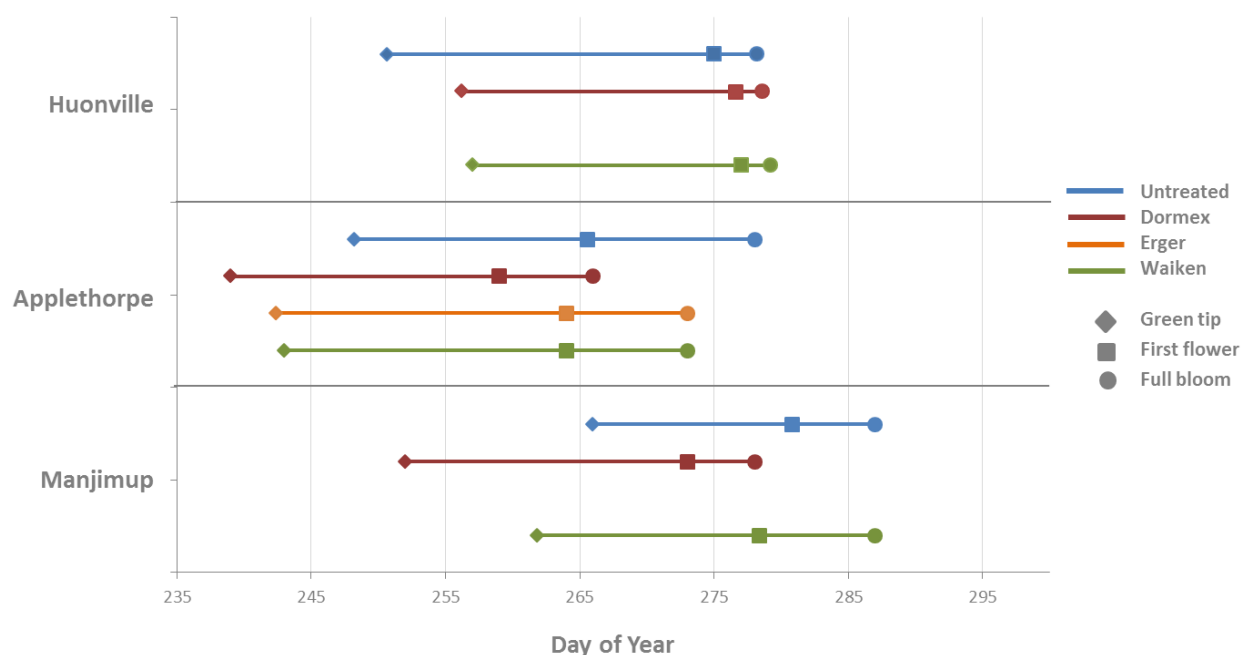


Figure 8. Green tip, first flower and full bloom in Gala apples treated with and without 'dormancy breaking' sprays Dormex®, Waiken™ and Erger® in Huonville, Applethorpe and Manjimup in 2015.

3. Changing cultural practices

(Appendices 2 and 3)

A review of the scientific literature undertaken as part of this project, together with information gained from personal communication with growers and industry suggest that irregular and protracted flowering can be difficult to manage and will likely require changes in thinning practices (Bound et al., 2004; Theron, 2013). Determining an appropriate thinning program is likely to be challenging when buds are at multiple stages of green tip and flowering on individual trees (Theron, 2013). Fruitlets may vary more in size and developmental stage, and careful hand thinning will likely be required to optimise crop uniformity (personal comm.). Where uniformity cannot be achieved, the greater spread of fruit maturity at harvest may require greater effort to pick at the appropriate time (personal comm.).

Impacts of increased frequency of extreme heat days on fruit quality and options for adaptation

Understanding relationships between summer temperatures and the incidence of sunburn under net and no net

1. Air temperature thresholds for sunburn damage

(Appendix 5)

Minimum air temperatures for potential sun damage were determined for 'Royal Gala' apple in Australia. The air temperature thresholds were 34.1 and 38.7°C, respectively, for browning and necrosis for non-netted fruit and 37.9°C for browning under netting (Figure 9).

When the air temperature thresholds were applied across southern Australia, it was found that some fruit-growing regions were more exposed to potential sun damage risk than others. Cooler summer regions (such as Huonville and Applethorpe) illustrated very little risk while warmer summer regions (such as Shepparton) displayed a greater potential risk, accompanied by substantial variability between years (Table 4). Managing this variability in potential risk is important to maintain yield and quality.

Air temperature thresholds can be used by growers as a guide for timing the use of overhead sprinklers for evaporative cooling in efforts to minimize potential damage.

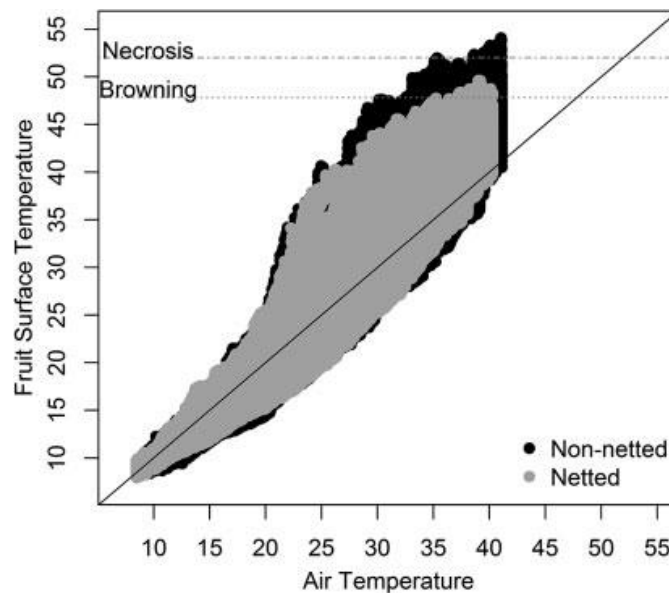


Figure 9. Fruit surface temperature (°C) recordings and related air temperatures (°C). Necrosis and browning fruit surface temperature thresholds represent 52 and 47.8 °C respectively. Figure sourced from Darbyshire et al. 2015.

Table 4. Distribution of potential damage days in January for sites in Australia’s growing regions for 10th, 50th and 90th percentiles of data. Table sourced from Darbyshire et al. 2015.

| Site | Browning, non-netted | | | Browning, netted | | | Necrosis, non-netted | | |
|---------------------------|----------------------|------|------|------------------|------|------|----------------------|------|------|
| | 10th | 50th | 90th | 10th | 50th | 90th | 10th | 50th | 90th |
| Spreyton ¹ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Huonville | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Applethorpe | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Batlow ¹ | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Yarra Valley ¹ | 0 | 2 | 5 | 0 | 0 | 1 | 0 | 0 | 1 |
| Manjimup | 0 | 3 | 5 | 0 | 0 | 2 | 0 | 0 | 1 |
| Lenswood ¹ | 0 | 3 | 6 | 0 | 0 | 2 | 0 | 0 | 1 |
| Young ¹ | 1 | 7 | 16 | 0 | 1 | 5 | 0 | 0.5 | 4 |
| Shepparton | 2 | 6 | 12 | 0 | 1 | 5 | 0 | 1 | 4 |
| Donnybrook ¹ | 3 | 7 | 11 | 0 | 1 | 3 | 0 | 0.5 | 2 |

¹additional locations included in this table were part of the *Crossing the threshold: adaptation tipping points for Australian fruit trees* project.

2. Predicting fruit surface temperature from weather data using the ‘thermodynamic Smart-Sinclair’ model

(Appendix 6)

The thermodynamic Smart-Sinclair model (Smart et al., 1976) was tested on ‘Royal Gala’ grown under

net and no net. The optimised model produced was able to predict fruit surface temperature with a root mean square error of 2 to 3°C. The presence of netting reduced the median fruit surface temperatures by 1.5 to 2.0°C. The mechanism for this netting effect was through the reduction of the intensity of the solar beam by interception and scattering, while still allowing sufficient air flow to enable transfer of heat from the fruit surface to the air.

This type of modelling can be used to understand processes and quantify the effects of various netting structures on fruit surface temperature and sun damage risk. However, the thermodynamic fruit surface temperature model cannot be used for predicting the effects of climate change due to the lack of reliable projected solar radiation and wind speed data for future climates. For applications such as assessing the benefits of netting in Australia's apple growing regions for a range of climate change scenarios, the air temperature threshold approach of Darbyshire et al. 2015 described above, is more appropriate.

Potential impact of an increased frequency in extreme heat events on the incidence of sunburn, and the effectiveness of netting as an adaptation strategy

(Appendices 1 and 7)

Minimum air temperature thresholds for sunburn damage in 'Royal Gala' apple grown with and without net (Darbyshire et al., 2015) were used to consider the risk of sunburn damage under future climates in pome fruit growing regions of Australia, and the effectiveness of netting to reduce this risk (Table 5). Exposure to sunburn browning-risk was highly dependent on the geographical location. Some locations were found to maintain minimal sunburn browning-risk up to 2050, while others will potentially experience the risk for a significant proportion of the January/February fruit growing period. Shepparton, Mt Barker and Manjimup will be most adversely affected, however the installation of over-tree netting substantially reduced the impact of sunburn browning.

Analysis of multiple locations enables the use of climate analogues (Whetton et al., 2013) for impact and adaptation assessments.

Table 5. Average sunburn browning risk (percentage of days in the January to February period) for 'Royal Gala' apples grown at sites across Australia, with and without netting.

Sunburn browning risk classifications:

| | | | | |
|------|------------|-------------|-------------|-------------|
| ≤ 5% | > 5 to 10% | > 10 to 20% | > 20 to 30% | > 30 to 50% |
|------|------------|-------------|-------------|-------------|

| Without Netting | 2030 | | | 2050 | |
|-----------------|---------|--------|--------|--------|--------|
| | Present | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 1.1 | 2.4 | 2.8 | 2.8 | 4.9 |
| Shepparton | 18.3 | 23.9 | 26.8 | 27.5 | 35.8 |
| Manjimup | 10.0 | 15.2 | 15.2 | 16.6 | 19.8 |
| Huonville | 2.4 | 3.4 | 3.8 | 4.5 | 4.2 |
| Orange | 2.4 | 3.8 | 4.4 | 3.7 | 8.4 |
| Mt Barker | 17.3 | 20.7 | 22.9 | 23.2 | 25.8 |

| With Netting | 2030 | | | 2050 | |
|--------------|---------|--------|--------|--------|--------|
| | Present | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 0.0 | 0.0 | 0.1 | 0.1 | 0.4 |
| Shepparton | 4.8 | 7.0 | 9.0 | 8.8 | 13.2 |
| Manjimup | 1.6 | 3.8 | 3.9 | 4.4 | 6.0 |
| Huonville | 0.3 | 0.6 | 1.0 | 1.2 | 1.1 |
| Orange | 0.1 | 0.1 | 0.1 | 0.1 | 0.7 |
| Mt Barker | 5.4 | 7.2 | 9.1 | 9.4 | 10.7 |

Black and white netting: impacts on the orchard environment, fruit yield and quality

(Appendix 8)

Observations from the Western Australian netting demonstration site (Figure 10) showed similar air temperature conditions (including winter chill accumulation) under the netted and non-netted orchard blocks. There was a slight increase in humidity under net which was associated with a higher incidence of pest and disease. There were no differences in bud burst and full bloom dates between trees under black, white and no net.

Fruit surface temperatures recorded in apples over the late summer period were higher in the non-netted apples (Figure 11). Fruit size was similar between netted and non-netted blocks; however fruit colour management using reflective mulch was required under the nets.



Figure 10. Western Australian netting demonstration site at the Lyster Matijari Orchard, Manjimup

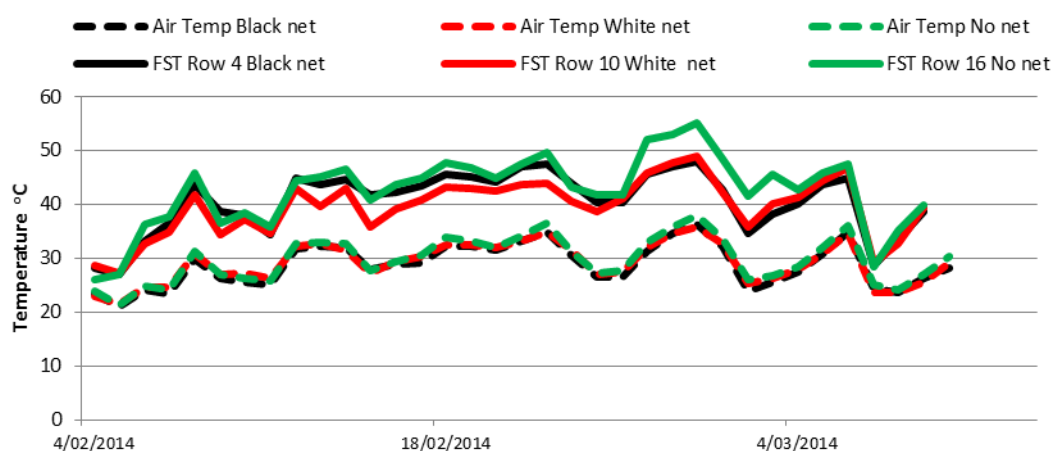


Figure 11. Fruit surface temperature (FST) and air temperature measured in the black net, white net and no net rows at the Lyster Matijari orchard (Manjimup) from February to mid-March 2014.

Impacts of warming temperatures on yield

(Appendix 9)

Modelling potential yield in apple using Malusim

In a recent report, Darbyshire and McClymont (2016) concluded that positive validation of MaluSim under Australian conditions was not achieved, based on poor prediction of yield by MaluSim for 'Royal Gala' and 'Cripps Pink' at multiple sites in Australia. However, performance of MaluSim in predicting fruit weight of 'Royal Gala' trees at the North Shepparton site, supported use of the model for preliminary investigation of influences of climate change on potential yield, as part of this project.

Potential impacts of warming temperatures on yield in apple

Using Malusim, the predicted impact of increased temperatures (+ 2°C) on yield in 'Royal Gala' apples in north Victoria was minor under the conditions modelled in this investigation. However, further research into possible effects of changes in harvest timing, leaf fall and elevated atmospheric carbon dioxide concentrations is required to better understand yield responses to climate change.

Communication, development and extension

Assessing the status of available information around climate change in the apple and pear industry in 2013

A review of climate change information available to the Australian apple and pear industry showed a lack of readily accessible, reliable and consistent information available to growers at the time. As a result it was concluded that, *a)* scientific outcomes from this project need to be published in a grower friendly format, *b)* research should be extended in a consistent manner through national grower workshops across the country and online blogs, and *c)* information generated needs to be stored online for easy access.

Improving industry understanding of likely changes in climate, potential impacts on apple and pear production, and options for adaptation

Outcomes from the national grower workshops (appendix 10) were overwhelmingly positive with the specific feedback varying depending on the location. A number of knowledge gaps were identified during the workshops, including the need for cultivar chilling requirements for existing and new cultivars, the role of soil temperature in dormancy breaking, and the need for more accurate in-season and long-term climate forecasting. There was a strong focus on the potential impact of extreme events on the industry under future climate scenarios, with less understanding about the potential impacts of more subtle increases in temperature.

Three grower publications were put together reporting on the latest project outcomes and information already available from either earlier research in Australia and/or other pome fruit growing regions. The publications were written with input from the project researchers and APAL (as the technical working group) on the topics of winter chill, netting for heat and climate scenarios. The guides will be available online (www.hin.com.au) and as hardcopies from APAL and/or the participating agencies.

Increasing knowledge and skills to enable informed decision making on climate change adaptation

Research outcomes were interpreted and communicated with a clear focus on practical on-farm application. For example, findings from the fruit surface temperature research were interpreted and communicated as regional sunburn browning-risk with analysis of the effectiveness of netting as an adaptation strategy to increased frequency of extreme heat days. The Western Australian netting demonstration site enabled on-site communication with growers in that state around the effectiveness of netting and the associated practical implications. Green tip and flowering data collection methods were developed for growers to use in their personal orchard record systems to determine cultivar performance and identify shifts in flowering time and/or quality. A winter chill website was developed to assist growers and, industry more broadly, to access and interpret winter chill data for their local region.

Building a connected and collaborative approach to climate change in the apple and pear industry

A strong network of researchers, extension officers, industry development officers, growers and other industry representatives was established nationally and continued to grow until project completion. The success of this project objective is discussed in the 'evaluation and discussion' (p39).

Evaluation and Discussion

Measuring project impact

The proposed project outcome was to *provide Australian apple and pear growers, pome fruit researchers and industry consultants with a greater understanding of predicted climate change in their region, the potential impacts and strategies for adaptation*. A formal evaluation of the project's ability to deliver on this outcome, was undertaken at the mid-way point through Horticulture Innovation Australia's independent mid-term review process.

Through extensive research, development and extension activities, this project delivered new knowledge to industry on regional climate change scenarios, potential impacts of changing climate on flowering and fruit quality, and options for adaptation.

Project outputs were produced across a broad variety of print, digital and oral communication mediums (refer to p13). The list includes 3 dedicated grower publications communicating climate risk and adaptation information for the apple and pear industry, a website for provision of up-to-date winter chill information, 6 grower workshops, 3 grower technical working group meetings, 2 industry surveys, 28 articles published in industry magazines, 5 presentations at industry conferences, 15 presentations at government and industry stakeholder meetings, 11 media items in-print and on radio, 9 technical reports, 2 dedicated project web pages, 6 regional chill factsheets, numerous blogs, 5 scientific publications and presentation at 2 scientific conferences.

The project trial sites were located in three growing regions (Western Australia, Victoria and Queensland), however significant effort was made to extend and communicate project outcomes more broadly across the industry. Grower workshops and technical working group meetings were held in New South Wales and South Australia. Collaboration with researchers from the University of Tasmania through the '*Crossing the threshold: adaptation tipping points for Australian fruit trees*' project and the dormancy-breaking spray trial facilitated effective communication with industry in that state. In addition, multiple members of the research and extension team organized and operated a project stand in the trade hall of the 2015 National Horticulture Convention in conjunction with the Department of Economic Development, Jobs, Transport and Resources.

To measure 'greater understanding' of climate change by the apple and pear industry, an extensive surveying process before and after project completion would have been required. This was not undertaken as part of the project, however, the extent of project outputs delivered across the country give a good indication of the level of engagement that this project successfully achieved.

In the next few years, the project impact will be measurable by assessing the level of uptake and use of the grower publications and 'winter chill and growing degree day' website. In addition, national networks developed over the last four years between members of the project team and industry, are likely to continue to provide ongoing benefit to Australian horticulture as its members move to reduce vulnerability to climate change risks.

Effectiveness of project activities in delivering project outputs and achieving intended outcomes

Efficiency of the delivery mechanism/s and appropriateness of the methodology

A mid-term project review conducted in 2014 by Professor Snow Barlow from The University of Melbourne found the research to be 'scientifically rigorous and directed towards the contracted objectives of the project'. The review highlighted the good progress made by the research and extension team in engaging with industry, and in the delivery of a broad information mix incorporating immediate adaptive strategies such as netting to reduce sunburn risk, and future long-term climate change impacts.

Our use of small grower-based technical working groups to receive guidance on research project direction and outputs was sound methodology, but required considerably more resources to maximize its value. The process of establishing these groups nationally, running meetings, compiling and disseminating outcomes, and maintaining communication with the groups throughout the project was significant. Ideally, the groups need to be coordinated by a local industry representative with strong connections to the industry in their region, and good knowledge of the industry itself.

Barriers to communication and extension around climate change adaptation

Effective communication between researchers and growers is particularly important in delivering messages on climate change impact and adaptation, due to the vast quantity of information and misinformation in the public sphere. A number of communication and extension barriers were identified during the course of project engagement activities (Table 6), and these learnings were used to improve the effectiveness of our communications.

For example, widespread confusion in the industry around measurement of winter chill and chilling requirements was identified as a significant barrier to effective communication of research findings related to climate change impacts on winter chill and flowering. As a result, the 'winter chill and growing degree day' website was developed (as part of a project variation) to provide chill calculation tools and supporting information for industry, with the aim of improving understanding and enabling better management of low winter chill years in orchards across Australia.

Table 6. Barriers to communication and extension around climate change adaptation

| Barriers | Comments |
|--|---|
| Skepticism of climate change | Communication with growers nationally suggested that this was a minority of industry. |
| Conflicting messages from Governments regarding potential climate change impacts and the need for adaptation | |
| Feeling of responsibility for climate change without having realistic strategies to combat it | |
| Resistance to implementing changes required for climate change adaptation | Could be for a variety of reasons including financial and family pressures. |
| Timing of communication- needs to be considered in the context of production stresses more broadly | Growers in the midst of battling drought are unlikely to be concentrating on understanding chilling requirements. Information provided needs to be carefully matched with local industry needs. |
| Large knowledge gaps in the science | For example, it is difficult for growers to make cultivar choices based on climate suitability due to the lack of basic understanding around chilling requirements and tolerance to heat. |
| Confusion around chilling requirements and measurement of winter chill | Generated historically by the reporting of winter chill in different units and general spread of misinformation. |
| Confusion around the terms 'climate variability' versus 'climate change' | |
| Confusion over the use of different scientific terminologies | Need to use consistent terminology in all communications, for example around winter chill and phenological stages. |

Feedback on activities and quality and usefulness of project outputs

Feedback on research and extension activities was obtained from a broad cross-section of apple and pear growers and industry representatives nationally, through meetings with APAL staff, and discussions and evaluations at grower workshops. A formal evaluation completed by 12 growers at the Bilpin workshop in 2015 indicated that 100% of them found the workshop content useful for their orchard businesses and that they would like to attend further events. Similarly positive results were obtained elsewhere through informal discussions.

In addition, feedback was sought via the project websites, through Australian Fruitgrower articles and, regular discussions with growers on-site during research data collection and various grower meetings. Grower experiences of local climate change impacts were often communicated during one-on-one conversations. The APAL industry conferences were utilized as an effective medium for sharing project outcomes. A dedicated project stand and display was set up in the exhibition hall at the National Horticulture Convention on the Gold Coast in 2015 for the purpose of sharing project outcomes, responding to targeted inquiries and obtaining feedback from industry nationally.

The value of online project outputs can be quantified through the number 'hits' to project website pages. The project pages on the Horticulture Industry Network site have received 987 hits since they were developed in 2014, indicating the usefulness of this medium for project communication.

Scientific feedback was obtained from within the project team as well as through linkages with researchers nationally. Critique of research methodology and results was sought from international scientists through publication in peer-reviewed journals, presentations at scientific conferences and through hosting visits from international researchers.

Feedback received was discussed with the project team during the monthly teleconferences and annual face-to-face meetings and was incorporated back into the project as deemed appropriate by the group.

Key learnings

Climate change will add significant variability into the pome fruit crop production system with respect to flowering and fruit quality. Most Australian growers are already used to dealing with some level of climate variability and it seems likely that impacts on flowering and fruit quality may be within the range of grower experience up to around 2030, but that by 2050 growers will be operating outside of current experience. This will present challenges for the Australian industry in the consistency of supply and in maintenance of the uniform orchard blocks that are a prerequisite for the efficient use of mechanisation.

Precise timeframes for impacts of warming temperatures on pome fruit production are difficult to determine because of the amount of variability in both the climate (including microclimate) and orchard production systems. For example, under the worst case scenario Manjimup is projected to receive an average of 46 chill portions in 2050. This means that in cold years there is likely to be plenty of chill for apple production, but warm years will challenge many current commercial cultivars. If the grower has adapted by planting lower chill cultivars and adjusted their management practices they are more likely to grow a good crop every year.

The Australian apple and pear industry in Australia, and globally, has a strong capacity for adaptation to the changing climate due to the availability of new technologies for crop sensing, opportunities for protected cropping, a strong research history in crop physiology, and availability of a broad diversity of scion and rootstock genetics. Genetic diversity in particular can be exploited to ensure commercial cultivars are better adapted to the changing climatic conditions.

Successful adaptation to the changing climate will be supported by capture and interpretation of data on tree phenology, climate and orchard practices. Australia's industry is made up of growing regions with diverse climates and much can be learnt about climate change impacts and options for adaptation by sharing of knowledge. In future, more comprehensive data will be collected on orchards through the use of sensing and mapping technologies. This data can be used to undertake more sophisticated and comprehensive analysis of flowering patterns and variability between and within locations.

Specific research learnings are listed under the stated project objectives.

1. Develop climate change scenarios for pome fruit growing regions of Australia in 2030 and 2050, including the likely impact of climate change on winter chill and extreme heat.

- Australia has undergone a consistent warming trend since 1910 however, at a local level the experience of climate change has been different in each pome fruit growing region. Changes in average minimum and maximum temperatures, and extreme heat for the period from 1968 to

2016 varied between locations.

- Milder growing regions have experienced a decline in annual winter chill accumulation since 1968, while the colder regions of Huonville and Orange have not changed.
- Increases in the number of extreme heat days have been experienced in Shepparton and Mt Barker, while the frequency of extreme heat days in Manjimup in the last seven years has been above the long-term average.
- The climate projections for 2030 and 2050 show that all pome fruit regions across Australia can expect to experience:
 - Declines in winter chill accumulation. Warmer winter growing regions such as Manjimup and Applethorpe were projected to experience a reduction in winter chill of 20% to 30% by 2050. A decline of between 10 and 15% chill was projected for the coldest regions (Huonville and Orange) over the same period.
 - An increase in the number of extreme heat days during the growing season. The greatest impacts were projected to be in regions such as Shepparton and Mt Barker, with hot summer climates.
- Climate change impacts on winter chill are likely to be within grower experiences of season-to-season variability up to approximately 2030. On-farm adaptation to this variability will reduce longer term climate change risk to orchard profitability. By 2050, it is likely that growers will be operating under climates outside of the current range of experience for a particular region.
- Expression of climate change projections in terms of meaningful horticultural climate metrics (chill portions and sunburn browning risk days) instead of average temperatures, improves their value to industry by directly linking projected changes in climate with impacts on production.

2. Understand how changes in autumn, winter and spring temperatures might impact the timing and quality of flowering in cultivars of apple and pear.

- Analysis of winter chill and flowering from 2012 to 2015 in Applethorpe, Shepparton and Manjimup showed:
 - Low winter chill, as observed in Manjimup, was associated with uneven chill accumulation caused by short periods of warm weather throughout the autumn and winter seasons.
 - Low winter chill in Manjimup was associated with greater variability in flowering dates between seasons, cultivars and individual trees, and irregular and protracted flowering across most apple cultivars, relative to the other sites.
 - The variable pattern of flowering observed in Manjimup was likely the result of mild winter conditions and inadequate chilling for some cultivars.
- Analysis using Manjimup as a climate analogue for Stanthorpe in 2030 indicated that growers in the Stanthorpe region were likely to experience a more variable and protracted pattern of flowering across many apple cultivars by 2030, but without any clear negative impact on productivity. Use of dormancy-breaking sprays is an adaptation option. There was with no clear need to shift to different cultivars or species at this stage (objective 3).
- Projections from the chill-overlap model for timing of full bloom in 'Cripps Pink' apple in 2030 and 2050 showed:
 - An earlier full bloom date on average in some high chill locations (for example, in Orange) in

2030 and 2050.

- A later full bloom date at the milder winter locations (Applethorpe, Manjimup and even Shepparton) in 2030, with average flowering dates delayed by more than a week in 2050.
- Changes in flowering time for 'Cripps Pink' in 2030 are likely to be within the current range of grower experience.
- Increased frequency of low chill years in milder winter growing regions will likely result in symptoms of inadequate chill in some cultivars. Advances in the timing of flowering might be observed in cooler winter regions. Changes in the timing of flowering can result in reduced yields in cases where the flowering period of polliniser trees no longer overlaps that of the commercial cultivar.

3. Identify adaptations to manage any negative effects of climate change on flowering.

- The dormancy-breaking spray trial in 'Gala' apple in Qld, WA and Tas demonstrated that:
 - Dormex®, Waiken™ and Erger® were able to advance flowering time and compact the flowering period.
 - Fruit maturity was advanced with dormancy-breakers and generally reflected differences in flowering dates.
 - Dormancy-breaking sprays are likely to be an effective tool for managing flowering in 'Gala', and other apple cultivars, in lower chill years in Australia.
 - Benefits from the use of dormancy-breakers are likely to be greater in low chill years when the potential impacts of inadequate chill on flowering are greatest. Therefore, benefits are likely to increase under future climate scenarios.
- Changes to cultural practices will be required to manage symptoms of inadequate chill such as delayed, irregular and protracted flowering:
 - Development of an appropriate chemical thinning program for managing buds at multiple stages of green tip and flowering on individual trees.
 - Careful hand thinning to optimise crop uniformity when fruitlets vary considerably in size and developmental stage.
 - Additional labour input to pick fruit at the appropriate stage of maturity when there is a greater spread of fruit maturity at harvest.
 - Pollination management to reduce the risk of poor flowering overlap in any particular year caused by large shifts in flowering dates between cultivars and seasons.
- The increased irregularity and unevenness of flowering is likely to be a greater management challenge for Australian growers than managing changes in flowering time, as growers are already experienced at dealing with large shifts in flowering dates between seasons.
- Using forced bud methodology to determine chilling requirements, apple cultivars fell into groups with low ('Cripps Red', 'Manchurian' crab apple), medium ('RS103-110', 'Granny Smith', 'Cripps Pink', 'Kalei') and higher chilling requirements ('Galaxy', 'Fuji', 'Hi-Early'). Groupings such as these enable growers to make more informed cultivar and polliniser choices at planting based on the winter chill climate in their region.

4. Understand how changes in the frequency of extreme heat days might impact on the incidence of sunburn in pome fruit and the effectiveness of netting as an adaptation strategy.

- Minimum air temperatures for potential sun damage in 'Royal Gala' apple were established:
 - 34.1°C and 38.7°C, respectively, for browning and necrosis for non-netted fruit.
 - 37.9°C for browning under netting.
- Air temperature thresholds were applied across southern Australia and potential sun damage risk and effectiveness of netting was determined under future climates:
 - Shepparton, Mt Barker and Manjimup were the most adversely affected by projected increases in the percentage of days with potential sunburn browning risk in January and February.
 - The percentage of risk days in Shepparton was projected to increase from 18% at present to 28 to 36% in 2050, with the installation of netting reducing the risk considerably, to around 9 to 13%.
- Most growing regions are likely to notice an increased sunburn risk by 2030 (if they haven't already). By 2050, growers in regions with currently milder summers, will need to have adapted their current orchard practices to manage the impacts that an increased frequency of heat events will have on fruit quality.
- The thermodynamic Smart-Sinclair model was tested on 'Royal Gala' grown under net and no net and was able to predict fruit surface temperature with a root mean square error of 2 to 3°C. Netting reduced the median fruit surface temperatures by 1.5 to 2.0°C.
- The thermodynamic Smart-Sinclair model can be used to understand processes and quantify the effects of various netting structures on fruit surface temperature and sun damage risk, but cannot be used for predicting the effects of climate change due to the lack of reliable projected solar radiation and wind speed data.

5. Understand how different colours of netting impact on the orchard environment, fruit yield and quality.

- Comparison of black and white netting at the Western Australian netting demonstration site showed little difference in environmental conditions or bud burst and flowering under the black netting, white netting and non-netted orchard blocks. Fruit surface temperatures were higher in the no net apples.

6. Understand how the changing climate might impact the yield potential of apples.

- The Malusim model for the prediction of potential apple yield, could not be positively validated under Australian conditions as it was generally a poor predictor of yield for 'Royal Gala' and 'Cripps Pink' at multiple sites in Australia.
- The MaluSim model was able to predict fruit weight of 'Royal Gala' trees at the North Shepparton site and supported use of the model for preliminary investigation of influences of climate change on potential yield. The predicted impact of increased temperatures (+ 2°C) on yield in 'Royal Gala' apples in north Victoria was minor under the conditions modelled in this investigation.

Recommendations

Industry

- The following tools and strategies are recommended for adaptation to an increased frequency of low chill years in milder growing regions of Australia:
 - Planting lower chill cultivars. Matching cultivars to their chilling climate is the best option, but it is not always possible due to market pressures and a lack of information on chilling requirements.
 - Management of delayed and variable flowering with the use of dormancy-breakers.
 - Development of a set of broad guidelines around the use of dormancy-breaking sprays based on existing knowledge. Such guidelines could include information on when dormancy-breaking sprays should be used, and in which cultivars and regions.
 - Adjustments to chemical and hand thinning practices to reduce variability in fruit size and maturity.
 - Use of the 'winter chill and growing degree day' website for monitoring in-season chill accumulation.
 - Preparation of an orchard management strategy to enact in low chill years. This would likely include monitoring of winter chill accumulation and the use of dormancy-breakers.
 - Comprehensive in-orchard monitoring of flowering dates across cultivars to provide early indication of cultivars that might be impacted by warmer winters, as well as identification of subtle shifts in the timing of flowering between cultivars and their pollinisers.
 - In blocks where flowering is becoming increasingly irregular, growers will need to assess the point at which the increased cost of inputs and effort required to produce a consistently high quality crop make a block of trees unprofitable.
- To reduce the risks to pollination from shifting flowering times, planting of multiple polliniser cultivars with early, middle and late flowering habits, to ensure a good supply of pollen throughout the flowering period is recommended where possible. Use of floral bouquets or artificial pollination methods can be considered to compensate for loss in flowering overlap.
- The following tools and strategies are recommended for adaptation by the apple and pear industry to increased frequency of extreme heat:
 - Continued investment in netting in locations such as Manjimup and Orange, where many orchards are currently un-netted.
 - Use of air temperature thresholds as a guide for using overhead sprinklers for evaporative cooling in efforts to minimize potential sunburn damage.
 - Planting heat tolerant cultivars. As for winter chill, matching cultivars to their growing climate is the best option, but it is not always possible due to market pressures and a lack of information on different heat tolerances of cultivars.
 - Development of orchard practice guidelines for managing extreme heat (bringing together

- aspects of tree canopy structure, evaporative cooling, netting types, irrigation, nutrition, spray-on protectants and other stress reduction products).
- Development of orchard practice guidelines for optimising post-harvest fruit quality in warm to hot summer/autumn conditions (pre and post-harvest management).
- For improved tactical and strategic planning in the orchard, use of the Bureau of Meteorology climate outlook videos (<http://www.bom.gov.au/climate/outlooks/#/overview/summary>), State of the Climate reports (<http://www.bom.gov.au/state-of-the-climate/>) and the 'climate change in Australia' website (<https://www.climatechangeinaustralia.gov.au/en/>) is recommended.
 - It is recommended that the Australian apple and pear industry utilise and exploit the genetic diversity available in scions and rootstocks globally, to ensure that commercial cultivars can be better adapted to the changing climatic conditions.
 - Climate analogues should be used to better identify the timeframes for impacts of low chill and extreme heat on apple and pear production, and the best strategies for adaptation. For example, growers in Manjimup are already successfully managing the impacts of inadequate chill in some years, lessons can be learnt from their knowledge and experience.
 - This project focussed specifically on climate change impacts on crop physiology, and it is recommended that the industry undertake a broad economic assessment of climate change impacts from storm events, drought, increased wind, changes in evapotranspiration, and so on.
 - The industry needs to consider how basic research gaps, such as knowledge around relationships between temperature and tree physiology, may be filled in future years to ensure the flow of new information and ideas into the industry does not become limited.

Extension and communications

- Having an extension and research team working side-by-side from project start to end has significant benefits for communications and industry engagement.
- National collaboration was enormously beneficial to the success of this project, as were linkages between projects and across industries.
- Having a core team responsible for communication ensured timely, relevant and consistent information was made available, and utilising well established local grower groups and extension officers ensured ease of facilitation.

Scientific

Priority research needs

- Determination of significant biological thresholds (chilling requirements, sunburn damage thresholds, pest and disease development thresholds) to enable conversion of weather and climate data into useful horticultural metrics for everyday decision making.
- Investigation of methods / programs for evaluation of new and existing scions and rootstocks, with the objective of providing sufficient information to enable matching of apple and pear cultivars with suitable growing climates, including matching chilling requirements with winter chill and heat

tolerance with summer temperatures.

- New genetics: breeding programs are needed that focus on lower chill cultivars with good tolerance for heat, alongside other quality parameters.
- Determination of genetic and/or physiological markers of flower bud progression into dormancy and out of dormancy prior to bud burst. This would improve the definition of apple and pear chilling requirements.
- Efficacy of using dormancy-breaking sprays for long-term adaptation to warming temperatures, including the extent to which dormancy-breaking sprays can be used as an adaptation to low chill years, relationships between dormancy-breaking sprays and fruit quality, particularly in cultivars and investigations into alternatives to Dormex®.
- Methods for managing heat in the orchard for improved fruit quality:
 - Efficient tree canopies for balancing multiple requirements, including low sunburn damage, optimal fruit quality (including colour development), water-use efficiency and disease management.
 - Understanding relationships between orchard temperatures during the growing season and fruit quality at harvest and after storage.
 - Use of plant growth regulators and stress reduction chemicals.

Additional research gaps

- Pest and disease management under warmer climates. Codling moth are likely to increase generation number per season, fruit fly are likely to have an extended range and disease management under netting on trellis systems will present new challenges, particularly when combined with the use of evaporative cooling.
- Determination of the limits of profitable apple production with regards to winter chill. Production areas with very low winter chill accumulation in South Africa and Southern Brazil rely heavily on dormancy-breakers and would be obvious target locations for a global investigative study.
- Potential impacts of low winter chill on marketable yield.
- For improved definition of apple and pear chilling requirements:
 - Cultivar specific parameterisation of the Dynamic model for improved chill model performance.
 - Relationship between bud temperature and dormancy breaking.
 - Standardisation of methods for determination of chilling requirements.
 - Investigation of the potential role of day length in dormancy breaking in apples.
 - Effectiveness of early versus late season chill in dormancy breaking.
 - Role of root-zone temperature and rootstocks in bud burst.
 - Relationship between temperatures received during autumn prior to dormancy and quality of bud burst and flowering.
 - Impacts of pruning and defoliation on modifying winter chill requirements.

- Validation of the chill-overlap model with flowering data from cultivars other than 'Cripps Pink' apple to determine how flowering time will be impacted by climate change.
- Better understanding of flowering in new and existing pear cultivars, and the likely impacts of changing climate.
- Fruit surface temperature thresholds for sunburn for a wide variety of cultivars. Transferability of fruit surface temperature thresholds across cultivars and locations needs to be investigated.
- Effectiveness of different types (colours, weaves) of netting in reducing the risk of sunburn damage and its effect on assimilation, transpiration and fruit quality.
- Impact of climate change on the duration of fruit development and maturity times for apple and pear cultivars of interest.
- Potential impacts of the extended growing season (caused by the later onset of cold temperatures in autumn and warmer springs) on canopy management and fruit quality.
- Impacts of warming spring and summer temperatures on flower bud initiation and development.
- The impact of elevated CO₂ temperature shifts on fruit maturation, colour development and leaf fall to improve predictions of yield under different climate scenarios.
- Pollination in a changing climate. Warming temperatures will impact bee behavior, synchronisation of flowering (due to changes in the timing of flowering), flower viability and floral bud initiation.
- Potential for POAMA (Predictive Ocean Atmosphere Model for Australia) to make in-season and short to medium-term climate forecasts with a level of accuracy necessary to inform decision making at tactical and strategic levels.

Scientific Refereed Publications

Darbyshire, R., McClymont, L., Goodwin, I. 2015. Sun damage risk of Royal Gala apple in fruit growing districts in Australia. *New Zealand Journal of Crop & Horticultural Science* 43, 222 -232.

McCaskill, M. R., McClymont, L., Goodwin, I., Green, S., Partington, D.L. How hail netting reduces apple fruit surface temperature: a microclimate and modelling study. *Agricultural and Forest Meteorology* 226–227, 148–160.

Parkes, H.A., Tabing, O., McClymont, L., Combret, M. and Wilkie, J.D. 2016. Variation in the flowering phenology of apple and pear in Australia. *Acta Horticulturae* 1130 (8), 55 - 61.

Parkes, H., Darbyshire, R. and White, N. Chilling requirements of apple varieties grown in mild Australian winter conditions. Prepared for *HortScience*.

Webb L., Darbyshire, R., Erwin, T. and Goodwin, I. 2016. A robust impact assessment that informs actionable climate change adaptation: Future browning-risk in apple crops. *International Journal of Biometeorology*. Doi:10.1007/s00484-016-1268-y.

Intellectual Property/Commercialisation

No commercial IP generated.

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Appendices

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Technical Report: Analysis of Historical and Future Climate and the Production of Pome Fruit

Neil White

February 2017



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Introduction

This report sets out our current knowledge of how climate change will affect pome fruit growing regions in Australia. All the pome fruit growing regions in Australia have seen a consistent warming trend since 1970 for both winter and summer temperatures. In response to this, growers have begun to adapt the management of their orchards to cope with these changes to remain profitable. These trends are likely to continue, so what can growers expect in the future?

Site Descriptions and Data Preparation

Trends in temperature over the period 1968 to 2015 have been presented as the yearly average change (anomaly) from a baseline period of 1981 to 2010 (30 years) for each of the sites shown in Figure 1.

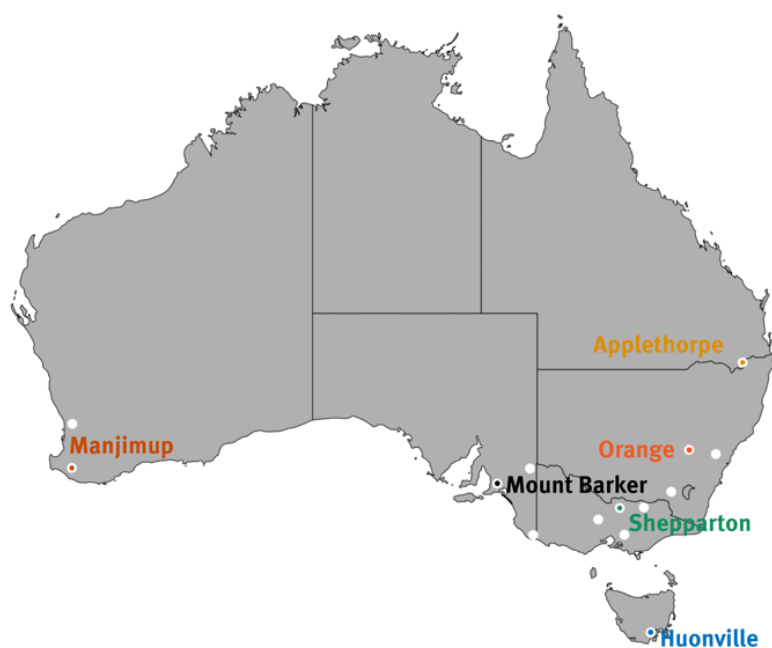


Figure 1 Australia's apple and pear industry centres (white) and locations referred to in the text.

Data were obtained from SILO¹ (Jeffrey et al. 2001), a repository of climate data for Australia. There are two sets of data available, a gridded daily data set and the patched point dataset (PPD). Data for the sites shown in Table 1, was extracted from the PPD which provides daily maximum and minimum temperatures from 1889 to the present. Interpolated values are inserted to maintain continuity when data are missing for some reason e.g., the station was not operating due to malfunction. Interpolation is

usually from daily surfaces, but in some cases, might come from more long-term, and hence less accurate, spatial data. The sites selected for the study had a generally low number of days when data was missing (Table 1).

¹ <http://longpaddock.qld.gov.au/>

Meteorological stations in Australia that record temperature are a small fraction of the total number of stations. Stations at local post offices that recorded data by hand have sometimes been closed in favour of automatic weather stations (AWS) nearby, often at an airfield. The PPD resolves some of these problems and provides data for stations regardless of their previous history. However, this reduces the reliability of datasets from stations with a lot of missing observations. Mount Barker and Orange were used here in preference to Lenswood and Batlow respectively, because these stations have more reliable historical temperature records.

Table 1. Description of weather stations used in the analysis.

| Station Number | Station Name ² (Short name) | Longitude/ Latitude | First Observation | Last Observation | Missing (%) |
|----------------|--|------------------------|-------------------|------------------|-------------|
| 41175 | Applethorpe | 151.95°E/ 28.62°S | 1 Jan 1968 | Current | 7.4 |
| 81049 | Tatura Institute for Sustainable Agriculture (Shepparton) | 145.39°E/ 36.43°S | 2 July 1965 | Current | 3.2 |
| 9573 | Manjimup | 116.14°E/ 34.25°S | 2 Jan 1968 | Current | 3.7 |
| 63254 | Orange Agricultural Institute (Orange) | 149.08°E/ 33.32°S | 2 Jan 1976 | Current | 20.3 |
| 94069 | Grove (Huonville) | 147.08°E/ 42.98°S | 1 Jan 1968 | 10 Feb 2010 | 20.3 |
| 23733 | Mount Barker | 138.85°E/ 35.07°S | 1 Jan 1968 | Current | 1.9 |

² Data for Shepparton and Huonville comes from the Tatura Institute for Sustainable Agriculture and Grove respectively.

Models for calculating winter chill rely on hourly data. However, hourly data is not generally available from the Bureau of Meteorology weather stations and needs to be generated from daily maxima and minima.

Daily data were converted to hourly using the routine in the chillR package (Luedeling et al. 2013) using the R Statistical Language (R Core Team 2015). This uses the interpolation routine developed in Linvill (1990). An example of this interpolation is shown in Figure 2

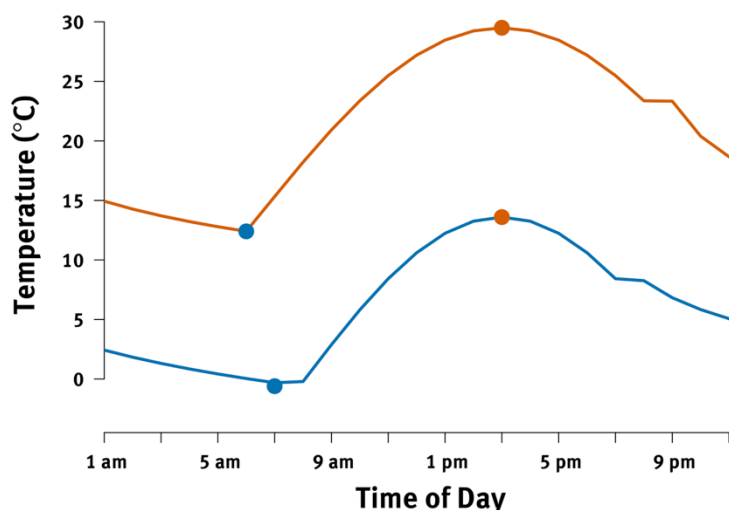


Figure 2 Examples of the use of the interpolation routine to convert daily maximum and minimum temperatures to hourly. The orange line is 21 December 2015 and the blue line is 21 June 2015 for Applethorpe. Dots indicate the maximum (orange) and minimum (blue) for each day that were used to generate the interpolated hourly data.

Reliability of techniques used to interpolate between daily and hourly temperatures

Hourly temperature data for 2013 in Applethorpe (collected from an on-site orchard temperature logger, ARS1) was used to assess the accuracy of the interpolation method. The daily maxima and minima were taken from the orchard hourly data set, and the interpolation method was applied to recreate the hourly data. The orchard hourly data was then compared with the interpolated hourly data, Figure 3.

The correlation coefficient is 0.97 indicating a close relationship between the two sets of data, however, the effect of the interpolation can still be seen. The sensitivity of the Dynamic Model to the discrepancies between observed and interpolated hourly data needs to be assessed in terms of chill accumulation and heat stress.

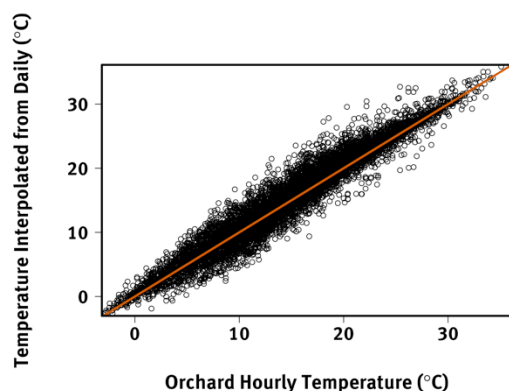


Figure 3 Measured hourly temperature data and hourly data interpolated from daily maximum and minimum for Applethorpe. Line shows the 1:1 correlation.

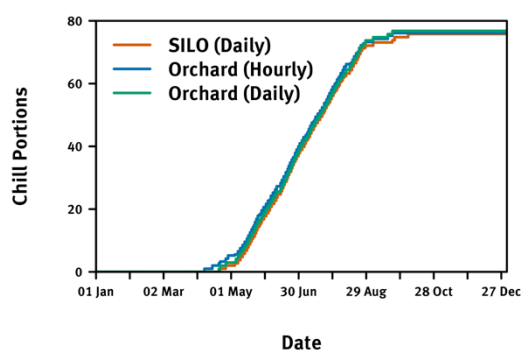


Figure 4. Comparison of chill portion accumulation calculated from orchard hourly data hourly data interpolated from the orchard daily maxima and minima, and the nearby AWS.

The chill portions calculated from the three datasets were in close agreement which is important as the SILO data needs to be used to consider future climate projections, Figure 4.

The impact of the interpolation on the calculation of heat thresholds is more problematic.

Interpolation from daily orchard data to hourly overestimated the number of hours exceeding 30°C by 36%. Importantly, based on the number of days exceeding the 30°C threshold, there was only a difference of two days between orchard daily and the automatic weather station (AWS) data. This is acceptable and is the approach that is used in our study.

Models of Chill Accumulation

What is winter chill?

The dormant winter phase is an evolutionary advantage that protects fruit trees from cold weather damage by preventing the growth of cold-sensitive shoots and flowers in response to a winter warm spell. For trees to resume growth in spring this dormant phase must be 'broken'. Perennial fruit trees break dormancy after certain winter conditions have passed - the tree has then determined that winter has finished and will begin to flower in response to warm temperatures. The winter chill required to break dormancy, the chilling requirement, differs by crop and variety, and possibly locality.

Accumulation of winter chill to break dormancy is largely a temperature dependent process. The relationship of different temperatures and temperature regimes to dormancy breaking are species and cultivar-specific but there are some general aspects that are thought to be involved:

- Freezing temperatures do not contribute to dormancy breaking;

- There are optimum temperatures for the accumulation of winter chill;
- Temperatures either side of the optimum decrease the contribution to winter chill;
- High temperatures can undo previously accumulated chill;
- Cycling moderate temperatures with effective chilling temperatures enhances the accumulation of winter chill
- It is still largely unknown when a tree becomes sensitive to the chilling temperature – it could even be before leaf drop.

These assumptions can be expressed as a set of calculations that together form a chill model. The three most common models are: Chill Hours, Utah Chill Units and the Dynamic Model.

Chill Hours

The Chill Hours model (Weinberger 1950) is by far the simplest model. It accumulates the number of the hours where the temperature is less than 7.2°C and greater than 0°C. There is a form that also includes hours below 0°C, but in this study, we have used the 0°C threshold.

Utah Chill Units

This model (Richardson et al. 1974) uses a slightly more complicated procedure in which low and high temperatures adversely affect the accumulation of chill. The method of calculation is as follows where T is the temperature recorded for the hour in °C.

| Lower Limit (T > °C) | Upper Limit (T ≤ °C) | Chill Units Contributed |
|----------------------|----------------------|-------------------------|
| | 1.4 | 0 |
| 1.4 | 2.4 | 0.5 |
| 2.4 | 9.1 | 1.0 |
| 9.1 | 15.9 | 0.5 |
| 15.9 | 18 | -0.5 |
| 18 | | -1.0 |

Hours spent at or below 1.4°C do not contribute to chill accumulation. Greatest chill accumulation is between 2.4 and less than or equal to 9.1°C. Temperatures above 15.9°C reduce the chill accumulation as they contribute negative chill units.

Dynamic Model

The Dynamic Model (Fishman et al. 1987, Erez et al. 1990), which calculates chill in Chill Portions, is the most complex of the chill models. It is the current best practice model, especially in warmer climates (Erez 2000, Luedeling et al. 2011) and is therefore the model we have used for winter chill calculations. In this model, accumulation of chill is a dynamic process whereby the equations describe the build-up of a hypothetical dormancy breaking factor (DBF) through a two-step process.

The accumulation of DBF is referred to as Chill Portions and a Chill Portion has accumulated when the amount of DBF reaches 1. At this point it forms part of the stable pool and cannot be destroyed. If less than 1 is currently in the labile pool it can be reduced. This is seen when warm temperatures occur and there is no chill accumulation. However, the current number of Chill Portions is not reduced. Production of DBF occurs between 0°C and 12°C and is optimal between 6°C and 8°C. The model also captures the situation observed in some tree crops where accumulation of chill is enhanced when if temperatures in the range 13°C to 16°C are cycled with lower temperatures.



Trends in Temperature and Chill Accumulation

Trends in temperature have been assessed in terms of annual temperature and seasonal maximum and minimum temperatures for each of the sites. The Bureau of Meteorology (BoM) maintains a web page that allows trends in climate variables to be assessed³. The maps shown in Figure 5 show consistent warming trends across the pome and stone fruit growing regions.

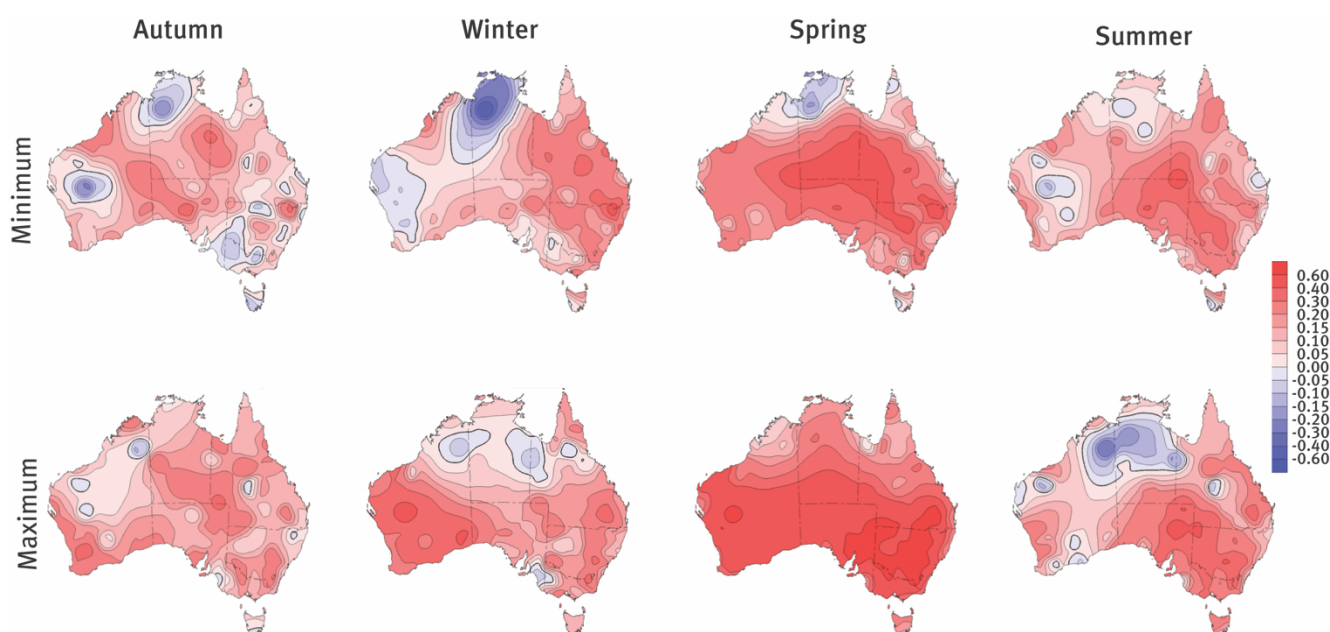


Figure 5. Trends in temperature from 1970 to 2015. Red shows that the trend in temperature has been towards hotter temperatures, while blue shows a trend towards cooler temperatures. The higher the intensity of colour the stronger the trend. © Commonwealth of Australia 2016. Australian Bureau of Meteorology.

Autumn and winter

Autumn and winter temperatures largely determine progression through dormancy, and significantly impact flowering timing and quality in pome fruit trees. For example, warm weather in autumn causes delays in leaf drop and slows the entrance into dormancy. Mild winters resulting in a lack of winter chill cause delayed, uneven and protracted flowering.

³ <http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries>

Minimum temperatures in autumn and winter have increased in Huonville, Orange and Mt Barker since 1968 (Figures 6). In Huonville and Orange, the warming trend is more apparent in minimum temperatures than maximums over this period, while Applethorpe, Shepparton, Manjimup and Mt Barker all show an increase in maximum autumn and winter temperatures (Figure 7).

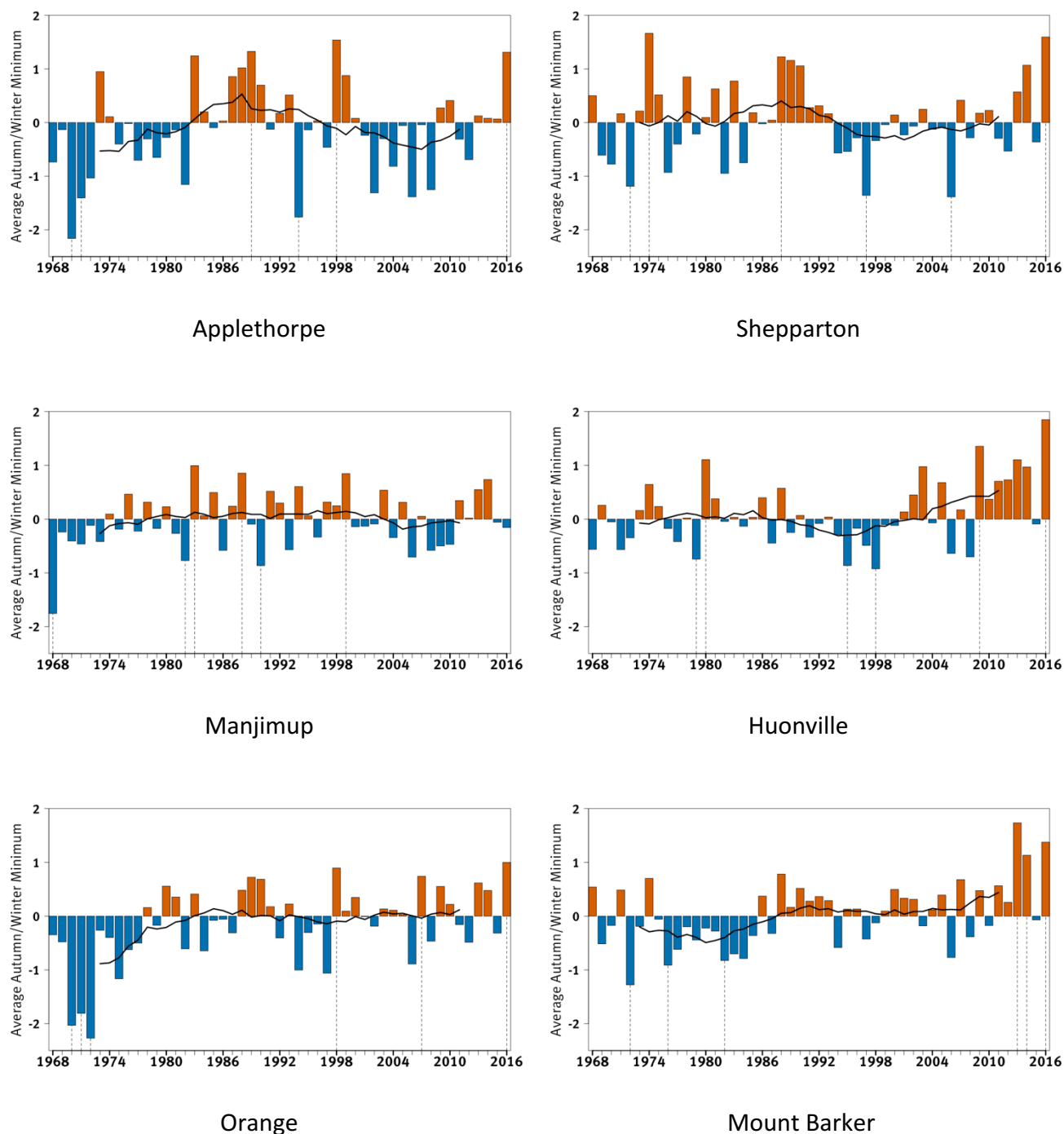


Figure 6. Average autumn-winter minimum temperature anomalies compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

At Applethorpe, Shepparton, and Mount Barker, it was more likely that after 1990, maximum temperatures during autumn and winter would be greater than the long-term average (Figure 7).

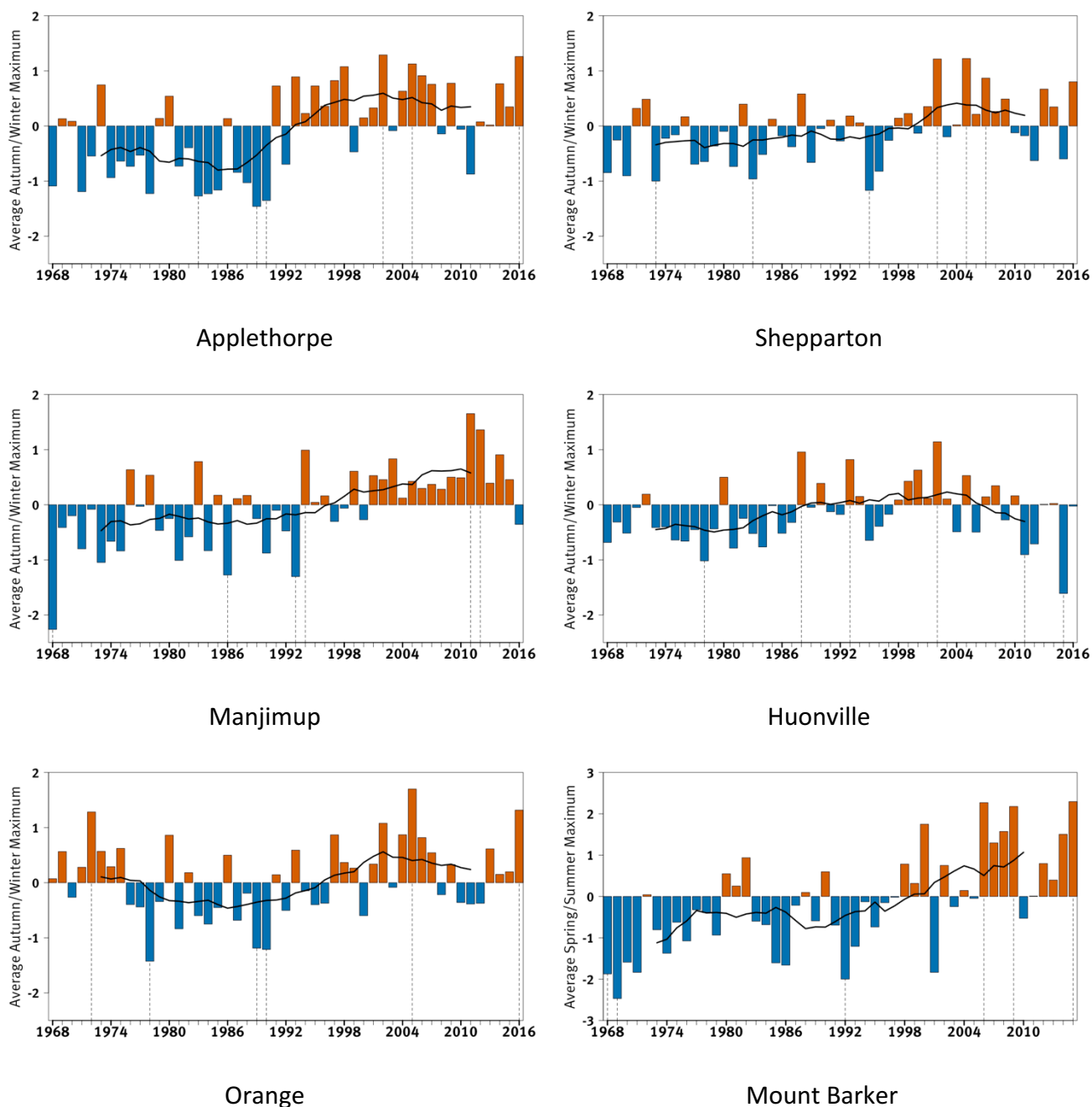
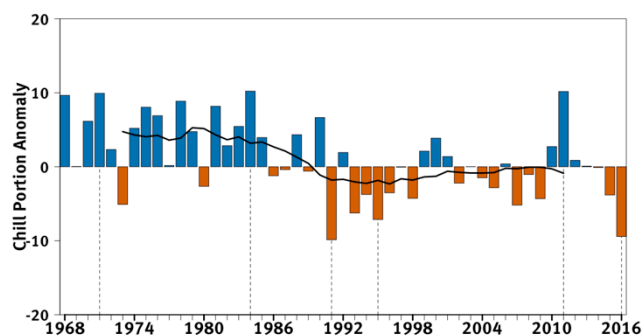


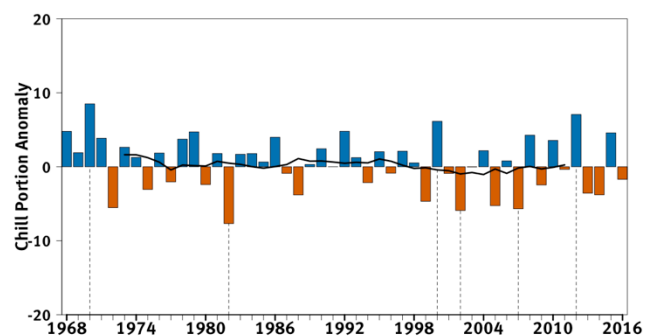
Figure 7. Average autumn-winter maximum temperature anomalies compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

Winter chill

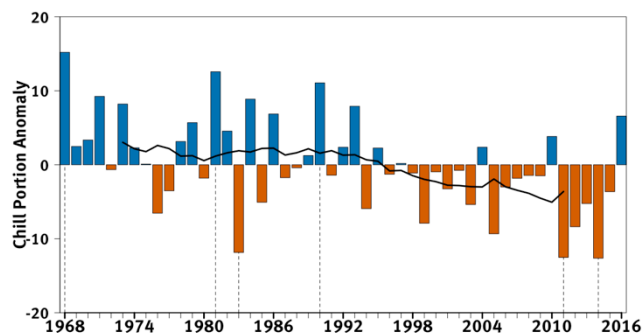
The milder growing regions of Applethorpe, Manjimup and Mt Barker have experienced a decline in the number of chill portions accumulated since 1968 (Figure 8). Shepparton has seen a small reduction in winter chill over this period, while the colder regions of Huonville and Orange have not changed. Eight out of ten years in Manjimup from 2006 to 2016 have had less winter chill than the long-term average, Figure 8.



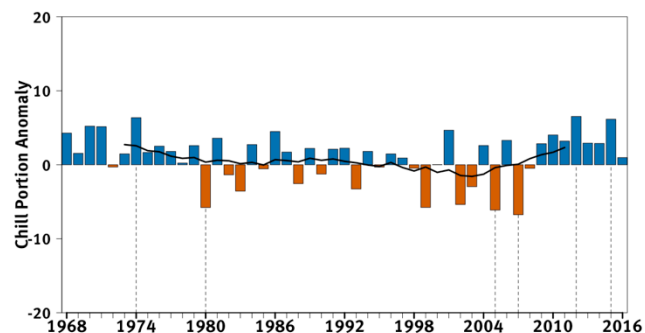
Applethorpe



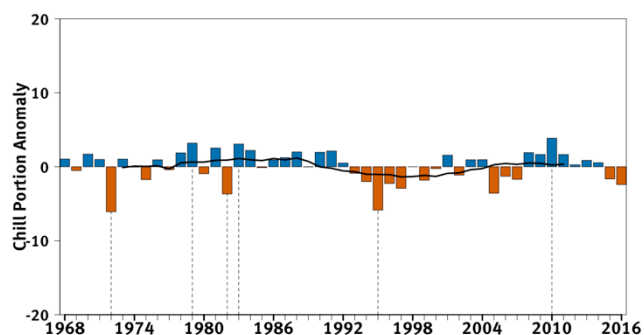
Shepparton



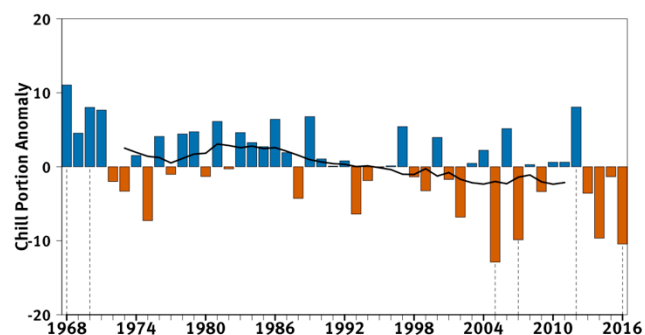
Manjimup



Huonville



Orange



Mount Barker

Figure 8. Annual anomaly (average change) in accumulation of chill portions (1 March – 31 August) compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

Spring and Summer

Temperatures experienced in spring and summer are an important driver of flower and fruit development and significantly impact on fruit quality in apple and pear trees. For example, warm

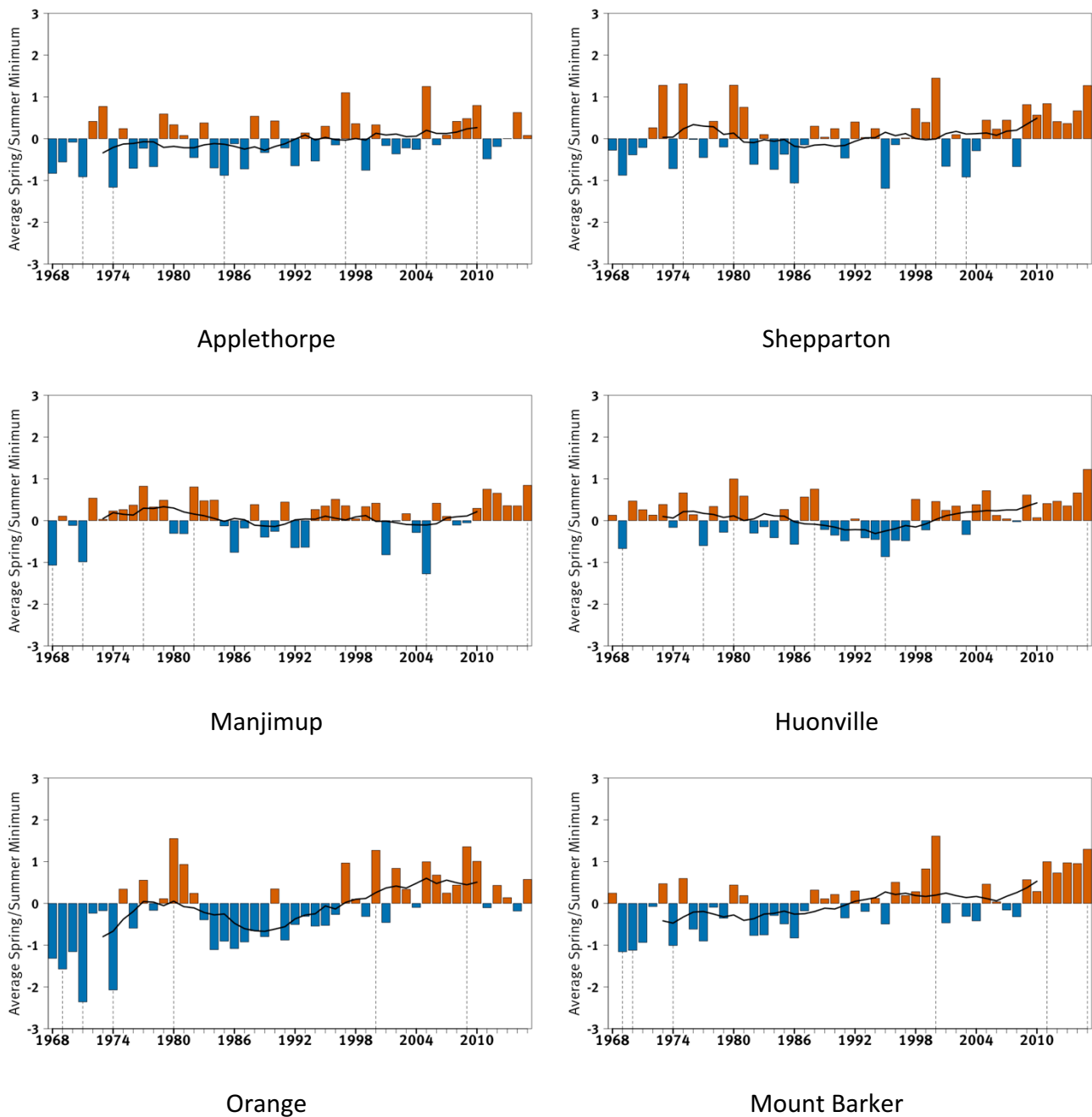


Figure 9. Average spring-summer minimum temperature anomalies compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

weather in spring tends to shorten the period of flowering, and heat in summer impacts colour development through inhibition of anthocyanins (Lin-Wang et al. 2011). Extreme summer temperatures inhibit fruit growth and cause sunburn browning (Flaishman et al. 2015).

There were clear warming trends in the minimum spring and summer temperatures at Orange and Mt Barker (Figure 9). At Shepparton, Orange, and Mount Barker it was three to four times more likely

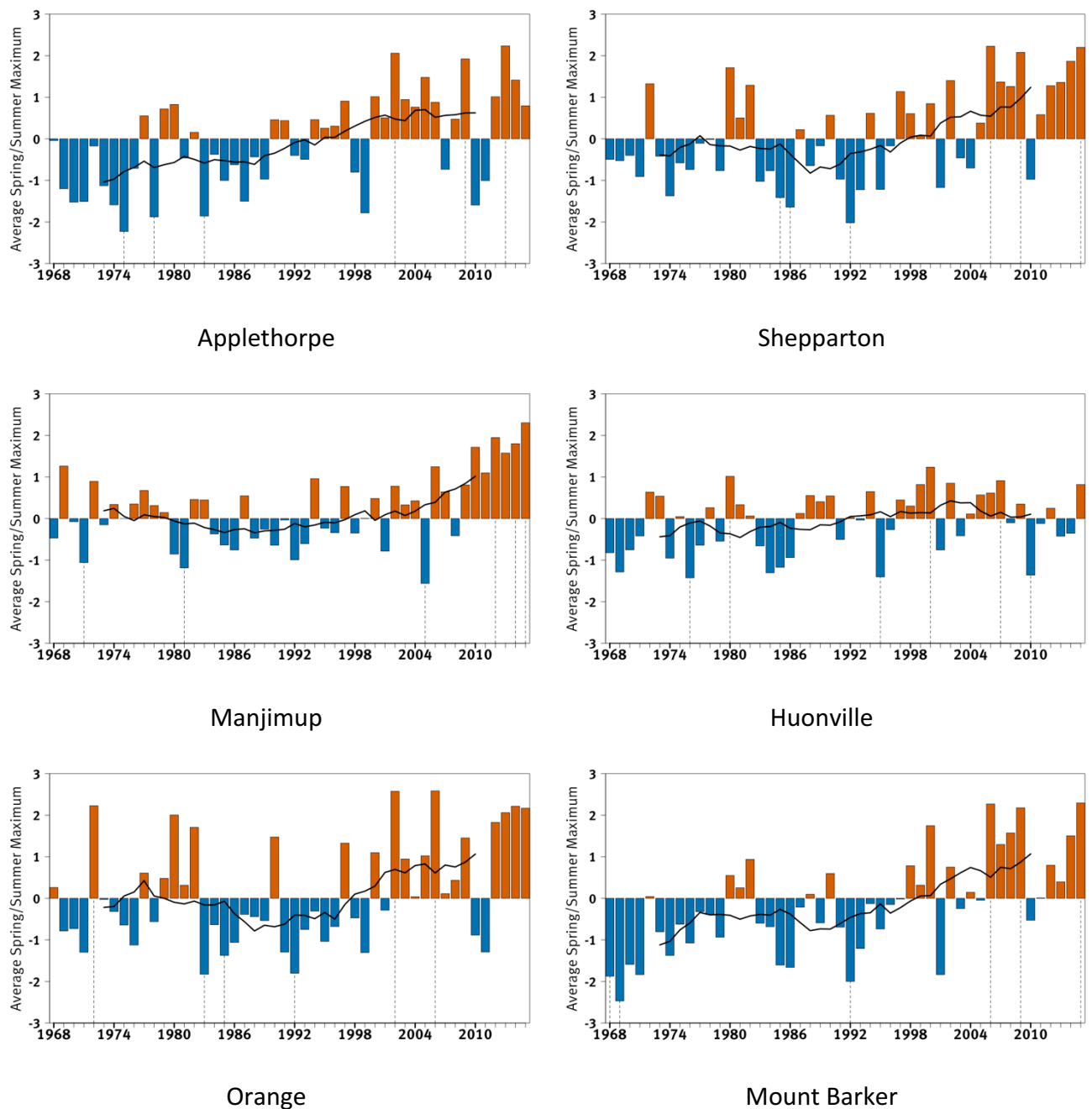


Figure 10. Average spring-summer maximum (right) temperature anomalies compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

that the average minimum temperature measured after 1990, was greater than the long-term average, compared to that measured before 1990. Spring and summer maximum temperatures have warmed in most locations since 1968, except for Huonville (Figure 10). This has implications for the frequency of extreme heat events, and warmer spring temperatures may have offset the reduction in chilling observed in milder growing regions.

Extreme Heat

Shepparton has experienced an increase in the number of extreme heat days (i.e. maximum temperature exceeded 35°C) received per year since 1968 (Figure 11). Maximum temperatures rarely exceed this threshold in Applethorpe and Huonville, and these sites have not seen much change over the period. Mount Barker showed a significant trend in the number of heat days and the last six years in Manjimup have been above the long-term average.

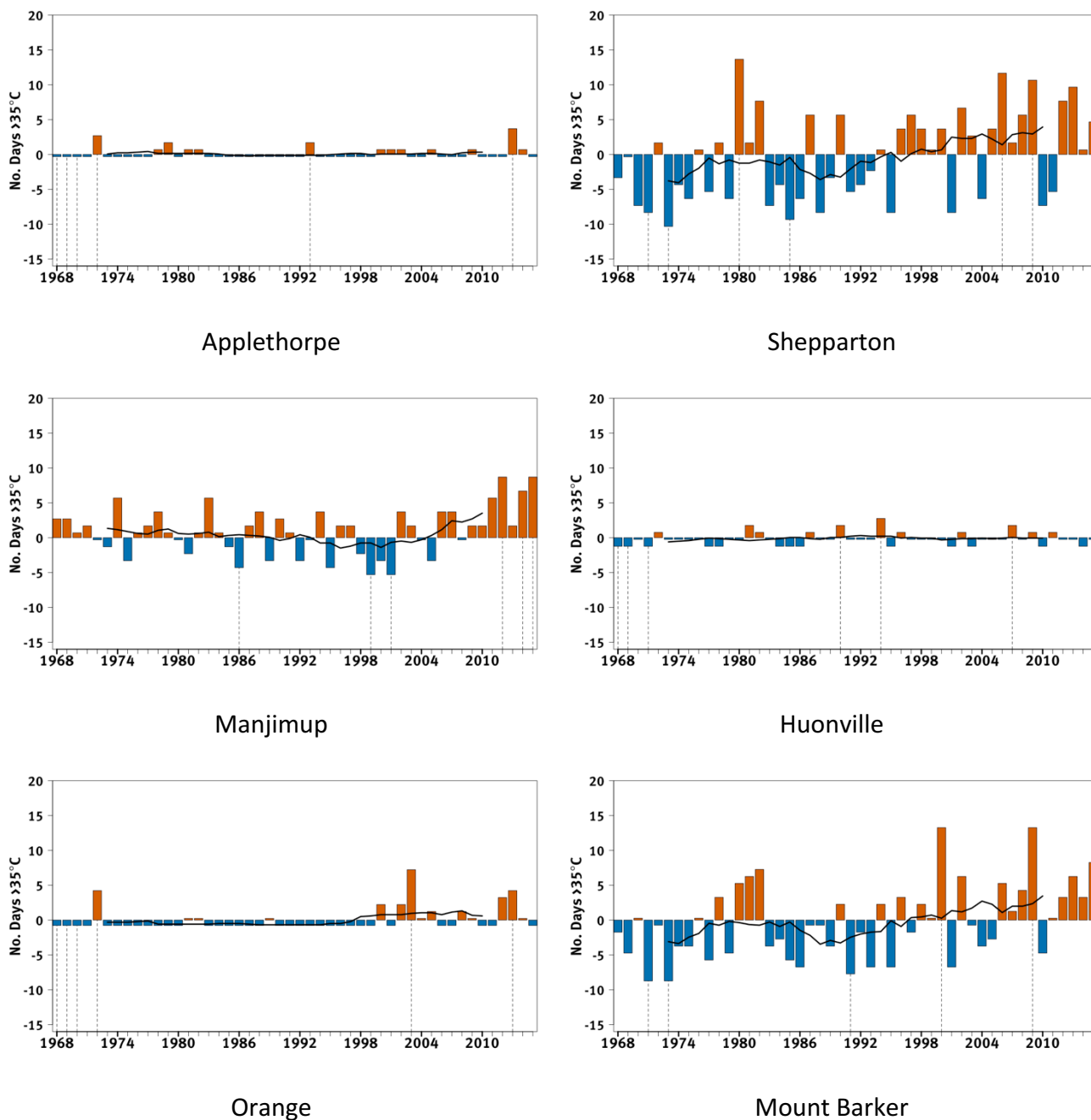


Figure 11. Annual anomaly (average change) in average number of days where maximum temperature exceeds 35°C compared to a base period of 1981 to 2010. The black line is an 11-year moving average.

Climate Scenarios for apple growing regions for 2030 and 2050

How were the scenarios chosen?

Future climate projections are derived using simulations of the earth's climate system (Global Climate Model or GCM) under different scenarios of future greenhouse gas and aerosol emissions. The scenarios are referred to as representative concentration pathways (RCP, see inset below) and represent a plausible set of future emissions. A GCM uses this information through the complex set of equations that determine how the climate responds to changes in the atmosphere. RCPs are classified by the amount of radiative forcing (see inset) that will be experienced in 2100.

Representative Concentration Pathways (RCPs)

Radiative forcing is the extra heat that the lower atmosphere will retain as the result of additional greenhouse gases. In 1979 this amounted to 1.7 W.m^{-2} . By 2014, this has risen to 2.9 W.m^{-2} . In 1979 the CO_2 concentration was 335 ppm. The current level as of February 2016 is 398 ppm.

RCP4.5 and RCP8.5 have been selected to represent the range of plausible future climates.

RCP4.5 achieving lower emissions due to some mitigation efforts and the CO_2 concentration reaching 540 ppm by 2100 (rising moderately rapidly and then peaking early) – setting a minimum to medium case climate change scenario

RCP8.5 a business-as-usual approach, with CO_2 concentration continuing to rapidly rise reaching 940ppm by 2100 – setting a worst-case climate change scenario

Source: (Butler and Montzka 2016, CSIRO 2016)

The measured and projected levels of atmospheric CO_2 are shown in Figure 12. It is worth noting that the projected level in 2100 under RCP 4.5 is the same as the level reached in 2050 under RCP 8.5. The observed emission trends (2005-2012) are in line with the worst-case scenario, RCP8.5, (Peters et al. 2012). Policy decisions made over the next decade or so will be critical in

determining the pathway that is taken. Data from BoM⁴ of the global temperature anomaly and yearly maximum atmospheric CO₂ recorded at Mauna Loa from 1958 to 2016 were used to derive a simple relationship between them that accounts for 82% of the variation (see inset Figure 12).

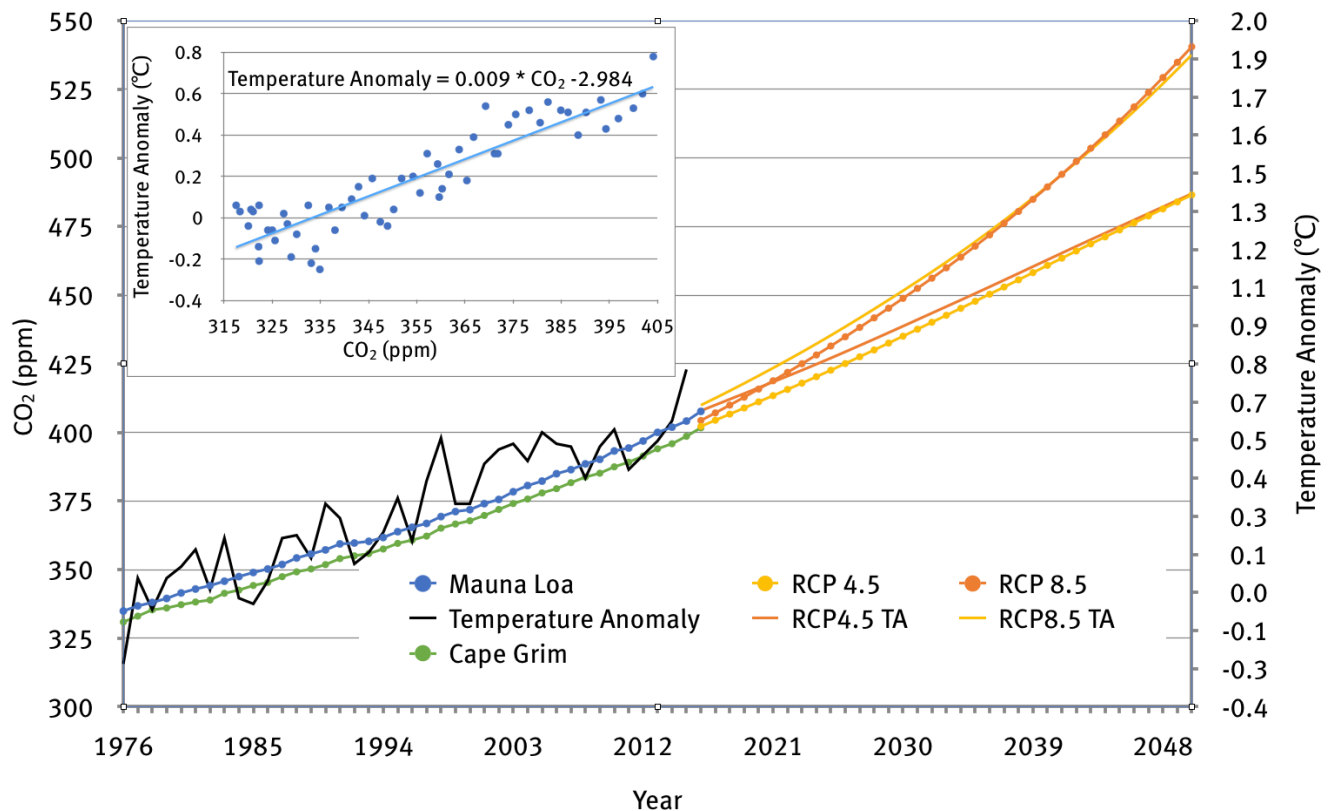


Figure 12. Measured (Cape Grim, Tasmania and Mauna Loa, Hawaii) and Future CO₂ for RCP 4.5 and RCP 8.5 and measured and predicted temperature anomaly (TA) using the relation shown in the inset.

To determine the projections of future climate change it is first necessary to extract the monthly change factors. Climate change factors allow the information from coarse-grained GCMs (typically 100-200 km) to be represented at a local scale. A climate change factor for January, 2030 using the ACCES 1.0 model might be + 1°C, this is added to the daily observations for January to create a possible climate. This process is repeated for each month, time scale and GCM. This allows a future climate set to be created that incorporates historical variability.

⁴ <http://www.bom.gov.au/climate/change/index.shtml#tabs=Tracker&tracker=global-timeseries>

While the actual changes may be small relative to daily temperature variations, the biological response may be significant because of the impact of threshold temperatures. Calculations of chilling, for example, use threshold temperatures to determine the contribution made to daily chill accumulation. A small shift in temperature throughout autumn and winter can have a large effect on the outcome as demonstrated for Manjimup in 2030, Figure 13. The individual temperature change for a given month and RCP may only be in the region of 0.5 to 1.2°C, but over the season this is enough to reduce the accumulated chill.

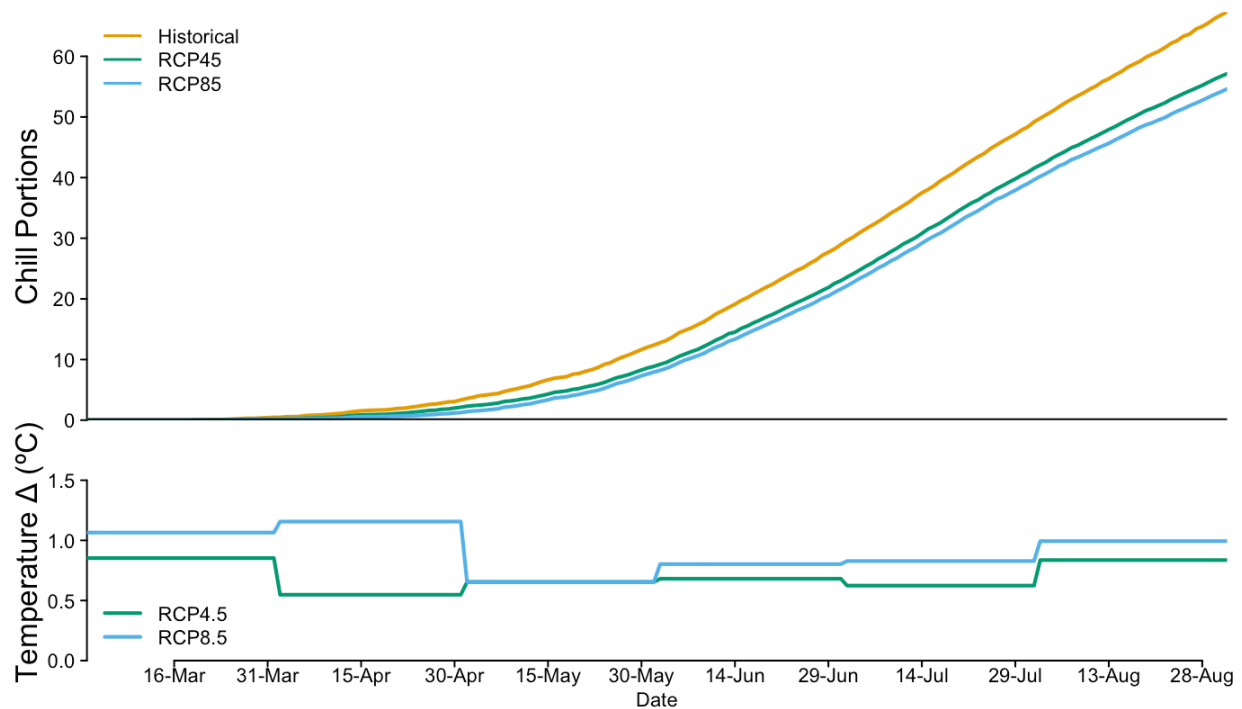


Figure 13. Accumulation of chill for historical average conditions at Manjimup and for a projected climate for 2030 under RCP 4.5 and RCP 8.5 (top). The monthly change in average temperature that caused the difference in the chill accumulation in the future is shown in the lower graph.

Selection of Global Climate Models

Global Climate Models (GCM) were selected from the list of models generated by the Climate Futures Tool at the Climate change in Australia website⁵. Three GCMs (Table 2) were selected based on a high M score (Watterson 1996) that measures the ability of the GCM to represent historical observations. A perfect match would have an M score of 1000. The GCMs selected and their average M scores were ACCCES1-0 (727), HadGEM2-ES (720) and MPI-ESM-LR (720). In this case the agreement between modelled and observed climate was based on temperature, rainfall and mean sea level pressure for the four seasons over the whole of Australia. These models scored greater than 800 for

⁵ <http://www.climatechangeinaustralia.gov.au>

surface temperature alone. For RCP 4.5, these GCMs were in a group (23/38 GCMs) that predicted warmer winter maximum and minimum temperatures. The projected change in temperature was from 0.5 °C to 1.5 °C. For RCP 8.5, HadGEM2-ES was grouped with those that showed a warmer minimum temperature, but hotter maximum temperatures 1.5 °C to 3.0 °C (13/40 GCMs). ACCESS1.0 and MPI-ESM-LR were grouped with those that showed warmer minimum and maximum temperatures in winter (24/40).

Table 2. Description of GCMs used in this study.

| GCM | Institute | Average M score * 1000 | Further Information and spatial resolution (latitude x longitude) |
|-----------------|--|---------------------------|---|
| ACCESS1-0 | CSIRO and Bureau of Meteorology | 727 | https://confluence.csiro.au/display/ACCESS/Home (1.25° x 1.875°) |
| HadGEM2- ESM | Met Office Hadley Centre | 720 | http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2 (1.25° x 1.875°) |
| MPI-ESM-LR | Max Planck Institute for Meteorology | 720 | http://www.mpimet.mpg.de/en/science/models/mpi-esm.html (1.865° x 1.875°) |

Calculation of Climate Projections for Station Data

Climate change factors were obtained from gridded data sets in the CIMP5 multi-model ensemble⁶ (see Taylor et al. 2011) and applied as monthly climate change factors to the daily data for each of the sites.

The method used to perturb the present climate to a future climate results in a shift that can be seen on a monthly scale (Figures 14 and 15). This is because the change factor applied to daily temperatures is the same within each month.

Figures 14 and 15 demonstrate that until 2030 the choice of the RCP has little impact, but by 2050, the differences caused by the higher emissions in the RCP8.5 pathway can be clearly seen.

⁶ <http://nrm-erddap.nci.org.au/erddap/index.html>

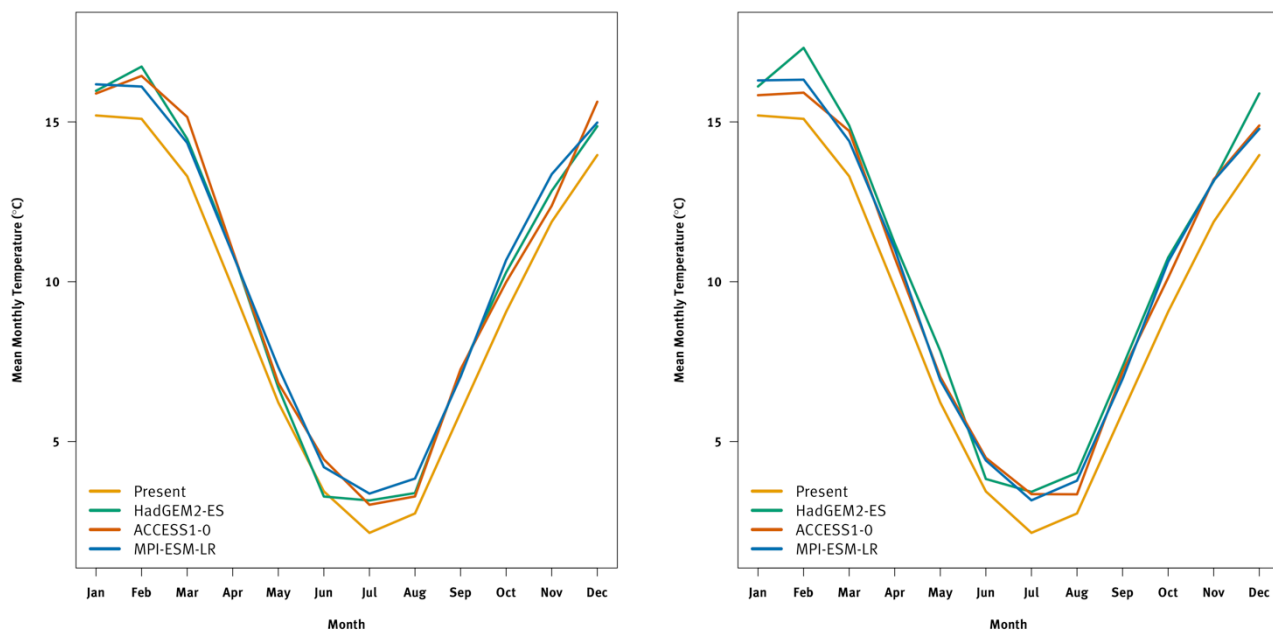


Figure 14. Mean monthly minimum temperatures for Applethorpe for 2030 under RCP4.5 (left) and RCP8.5 (right).

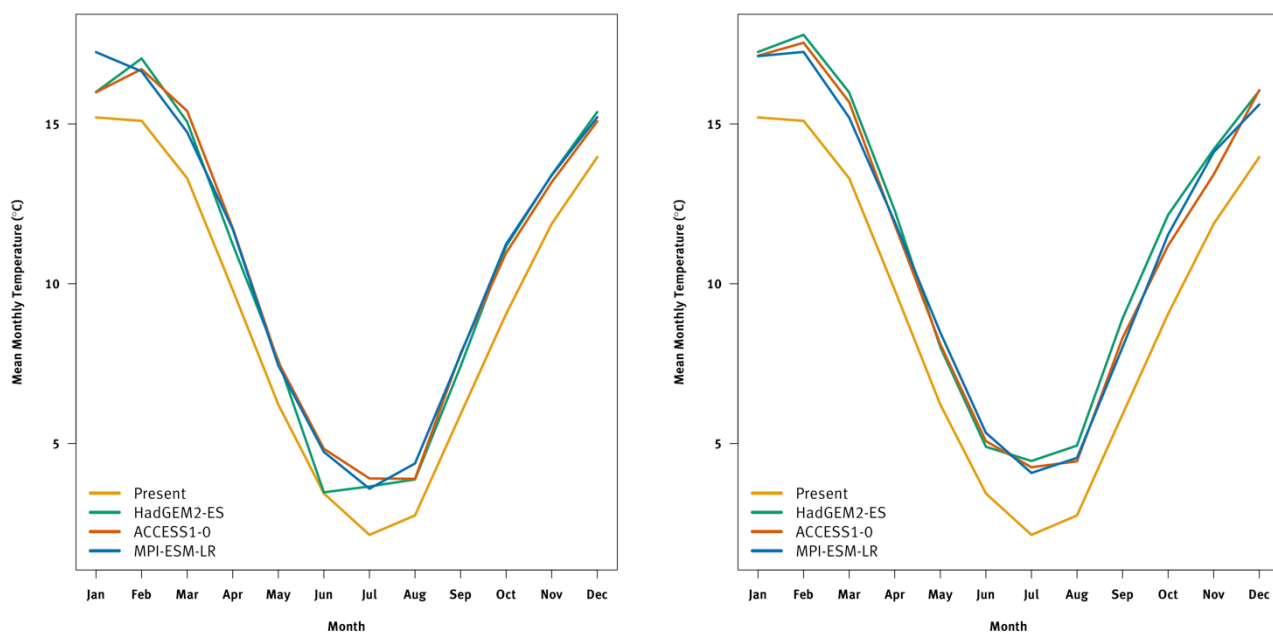


Figure 15. Mean monthly minimum temperatures for Applethorpe for 2050 under RCP4.5 (left) and RCP8.5 (right).

Future Climate Projections and the Impact on Flowering

The relationship between chilling and flowering can be described mathematically (Pope et al. 2014) such that the amount of chill that accumulates affects the flowering date because the

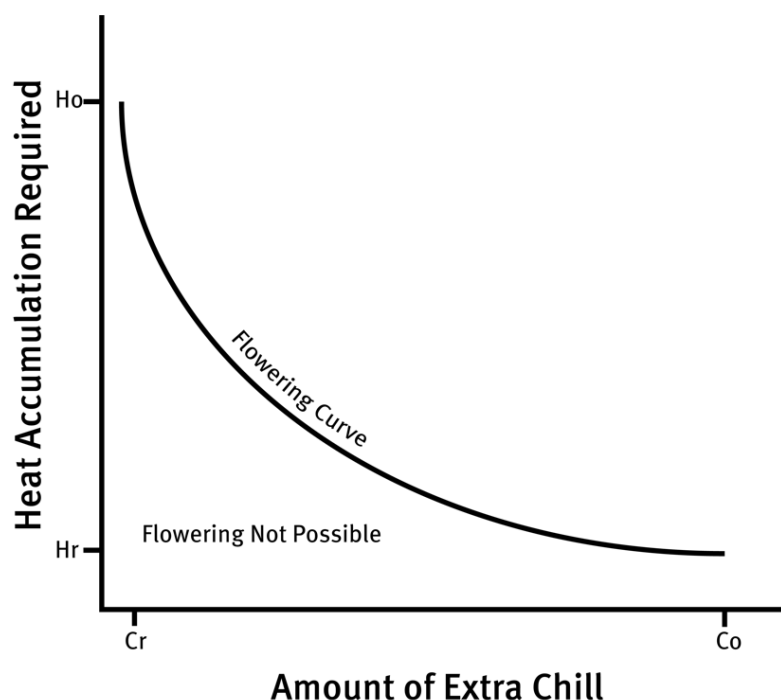


Figure 16 The Chill-Overlap Model. C_r is the chill required for flowering. C_o is the maximum additional chill that will reduce the heat requirement. H_r is the heat required when C_o chill is accumulated and H_o is the heat required when chill is an C_r (Redrawn from Darbyshire et al. 2016).

amount of heat required to promote flowering is altered. (Darbyshire et al. 2016) found that for Cripps Pink apples the minimum amount of chill required is 34 Chill Portions. Less than this critical amount of chill cannot be compensated for with heating and there is no effective flowering. If additional chill is accumulated, then there is a lower requirement for heat. This relationship between the accumulation of chill and the heat requirement is referred to as the Chill-Overlap Model, Figure 16.

Future chill accumulation, as measured by Chill Portions (CP), will decline in 2030 and 2050 under both, the RCP 4.5 and RCP 8.5 scenarios at growing regions across Australia (Table 3). The highest declines will be for Manjimup, Applethorpe and Mt Barker, although all sites show a decline. The smallest declines are at Orange and Huonville which decline by less than 5% in 2030 and by less than 15% in 2050 under either RCP4.5 or RCP8.5.

Using the mathematical relationships embodied in the Chill-Overlap model (Figure 16) it is possible to compare how full bloom dates might change in the future and whether the increased temperatures during spring and summer can compensate for the reduced chill accumulation (Table 5).

Table 3 Summary of average chill portions (1 March – 31 August) for 2030 and 2050 using a moderate (RCP4.5) to worst case scenario (RCP8.5) modelling approach based on historical data from 1985 to 2014. Mean of 30 years with lowest and highest in parentheses.

| | Present | 2030 | | 2050 | |
|--------------|--------------|-------------|-------------|-------------|-------------|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 72 (62-83) | 63 (48-75) | 60 (44-73) | 56 (41-69) | 51 (36-65) |
| Shepparton | 84 (73-93) | 75 (63-85) | 74 (62-86) | 71 (58-81) | 67 (57-79) |
| Manjimup | 67 (55-82) | 57 (43-76) | 55 (42-75) | 50 (36-72) | 47 (33-68) |
| Huonville | 105 (94-113) | 98 (81-112) | 97 (78-110) | 93 (74-105) | 90 (71-104) |
| Orange | 100 (90-110) | 94 (85-104) | 93 (82-101) | 90 (81-99) | 87 (78-94) |
| Mount Barker | 84 (67-93) | 74 (55-88) | 73 (53-88) | 70 (53-84) | 65 (47-80) |

The concept of safe winter chill (SWC) was introduced by Luedeling et al. (2009) a measure that can be thought of as the number of chill portions that a grower could expect in 90% of years.

Table 4 Safe winter chill calculations for the period 1985 to 2014.

| | Present | 2030 | | 2050 | |
|--------------|---------|--------|--------|--------|--------|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 67 | 55 | 55 | 47 | 46 |
| Shepparton | 76 | 67 | 68 | 66 | 59 |
| Manjimup | 60 | 49 | 52 | 44 | 41 |
| Huonville | 99 | 91 | 94 | 88 | 86 |
| Orange | 94 | 87 | 87 | 85 | 81 |
| Mount Barker | 74 | 62 | 66 | 60 | 56 |

Reductions in the SWC in Applethorpe, Manjimup and Mount Barker were similar and ranged from 16% to 17% in 2030 and 18% to 32% in 2050.

Orange, a location with a high chill accumulation the average date of full bloom is advanced (earlier bloom) by 4 to 5 days. Other locations showed a delayed full bloom date with the greatest impact felt at Manjimup, the location with the least chill at present and into the future.

Table 5 Summary of average date of full bloom (Cripps Pink) for 2030 and 2050 using a moderate (RCP4.5) to worst case scenario (RCP8.5) based on historical data from 1985 to 2014.

| Average Predicted Full Bloom Date | | 2030 | | 2050 | |
|---|--------|--------|--------|--------|--------|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 4 Oct | 7 Oct | 9 Oct | 12 Oct | 16 Oct |
| Shepparton | 30 Sep | 3 Oct | 3 Oct | 5 Oct | 6 Oct |
| Manjimup | 16 Oct | 22 Oct | 25 Oct | 30 Oct | 2 Nov |
| Huonville | 26 Sep | 27 Sep | 29 Sep | 29 Sep | 29 Sep |
| Orange | 2 Oct | 28 Sep | 28 Sep | 28 Sep | 27 Sep |
| Mount Barker | 1 Oct | 5 Oct | 4 Oct | 6 Oct | 8 Oct |

Delays in full bloom date are caused when less winter chill is accumulated during the autumn and winter period and, consequently, more heat is needed to promote flowering. Manjimup is likely to experience the greatest delay in full bloom dates in future climates compared with other locations. This is because chill accumulation above 34 CP, this is Cr Figure 16- the chill overlap model, in Manjimup drops from 22 CP in the present climate, to 14 – 16 CP in 2030, and 10 – 12 CP in 2050. To compensate for this, a greater amount of heat needs to be accumulated (i.e. moving from Hr towards Ho in Figure 16) and this required an extra 6 to 9 days in 2030, and 14 to 17 days in 2050. In comparison, at Orange the much cooler winter temperatures and high chill accumulation lowered the requirement for heat. This helped to advance the date full bloom because of higher spring temperatures (Figure 9 and Figure 10).

Future Projections of Impact on Quality

One of the main risks for production is extreme heat days as this leads to sunburn browning. Sun damage risk in Royal Gala was studied in apple growing regions in Australia (Darbyshire et al. 2015). They devised a browning risk day for non-netted and netted orchards based on air temperatures and

found that daily maximum temperatures greater than 34.1 °C in non-netted orchards and 37.9 °C in netted orchards were associated with an increased risk of browning. While that study and Webb et al. (2016) considered January temperatures, we have extended the analysis to include February as this coincides with the fruiting period. Using the daily maximum temperatures for January and February from 1981 to 2010 (present) and future climates in 2030 and 2050 we calculated the browning risk as the percentage of days that exceeded the temperature thresholds with and without netting. Following Webb et al. (2016), we classified browning risk in 5 categories:

| | | | | |
|------|------------|-------------|-------------|-------------|
| ≤ 5% | > 5 to 10% | > 10 to 20% | > 20 to 30% | > 30 to 50% |
|------|------------|-------------|-------------|-------------|

Table 6. Summary of mean values for browning risk (percentage of days) for January and February.

| Without Netting | | 2030 | | 2050 | |
|-----------------|---------|--------|--------|--------|--------|
| Site | Present | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 1.1 | 2.4 | 2.8 | 2.8 | 4.9 |
| Shepparton | 18.3 | 23.9 | 26.8 | 27.5 | 35.8 |
| Manjimup | 10.0 | 15.2 | 15.2 | 16.6 | 19.8 |
| Huonville | 2.4 | 3.4 | 3.8 | 4.5 | 4.2 |
| Orange | 2.4 | 3.8 | 4.4 | 3.7 | 8.4 |
| Mt Barker | 17.3 | 20.7 | 22.9 | 23.2 | 25.8 |

| With Netting | | 2030 | | 2050 | |
|--------------|---------|--------|--------|--------|--------|
| Site | Present | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Applethorpe | 0.0 | 0.0 | 0.1 | 0.1 | 0.4 |
| Shepparton | 4.8 | 7.0 | 9.0 | 8.8 | 13.2 |
| Manjimup | 1.6 | 3.8 | 3.9 | 4.4 | 6.0 |
| Huonville | 0.3 | 0.6 | 1.0 | 1.2 | 1.1 |
| Orange | 0.1 | 0.1 | 0.1 | 0.1 | 0.7 |
| Mt Barker | 5.4 | 7.2 | 9.1 | 9.4 | 10.7 |

Shepparton, Mount Barker and Manjimup will be most adversely affected without netting, however, this can be largely offset with netting. Without netting Manjimup moves to the same category by 2030 that Shepparton and Mount Barker currently experience. Applethorpe, Huonville and to a lesser extent Orange are in low risk categories and are likely to remain that way in the future.

Discussion and Conclusions

Climate change represents an important factor for perennial tree crops whether that is because of reduced chill or increased risk of sunburn browning. There has been a tendency to consider that apples generally have a high chilling requirement, yet successful crops are grown in South Africa (Cook 2010) and Manjimup where the chill is low in comparison to traditional growing regions. Low chill can cause a range of problems, including delayed or erratic bud break, bud abscission, lower flower and fruit quality and reduced yield (see table in Atkinson et al. 2013). Safe winter chill (Luedeling et al. 2009) under future climates is a possible indication of what to expect. Applethorpe records a lower SWC in 2030 for the more optimistic RCP4.5, than present day Manjimup (Table 4).

Perennial tree crop industries are particularly vulnerable to climate change because of the cost and longevity of orchard establishment. While many growers have been adapting to the trends already evident in a highly variable climate, the impact of future climate might be underestimated because of the language used by climate scientists and the media. A 1-2°C increase in temperature might seem trivial considering daily fluctuations, however, as can be seen from the analyses these can accumulate across the season and have larger impacts through delayed flowering and increased risk of sun damage.

The impact of changes in temperatures on flowering in the future are complicated by the interaction between a reduction in chill accumulation during winter and increased spring and summer temperatures. While the chill-overlap model is useful in understanding these relationships, it is based largely on hypothetical processes. Gaps in our knowledge, such as understanding when plants start and stop chill accumulation need to be based on physiology, i.e. the understanding of the chemical processes (Atkinson et al. 2013). This has proved difficult because there are no outward signs that can be used. It is hoped that chemical markers for these processes can be found so that our understanding will be greatly advanced. This would have the advantage of being able to make better estimates of how things might change in the future and possibly lead to breakthroughs in breeding programs. At a more fundamental level, our current best model for measuring and predicting chill accumulation, the Dynamic Model, uses parameters that have only been parameterised for peach

because the onerous experimental procedures required to derive them. Furthermore, it relies on a hypothetical factor that may or may not exist. The model, especially as part of the chill overlap model, remains the most useful way of predicting flowering.

Take-home messages from the historical record:

- All pome fruit growing regions have generally seen an increasing trend in maximum temperatures in winter and maximum and minimum spring temperatures.
- The strongest downwards trend in chill accumulation has occurred at the milder locations of Applethorpe, Manjimup and Mount Barker.
- Spring and summer maximum temperatures at all locations, except Huonville, show an upward trend. This is particularly noticeable for Manjimup which has recorded a higher than long-term average maximum since 2009.
- Extreme heat is an emerging problem in Manjimup and growing regions in NSW. Heat damage has been a problem in Victoria and the increase observed in Manjimup has prompted detailed studies of how and when browning occurs and a trial of nets in those areas.

Take-home messages from the future scenarios:

- Small increases in average temperatures multiply their effect through the accumulation of time above or below thresholds.
- The response of the pome fruit tree to reduced chill may be partially offset by increased spring and summer temperatures, but our current best understanding of this suggests that this cannot occur indefinitely.
- Up to 2030-2040, the differences between the climate change scenarios are small. The children of the growers who are farming today, may in 2050, be facing a very different growing environment. In Applethorpe, where a low chill year is 60 CP now, will feel like a good year and the worst years will be like nothing that has been encountered before.
- There is a complex interplay between chilling and warming on the timing of flowering that we are only just starting to understand. Much of our knowledge of how pome fruit trees respond has been in conditions where chill has been more than adequate. The chill overlap model has been useful as model of this situation, but the biological basis is uncertain.
- Extreme heat will continue to be a problem in hot summer regions such as Shepparton where it already presents challenges for fruit quality, and is an emerging problem for regions like Manjimup which currently have a milder summer climate. The impact on marketable quality is well known and investment in netting seems to be the most practical solution.

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Flowering in pome fruit trees across Australia

Implications of a changing climate

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Summary

Australia has warmed by 1°C in the last 100 years and temperatures are predicted to continue warming. This will result in reduced winter chill for many apple and pear growing regions of Australia and it is not clear how this will impact on pome fruit production. To better understand how climate change will impact flowering in pome fruit trees, research was undertaken to evaluate the timing and quality of flowering in cultivars of apple and pear across Australia, and how they relate to temperatures received in the orchard. Green tip, flowering and temperature data was collected in the spring of 2012, 2013, 2014 and 2015 for cultivars of apple and pear grown in the climatically distinct regions of Applethorpe (Queensland), Shepparton (Victoria) and Manjimup (Western Australia).

For all years of the study, Shepparton received the most winter chill with 89 chill portions on average, followed by Applethorpe (75 chill portions) and Manjimup (63 chill portions). Low winter chill in Manjimup was associated with greater variation in green tip and full bloom dates between years, cultivars and individual trees, compared with observations from Applethorpe and Shepparton. Additionally, trees in Manjimup displayed a long and protracted flowering period compared with the other sites. The patterns of flowering observed in Manjimup are possibly the result of inadequate chill. Shepparton, the site with the most winter chill, showed the greatest consistency in green tip and flowering dates.

Results from this research support findings from previous studies, performed in other parts of the world, showing that apples grown in warmer climates exhibit increased variability in flowering. Uneven and irregular flowering results in the reduced ability to predict timing of orchard operations, more difficult pollination management, challenges for thinning and crop load management, and can result in increased variability of fruit maturity at harvest.

As the climate warms, low chill years will become more frequent in milder growing regions of Australia, and will likely result in symptoms of inadequate chill in some cultivars. Advances in the timing of flowering might be observed in cooler growing regions. Australian growers already manage seasonal changes in flowering time and it may be the increasingly protracted and variable flowering that presents the greater management challenge.

Options for adaptation to low chill years include planting lower chill cultivars, management of delayed and variable flowering with the use of dormancy-breakers, and adjustments to chemical and hand thinning practices to reduce variability in fruit size and maturity.

Climate change will add significant variability into the pome fruit crop production system. This will present challenges for the Australian industry in its ability to consistently supply high quality fruit into export markets, and in maintenance of the uniform orchard blocks required to maximise the benefits of mechanisation. Ongoing observations of flowering performance and its relationship with chilling, will be necessary for making informed predictions about future block and cultivar profitability.

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Introduction

Flowering timing and quality in apple and pear trees is determined by interactions between the genetics of a cultivar and the temperatures it experiences in the orchard throughout the year. Cultivars require a certain amount of winter chill and a certain amount of heat for bud dormancy release and flowering, and these requirements are largely genetically determined (Cannell 1989, Saure 1985, Samish 1954). Day length is not believed to have a significant role in the timing of flowering in apple (Dennis 2003).

Australia has warmed by 1°C in the last 100 years, and temperatures are predicted to continue warming (State of the climate 2016). This will result in reduced winter chill for many apple and pear growing regions of Australia (Darbyshire et al. 2013b, Hennessy and Clayton-Greene 1995). It is not yet clear what the impact of this will be on the timing and quality of bud dormancy release and flowering in commercial pome fruit cultivars, and therefore the potential impacts on productivity. Advances in flowering time with increased temperatures has been observed in temperate fruit trees globally (Legave et al. 2013), however, effects of recent warming in Australia on pome tree flowering are not as clear (Darbyshire et al. 2013a).

Changes in timing of flowering may have impacts on yield through the loss of flowering overlap between a cultivar and its pollinisers, and potential for increased frost risk (Kaukoranta et al., 2010). Variable and protracted patterns of flowering are likely to occur in locations where the warmer climate leads to inadequate chill (Erez 2000). Poor quality of flowering impacts production and profitability through reductions in fruit set, difficulties with chemical thinning, and greater variability of fruit maturity at harvest (Theron 2013, Oukabli 2003).

Understanding potential impacts of climate change is essential for the timely implementation of appropriate adaptation strategies (Cobon et al. 2009). To understand how warming temperatures might impact on flowering, it is necessary to first understand the existing flowering behaviour of pome fruit tree cultivars across Australia, and how it relates to temperatures received in the orchard.

Study objectives

The objective of this research was to *evaluate the timing and quality of green tip and flowering in cultivars of apple and pear across Australia and how they relate to temperature, to contribute towards understanding of how climate change will impact on pome fruit production.*

Materials and methods

Site description

Green tip and flowering data was collected in the spring of 2012, 2013, 2014 and 2015 for cultivars of apple and pear grown in commercial orchards and research facilities situated in Applethorpe (Queensland), Shepparton (Victoria) and Manjimup (Western Australia) (Figure 1 and Table 1).

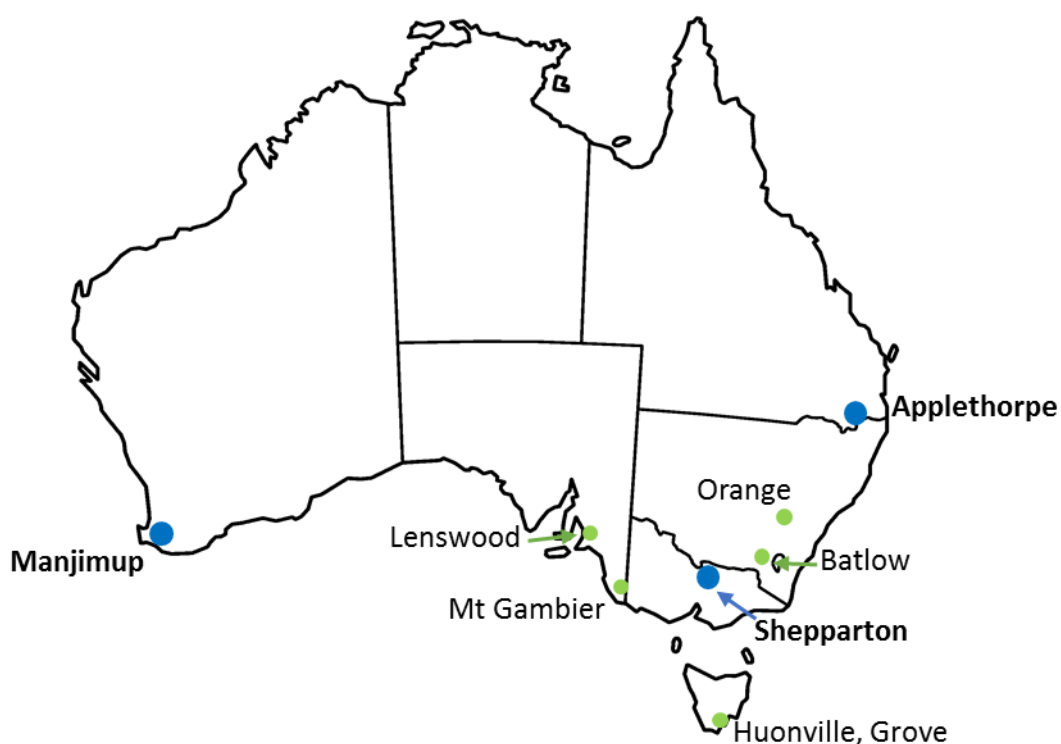


Figure 1. Site locations across Australia (large blue dot).

Table 1. Site details.

| State | Location | Orchard | Latitude and Longitude | Cultivars |
|-------|-------------|--|------------------------|---|
| Qld | Applethorpe | Department of Agriculture and Fisheries Qld, Applethorpe Research Facility | 28.52 S 151.90 E | All apples and pears (except Josephine) |
| | | C Pozzebon & Co Orchard | 28.63 S 151.97 E | Josephine pear |
| Vic | Shepparton | Silverstein's orchard, Shepparton East | 36.42 S 145.46 E | All apples and pears |
| WA | Manjimup | Department of Agriculture and Food WA, Manjimup Horticultural research Institute | 34.18 S 116.07 E | All apples |
| | | Newton Brothers Orchards | 34.13 S 116.07 E | All pears |

The three study sites are climatically diverse with Shepparton experiencing the hottest summers and Manjimup the warmest winters. Applethorpe has the highest average spring temperatures (Figure 2).

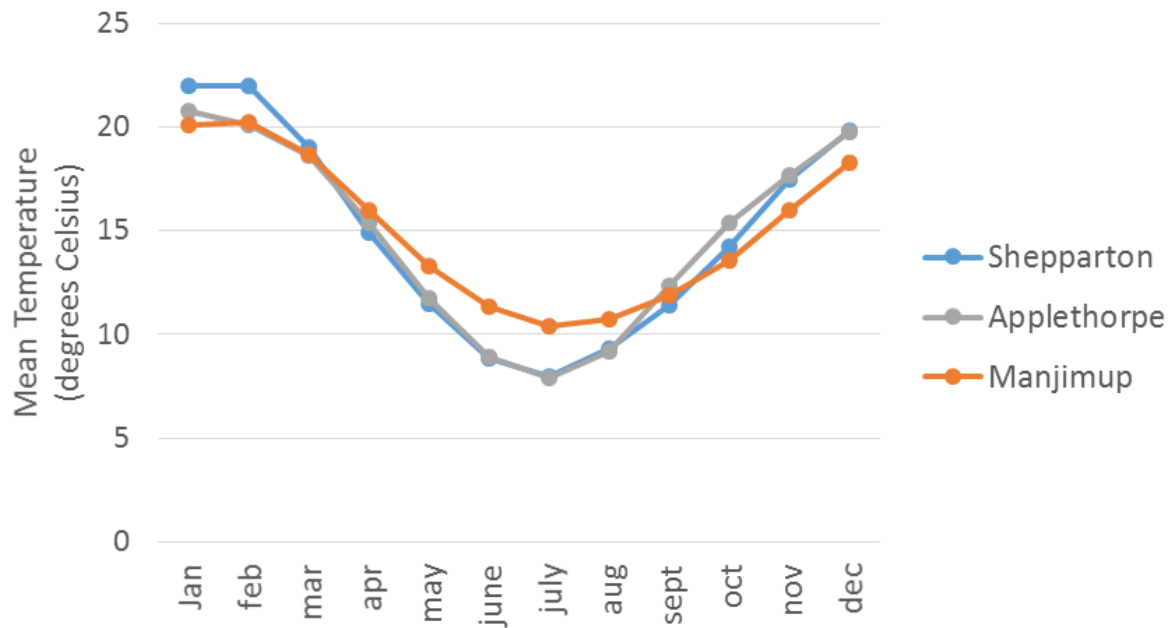


Figure 2. Mean monthly temperatures for Shepparton, Applethorpe and Manjimup.

Green tip and flowering data collection

Cultivars (including crab apple pollinisers) and rootstocks used for phenology data collection are described in Table 2. All observations were taken on mature productive trees.

Table 2. Description of trees used for phenology observations.

| Study site | Tree crop | Cultivar | Rootstock ¹ | Number of trees (yearly observation) | Net |
|-------------|-----------|--------------------------|------------------------|---|-----|
| Applethorpe | Apple | Braeburn | M.26 | 5 | Yes |
| | | Cripps Pink (Pink Lady™) | M.26 MM.106 | 5 3 | Yes |
| | | Cripps Red (Sundowner™) | M.26 MM.106 | 5 5 | Yes |
| | | Fuji | M.26 | 5 | Yes |
| | | Galaxy (Gala) | M.26 | 5 | Yes |
| | | Granny Smith | M.26 MM.106 | 4 5 | Yes |
| | | Hi Early (Red delicious) | M.26 | 5 | Yes |
| | | Jonathan | M.26 | 5 | Yes |
| | | Kalei | M.26 MM.106 | 5 5 | Yes |
| | | Manchurian Crab apple | MM.102 | 5 | Yes |
| | Pear | Josephine | D6 | 5 | Yes |
| | | Packham's Triumph | D6 | 5 | No |
| | | Williams' Bon Chrétien | D6 | 5 | No |
| | | Wintercole | D6 | 5 | No |
| Shepparton | Apple | Braeburn | MM.106 | 5 | Yes |
| | | Cripps Pink (Pink Lady™) | MM.106 | 5 | Yes |
| | | Cripps Red (Sundowner™) | M.26 MM.106 | 5 5 | Yes |
| | | Galaxy (Gala) | MM.106 | 5 | Yes |
| | | Granny Smith | MM.106 | 5 | Yes |
| | | Manchurian Crab apple | MM.106 | 5 | Yes |
| | Pear | Josephine | D6 | 5 | Yes |
| | | Packham's Triumph | D6 | 5 | Yes |
| | | Williams' Bon Chrétien | D6 | 5 | Yes |
| Manjimup | Apple | Braeburn | MM.109 | 2 | No |
| | | Cripps Pink (Pink Lady™) | MM.104 M.26 | 2 2 | No |
| | | Cripps Red (Sundowner™) | MM.104 M.26 | 3 1 | No |
| | | Galaxy (Gala) | MM.104 | 2 | No |
| | | Granny Smith | MM.104 | 2 | No |
| | | Hi Early (Red delicious) | MM.104 | 2 | No |
| | | Jonathan | MM.106 | 2 | No |
| | | Golden Hornet Crab apple | MM.104 | 2 | No |
| | | Red Fuji (Fuji) | MM.104 | 2 | No |
| | Pear | Josephine | D6 | 5 | No |
| | | Packham's Triumph | D6 | 5 | No |
| | | Williams' Bon Chrétien | D6 | 5 | No |

¹ Rootstock effects were not considered in this analysis as previous studies indicated that rootstocks did not significantly impact the timing of green tip and flowering dates in data collected for this study (Darbyshire 2016).

Green tip and flowering data was collected three times per week at the whole tree level. For each tree, the date of green tip, first open flower and full bloom were recorded. A tree was defined as being at 'green tip' when 5% of the buds had observable green tips, corresponding to the 07 stage in the international BBCH code for pome fruit (Meier et al. 1994). A tree was defined as being at 'full bloom' when 80% of the flowers were open, (BBCH code stage 65).

Assessments of flowering quality were made based on the duration between first open flower and full bloom, on the assumption that a protracted period of time between these events was a reflection of variable and uneven flowering. This assumption was based on our observations of flowering in Manjimup and Applethorpe.

A 95% confidence interval was used to represent variability in data about the mean. It indicates that 95% of the data values recorded, fall within this particular interval.

Ideally, green tip and flowering data would have been collected from a number of orchards across each region to fully capture variation within regions caused by microclimate, soils, differences in tree structure, nutrition, and so on. Time and resources required to collect such data were not available and therefore observations were taken from representative orchards in each region. In future, more comprehensive data will be collected on orchards through the use of sensing and mapping technologies, which will enable more sophisticated and comprehensive analysis of flowering patterns and variability between and within locations.

Calculation of winter chill

The Dynamic model (Erez et al. 1990, Fishman et al. 1987) was used to calculate winter chill from on-site hourly temperature data recorded in the orchard. This is the current 'best-practice' model and has been shown to perform better than other models for calculating winter chill, particularly in mild winter climates such as Australia (Darbyshire et al. 2013a, Luedeling et al. 2009).

Note that, while chill is commonly referred to as 'winter chill', it has been calculated here from the beginning of autumn until the end of winter (1 March to 31 August). The point at which tree buds become sensitive to chilling temperatures remains to be determined.

Results and discussion

Winter chill and spring heat

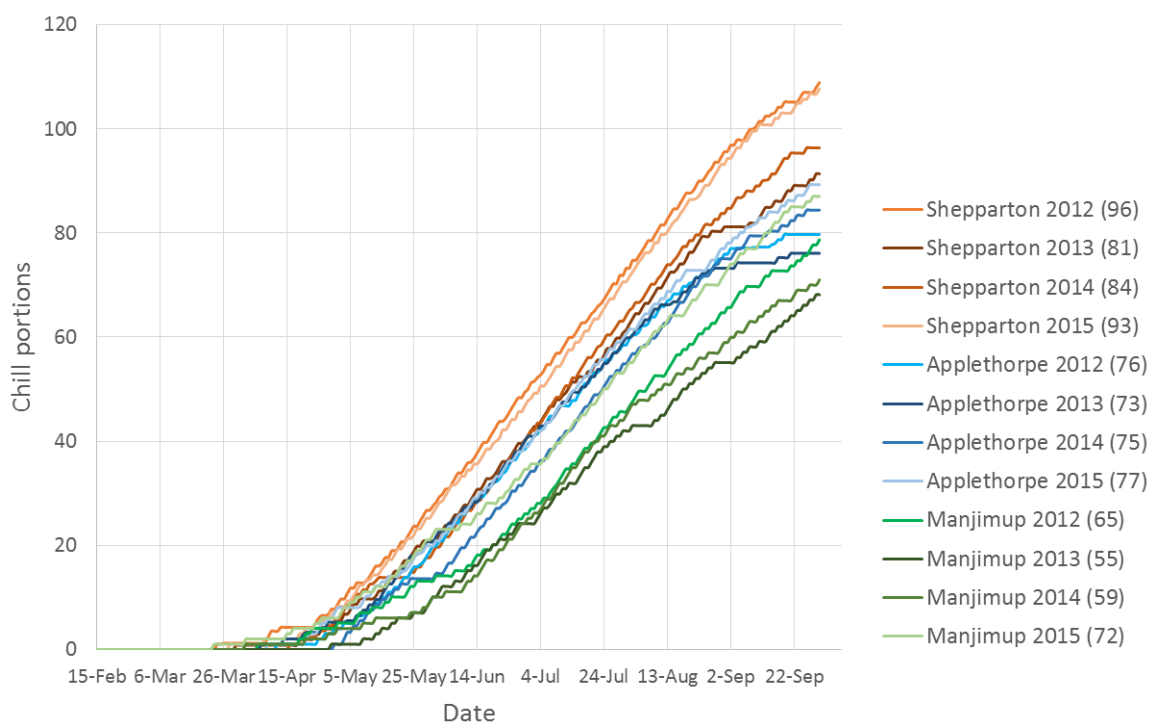


Figure 3. Chill accumulation across sites and years. Number in brackets is the total chill portions received up to 31 August.

The pattern of winter chill accumulation was different between locations and years (Figure 3). For all years of the study, Shepparton was the coolest site, followed by Applethorpe and Manjimup. Shepparton and Applethorpe received above-average chill portions for the four year period, while Manjimup received below-average chill in 2013 and 2014. Historical chill portion averages for the 1981 to 2010 period are Shepparton 78, Applethorpe 70 and Manjimup 64.

Lower winter chill tended to be associated with a later start to chill accumulation (that is a warmer autumn), and a more uneven chill accumulation curve. For example, 2012, 2013 and 2014 in Manjimup were distinguished by the irregular accumulation of chill portions caused by climatic conditions where cold autumn and winter temperatures were interspersed with spells of warm weather. This resulted in somewhat 'wobbly' chill accumulation curves.

In this study, winter chill accumulation was calculated from 1 March to 31 August according to previously published protocols (Darbyshire et al. 2016). Questions remain about when to start and stop calculating chill. It is not clear that it is meaningful to start calculating chill for late season cultivars before fruit has been harvested, and / or before leaves have fallen, or indeed to stop calculating chill before a cultivar such as 'Hi Early' has reached green tip. It seems likely that the period of sensitivity to chill accumulation will vary between cultivars, however, with current gaps in understanding of the physiological processes involved in the movement through dormancy, it is not possible to determine cultivar-specific chilling periods.

It is also quite likely that there are differences in the impact of chilling temperatures on the dormancy-breaking process depending on the time of year. For example, chill received earlier in the winter may be more effective than chill received in late winter. Further research is required to fully elucidate these features of dormancy-breaking in pome fruit.

Table 3. Average spring temperatures¹ for 2012 to 2015 in Applethorpe, Shepparton and Manjimup.

| Location | Year | Average monthly temperature | | |
|--------------------|--------------------------------|-----------------------------|---------|----------|
| | | September | October | November |
| Applethorpe | Long term average ² | 12.4 | 15.4 | 17.7 |
| | 2012 | 12.8 | 15.2 | 19.2 |
| | 2013 | 14.9 | 17.1 | 18.5 |
| | 2014 | 12.5 | 17.5 | 21.8 |
| | 2015 | 11.8 | 17.0 | 20.2 |
| Shepparton | Long term average ² | 11.4 | 14.2 | 17.5 |
| | 2012 | 11.8 | 13.9 | 19.1 |
| | 2013 | 13.3 | 14.1 | 16.8 |
| | 2014 | 12.1 | 16.0 | 18.9 |
| | 2015 | 11.5 | 18.6 | 18.9 |
| Manjimup | Long term average ² | 11.9 | 13.6 | 16.0 |
| | 2012 | 12.9 | 15.5 | 16.3 |
| | 2013 | 12.6 | 15.0 | 18.0 |
| | 2014 | 13.6 | 15.4 | 16.3 |
| | 2015 | 13.2 | 17.1 | 18.6 |

¹Temperature data sourced from Australian Bureau of Meteorology website

²As determined by the Australian Bureau of Meteorology

According to the long term average, Applethorpe has the warmest spring, compared with Shepparton and then Manjimup (Table 3). With few exceptions, spring temperatures were above-average at all sites throughout the period of the study.

Green tip and flowering

Differences in chill accumulation and spring heat between locations and years were accompanied by variability in the timing and pattern of green tip and flowering of apple and pear cultivars. Results were analysed to develop a picture of green tip and flowering patterns in Applethorpe, Shepparton and Manjimup over the four years of the study.

Green tip and flowering time

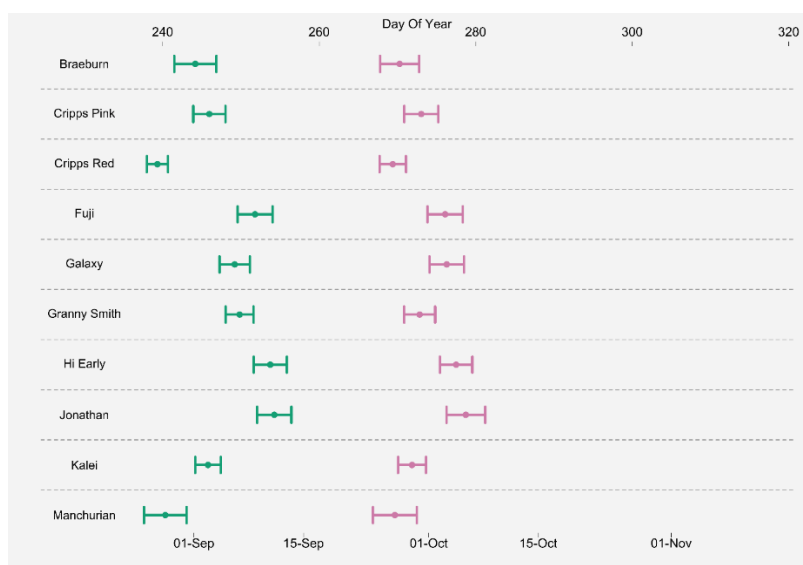
Variation between cultivars and locations

Green tip and flowering dates were later in Manjimup than in Applethorpe and Shepparton (Figure 4). Across all cultivars, the average green tip date was 4 September in Applethorpe, 3 September in Shepparton and 25 September in Manjimup, while the average full bloom date was 1 October in Applethorpe and Shepparton, and 25 October in Manjimup.

Variability in green tip and full bloom dates between years and individual trees was greater in Manjimup compared with Applethorpe and Shepparton, as reflected by the length of the bars in Figure 4. Variability in green tip and full bloom dates between cultivars was also greater in Manjimup compared with the other sites. Average green tip dates for all cultivars were spread across 32 days in Manjimup compared with 15 days in Applethorpe and 5 days in Shepparton. Similarly, average full bloom dates were spread across 19 days in Manjimup compared with 9 days in Applethorpe and 7 days in Shepparton.

Overall, Shepparton, the site with the greatest winter chill, showed the most consistency in green tip and flowering time from year to year, while the relatively low chill in Manjimup was associated with the greatest variability. Greater consistency has benefits for flowering and pollination management, including determination of appropriate polliniser plantings and planning of pollination services. It also benefits tactical decision making for orchard operations generally. Improvements in the ability of models to predict flowering dates would remove the uncertainty associated with variability, making it easier to manage.

Applethorpe



Shepparton



Manjimup

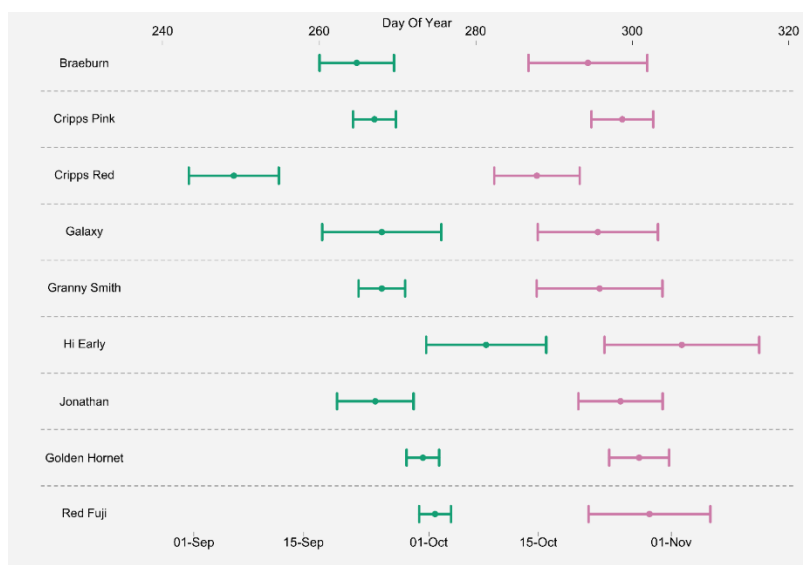


Figure 4. Green tip (green) and full bloom (pink) dates for apple cultivars in Applethorpe, Shepparton and Manjimup. Data is the average of observations from 2012 to 2015 with bars indicating the confidence interval.

Differences in Green tip and flowering patterns between locations were less consistent for pear cultivars (Figure 5). In Manjimup, full bloom dates for ‘Josephine’, ‘Packham’ and ‘Williams’ were later across all years compared with the other sites. Shepparton showed the least variability in full bloom dates across years, trees and cultivars.

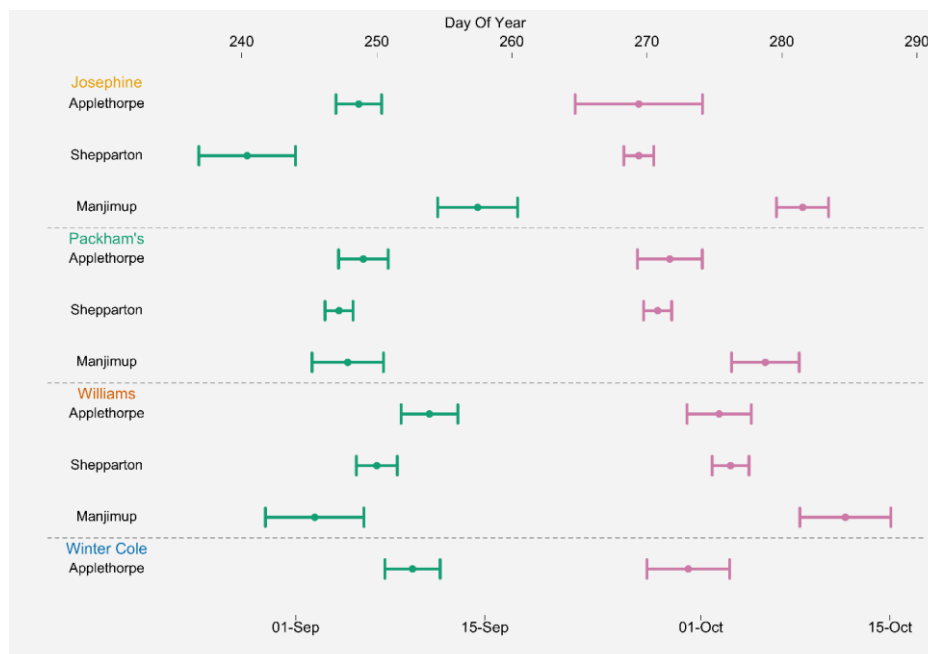


Figure 5. Green tip (green) and full bloom (pink) dates for pear cultivars in Applethorpe, Shepparton and Manjimup. Data is the average of observations from 2012 to 2015 with bars indicating the confidence interval.

Variation between years

Variability in the dates of green tip and flowering between individual years was evaluated to determine the degree to which growers are currently managing shifts in flowering timing from season to season at each location.

In Applethorpe, green tip and flowering were consistently later across all cultivars in 2014 compared with the other years of the study (Figure 6 shows comparison between 2013 and 2014, data for other year comparisons not shown). On average, green tip was 9 days later in 2014 compared with 2013, and full bloom was 12 days later (Figure 6).

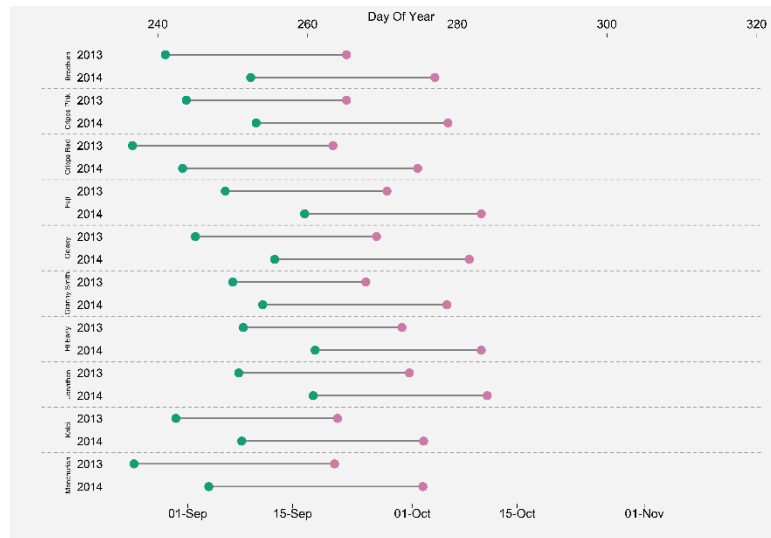
This consistent shift in timing was associated with an unusual autumn and winter chill accumulation pattern (Figure 7). Total chill accumulated up to 31 August was similar in 2013 and 2014, 73 and 75 chill portions respectively. However, in 2014 there was a warm week in late-May to early-June that resulted in a pause in accumulation of chill, which can be seen in the chill curve (Figure 7). Even though the total chill accumulated for 2014 eventually caught up with the other curves by the end of August, this plateau appears to have impacted the timing of flowering (although other factors such as the role of heat cannot be ruled out in this study). There was little difference in green tip and flowering dates between the other years.

In Shepparton, there was little variability in green tip and flowering dates between any of the four years of the study. When averaged across cultivars, green tip varied by 5 days between 2013 and 2014, and full bloom dates varied by 4 days (Figure 6). Plateaus in the accumulation of chill in late-May, early-June of 2013 and 2014 (Figure 7) were not associated with big shifts in flowering time as

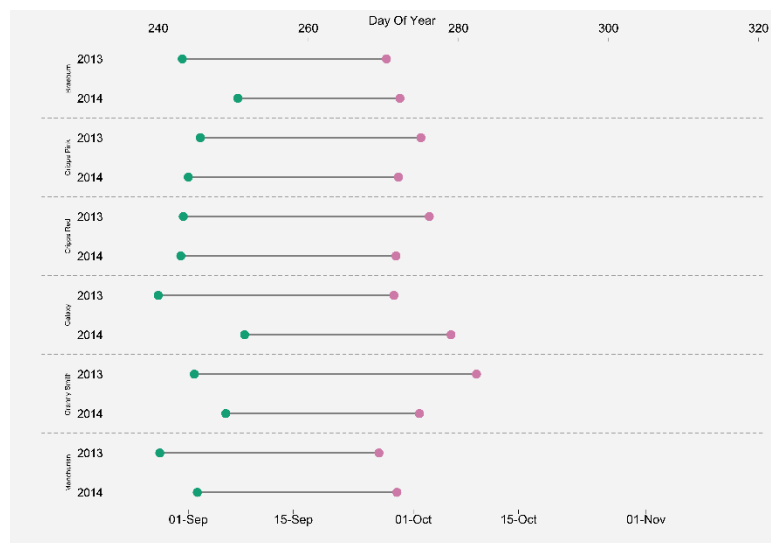
was observed for Applethorpe, perhaps due to the higher amount of overall chill received in Shepparton.

In Manjimup, green tip and flowering dates were highly variable between years. 2013 was a lower chill year than 2014, with 55 and 59 chill portions received respectively. Shifts in green tip and full bloom dates were not consistent between cultivars (Figure 6). For example, in 2014, full bloom was 15 days earlier in 'Galaxy' and 10 days later in 'Hi Early' compared with full bloom dates for those cultivars in 2013, while the full bloom dates for 'Granny Smith' were similar in both years (Figure 6).

Applethorpe



Shepparton



Manjimup

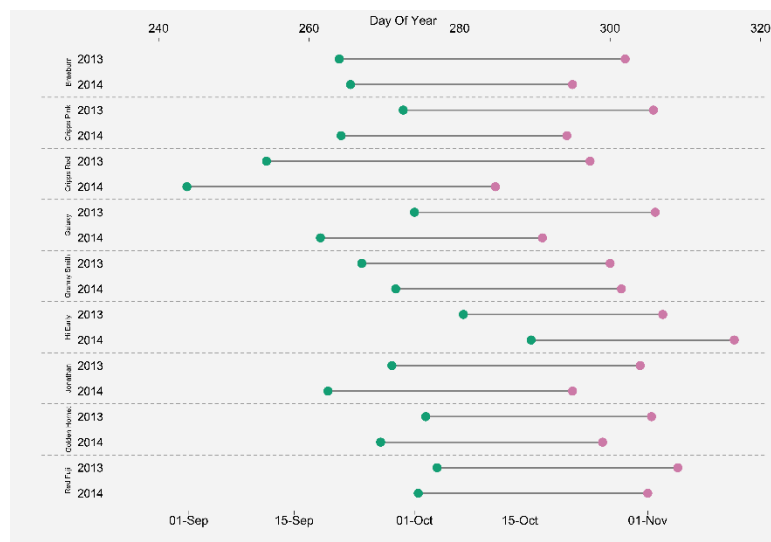
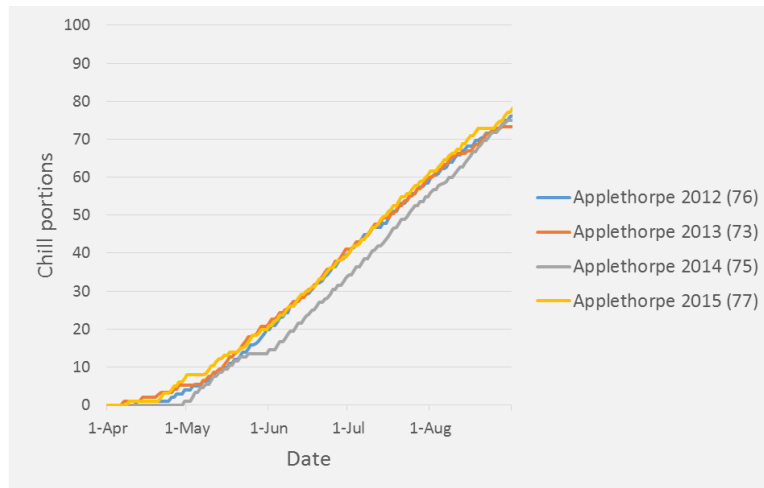
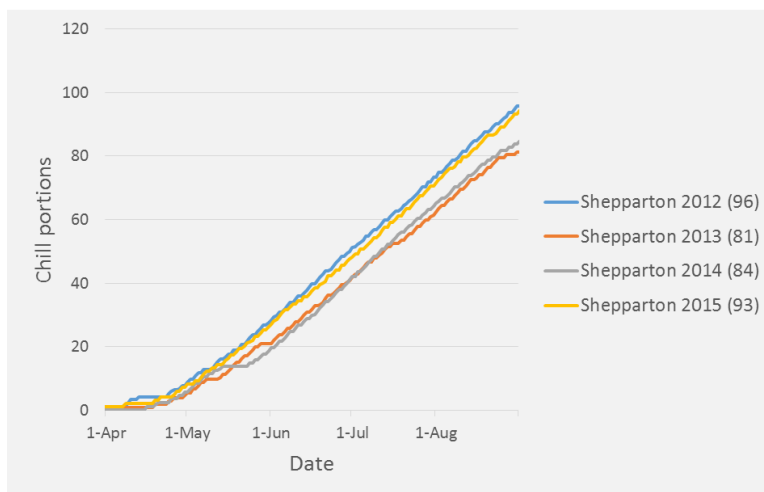


Figure 6. Green tip (green) and full bloom (pink) dates for apple cultivars grown in Applethorpe, Shepparton and Manjimup, 2013 and 2014. Data points are the average of individual tree observations.

Applethorpe



Shepparton



Manjimup

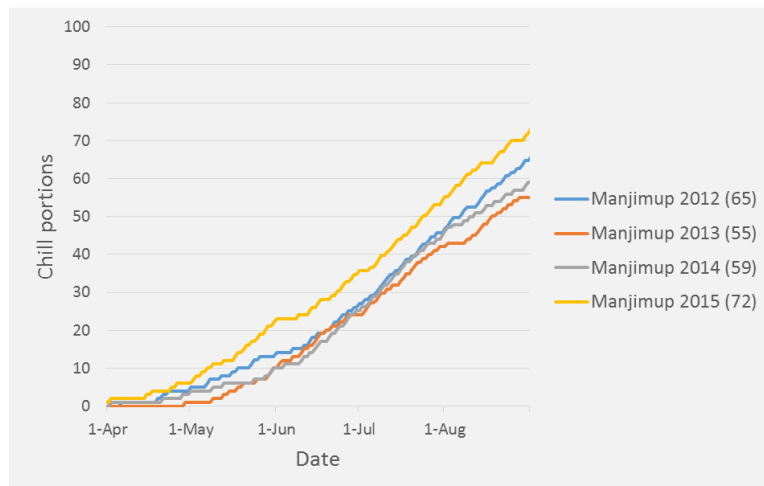


Figure 7. Chill accumulation in Applethorpe, Shepparton and Manjimup, 2012 to 2015. Number in brackets is the total chill portions received up to 31 August.

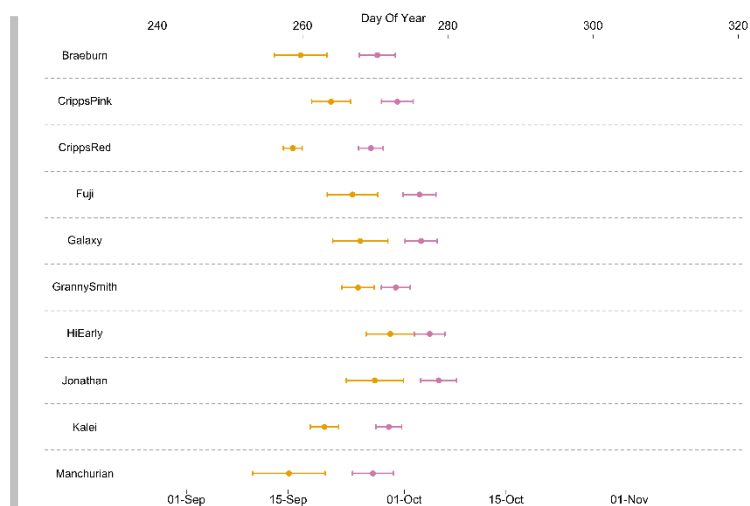
Quality of flowering

Variation between cultivars and locations

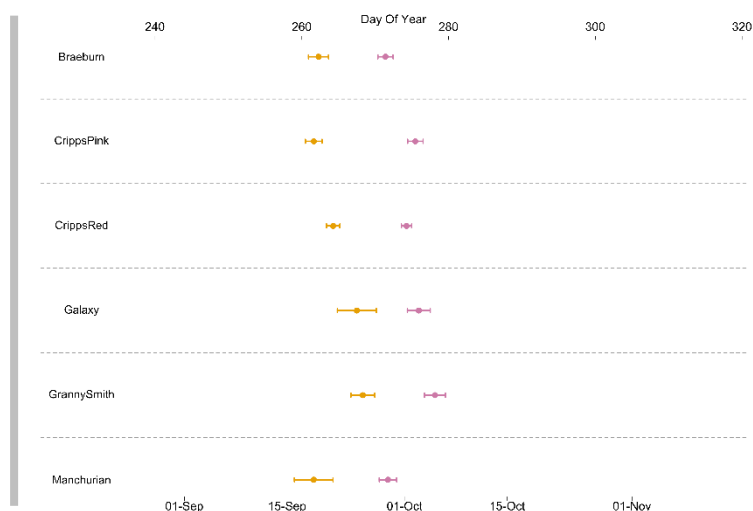
The duration between the first flower opening and full bloom was more than twice as long in Manjimup (21 days) as it was in Applethorpe (9 days) and Shepparton (10 days), when averaged across cultivars and years (Figure 8). The protracted pattern of flowering was consistently observed in Manjimup over the period of the study and was largely the result of irregular and uneven bud movement within individual tree canopies (data not shown).

A prolonged and irregular period of flowering can be difficult to manage for a number of reasons. Determining an appropriate chemical thinning program is challenging when buds are at multiple stages of green tip and flowering on each tree within the block, at any given time (Theron 2013). Fruitlets are likely to vary greatly in size and development stage, and therefore careful attention is required at the time of hand thinning to ensure that fruitlets are thinned in a manner that optimises crop uniformity and reduces the spread of fruit maturity at harvest (Theron 2013, Erez 2000).

Applethorpe



Shepparton



Manjimup

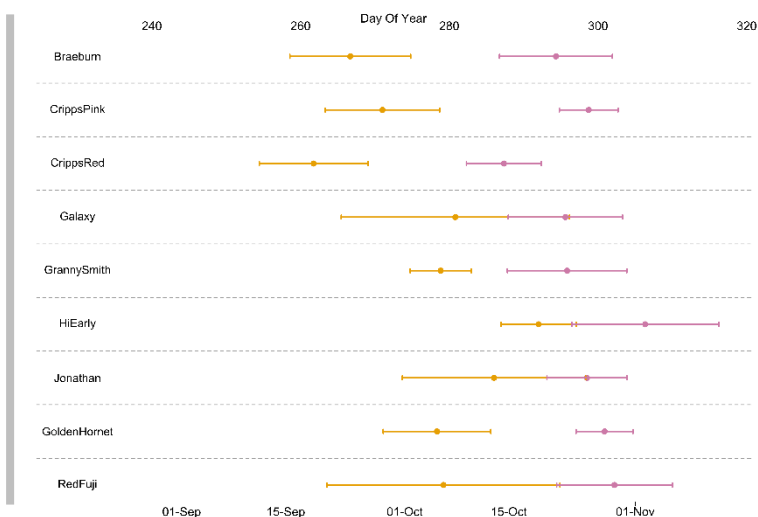


Figure 8. First flower (orange) and full bloom (pink) dates for apple cultivars in Applethorpe, Shepparton and Manjimup. Data is the average of observations from 2012 to 2015. Bars indicate the confidence interval.

In cultivars of pear, the duration of the period between the first flower opening and full bloom was the greatest in Manjimup (Figure 9), as was observed in apple. However, the patterns of flowering were less consistent within and between locations.

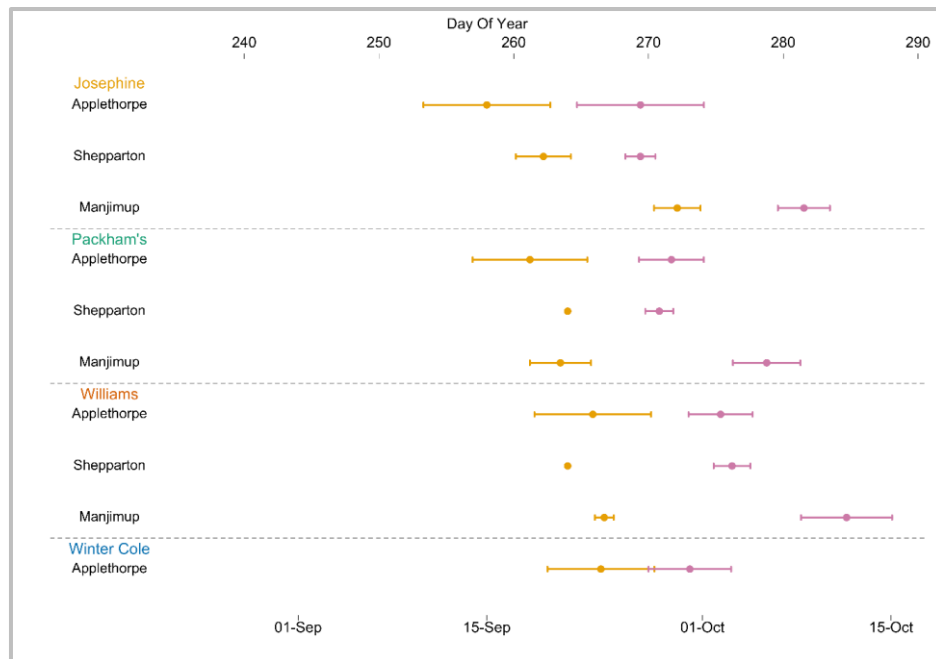


Figure 9. First flower (orange) and full bloom (pink) dates for pear cultivars in Applethorpe, Shepparton and Manjimup. Data is the average of observations from 2012 to 2015. Bars indicate the confidence interval.

Flowering overlap and pollination

Overlap of flowering between a cultivar and its pollinisers is essential for good fruit set (Ramirez and Davenport 2013). Changes in the timing of flowering between seasons or across years that result in the loss of flowering synchronisation can therefore result in reduced yields. Large shifts in flowering dates, like those observed between cultivars and years in Manjimup (Figure 8), increase the risk of poor flowering overlap in any particular season and make it more difficult to select appropriate pollinisers. Use of floral bouquets or artificial pollination methods can compensate for loss in flowering overlap, however, these methods require significant additional labour (Dennis 2003).

The chances of achieving good flowering overlap each season are greatly increased by planting multiple polliniser cultivars with early, middle and late flowering habits, to ensure a good supply of pollen throughout the flowering period of the commercial cultivar, and to reduce frost risk (Delaplane and Mayer 2000, Dennis 2003). Cultivars that flower profusely over an extended period of time generally make good pollinisers (Jackson 2003).

Shifts in flowering timing do not affect fruit set if similar shifts occur in both the cultivar and its pollinisers. This was observed in Applethorpe in 2014, when flowering in all cultivars was consistently delayed compared with flowering in 2013.

Flowering and temperature: implications of a changing climate

Apple trees in Manjimup exhibited greater variability in green tip and flowering dates, and a more protracted flowering period, compared with trees in Applethorpe and Shepparton. Delayed and uneven flowering are symptoms of inadequate chill and it seems likely that the observed patterns of

flowering in Manjimup were a response to mild autumn and winter conditions received throughout the period of this study. This finding is supported by numerous studies in the literature describing irregular flowering in apples grown in warm, low chill climates (Oukabli 2003, Saure 1985, Theron 2013, Erez 2000). Abnormalities in the late stages of apple flower bud development have also been reported in low chill regions (Oukabli 2003) however, flower viability was not assessed in our study.

The timing of flowering varied from year to year within each location, with the greatest differences observed in Manjimup. This variability was caused largely by differences in temperatures from season to season, and Australian growers have always had to manage these seasonal shifts in the timing of dormancy-break. The relative importance of cold and warm temperatures in determining the timing of flowering is likely to vary between locations and years. For example, in cold growing regions where plenty of winter chill is received and chilling requirements are well satisfied by the middle of winter, dormancy-break will be promoted by warm temperatures in late winter and early spring (Saure 1985). In this case, from around mid-winter onwards the trees are sitting in a phase of dormancy known as 'eco-dormancy', that is the buds are ready to burst when the environmental conditions are right for growth.

This response to heat is evident in cold pome fruit growing regions of the Northern Hemisphere, where clear advances in flowering dates have been observed with warmer spring temperatures caused by the changing climate (Legave et al. 2013).

In warmer growing locations and years, the timing of dormancy-break and flowering are likely to be determined primarily by the accumulation of enough chill (Saure 1985). That is, dormancy tends to be prolonged and there is little or no eco-dormancy period, buds burst as soon as they have received enough chill (Theron 2013). It is likely that pome trees growing in the warmer regions of Manjimup, and Applethorpe in some years, do not experience any significant eco-dormancy.

As the climate warms, most growing regions of Australia will receive less winter chill (Darbyshire et al. 2013b). The impacts that this will have on flowering over the next 10 to 20 years will vary between different parts of the country.

Cooler regions such as those in Tasmania and NSW with plenty of chilling may experience advances in the timing of flowering as spring temperatures increase. As chill accumulation falls below the chilling requirements of cultivars in warmer growing regions of Australia they will likely see increasing variability in green tip and flowering dates from season to season, and between cultivars. Delayed, uneven and protracted flowering will occur in the medium to higher chill cultivars, as was observed in Manjimup during this study. Low chill years will be experienced more often as the climate warms.

Irregular and protracted flowering presents a significant management challenge for growers. Options for orchard adaptation to warming autumns and winters include the planting of lower chill cultivars, management of delayed and variable flowering with the use of dormancy-breakers, and adjustments to chemical and hand thinning practices to reduce variability in fruit size and maturity.

It should be noted that, while exposure to enough chill is essential for quality flowering in pome fruit (defined here as the uniform blossoming of viable flowers), once chilling requirements have been met, the quality of flowering can be further influenced by other factors such as heat, nutritional status and water stress. These factors were not considered here.

While this study looked at temperature and the timing and quality of flowering, climate change will have other impacts on flowering and pollination. Warming temperatures will potentially impact on floral initiation, bee activity and fruit set (Dennis 2003, Atkinson et al. 2001, Ramirez and Davenport 2013). In addition, this study did not collect data on leaf area development during the green tip and full bloom period. Weak leaf development is a symptom of delayed foliation (Saure 1985) caused by inadequate winter chill and reduced leaf area in the weeks after full bloom has been shown to have negative impacts on fruit set and development (Proctor and Palmer 1991, Lauri et al. 1996). Further research is required to fully determine the nature of these impacts on the Australian pome fruit industry.

The discussion and conclusions from this study were based primarily on the results from observations in apples. While results from the pear data were generally consistent with that observed in apples, further research would improve the understanding of flowering in this crop. Since the vast majority of pears are grown in Victoria (89%) (Australian Bureau of Statistics) there was less opportunity to collect extensive datasets from diverse climatic regions.

Conclusions

Results from this research support findings from previous studies performed in other parts of the world showing that apples grown in warmer climates exhibit increased variability in flowering within the canopy, between individual trees and between varieties and years (Erez 2000, Theron 2013, Cook and Jacobs 2000). Increased variability in flowering results in the reduced ability to predict timing of orchard operations, more difficult pollination management, challenges for thinning and crop load management, and can result in increased variability of fruit maturity at harvest.

The Australian apple and pear industry is aiming to increase global competitiveness in an effort to help secure new export markets. Success in the global market requires consistent supply of high quality fruit from season to season at competitive prices. Additional variability in the crop production system from a warming climate will challenge the Australian industry's ability to achieve the desired export goals on two fronts: consistency of supply, and in the maintenance of uniform orchard blocks that are a prerequisite for efficient use of labour-saving technologies.

Variability caused by inadequate chilling can be managed with the use of additional input of products and labour, however, grower capacity to respond to these challenges will vary depending on individual social and financial factors. An important assessment for growers to make of their orchard businesses will be *'at what point will the increased cost of inputs and effort required to produce a consistently high quality crop make a block of trees unprofitable?'* Ongoing orchard observations of flowering performance and relationships with winter chill will be necessary for making meaningful predictions about future block and cultivar profitability.

Key messages

- Low winter chill, as observed in Manjimup, was associated with an uneven (or 'uneven') chill accumulation curve caused by short periods of warm weather throughout the autumn and winter seasons.
- Green tip and full bloom dates were more variable between years, cultivars and individual trees in Manjimup, and trees consistently displayed a long and protracted flowering compared with Applethorpe and Shepparton.
- Shepparton, the site with the most winter chill, showed the greatest consistency in green tip and flowering dates from year to year.
- The patterns of flowering observed in Manjimup are likely the result of inadequate chill. Low winter chill at this site was associated with:
 - High variability in flowering dates between seasons, cultivars and individual trees of the same cultivar.
 - Irregular and protracted flowering across most cultivars of apple.
- Large shifts in flowering dates between cultivars and seasons, increases the risk of poor flowering overlap in any particular year and makes it more difficult to select appropriate pollinisers. Greater predictability in the timing of green tip and full bloom has benefits for flowering and pollination management, and for planning of orchard operations generally.
- Irregular and protracted flowering can be difficult to manage for a number of reasons:

- Determining an appropriate chemical thinning program is challenging when buds are at multiple stages of green tip and flowering on individual trees.
 - Fruitlets will vary more in size and developmental stage, and careful hand thinning is required to optimise crop uniformity.
 - Greater spread of fruit maturity at harvest requires greater effort to pick fruit at the appropriate stage of maturity.
- As the climate warms, low chill years will become more frequent in milder growing regions of Australia, and will likely result in symptoms of inadequate chill in some cultivars. Advances in the timing of flowering might be observed in cooler growing regions.
 - Australian growers already manage seasonal changes in flowering time and it may be the increased irregularity of flowering that presents the greater management challenge.
 - Options for adaptation to low chill years include planting lower chill cultivars, management of delayed and variable flowering with the use of dormancy-breakers, and adjustments to chemical and hand thinning practices to reduce variability in fruit size and maturity.
 - Risks to pollination from shifting flowering times can be reduced through planting multiple polliniser cultivars with early, middle and late flowering habits, to ensure a good supply of pollen throughout the flowering period. Use of floral bouquets or artificial pollination methods can compensate for loss in flowering overlap.
 - Climate change will add significant variability into the pome fruit crop production system. This will present challenges for the Australian industry in the consistency of supply and in maintenance of the uniform orchard blocks that are a prerequisite for the efficient use of mechanisation.
 - An important assessment for growers to make of their orchard businesses will be 'at what point will the increased cost of inputs and effort required to produce a consistently high quality crop make a block of trees unprofitable?' Ongoing observations of flowering performance and its relationship with chilling, will be necessary for making informed predictions about future block and cultivar profitability.

Recommendations

Industry

- Warmer temperatures will mean less winter chill for most growing regions of Australia. Successful adaptation by the apple and pear industry will require:
 - Comprehensive in-orchard monitoring of flowering dates across cultivars to provide early indication of cultivars that might be impacted by warmer winters in the future changing climate, as well as identification of subtle shifts in the timing of flowering between cultivars and their pollinisers.
 - Information about chilling requirements of new and existing cultivars so that growers can make cultivar choices appropriate to their particular growing environment.
 - Consideration of chilling requirements in apple and pear breeding programs when selecting potential new cultivars for development and release. Selecting for lower chill cultivars.
 - Good understanding of the efficacy of dormancy-breaking sprays.
- Growers in warmer growing regions of Australia would benefit from preparing a strategy for managing low chill years. Monitoring of winter chill accumulation and use of dormancy-

breakers in low chill years is a logical inclusion. Changes to chemical and hand thinning practices may also form part of the strategy.

- Where shifting full bloom dates are likely to be a problem, consideration should be given to planting more than one polliniser cultivar to improve the chances of flowering overlap every year.
- Models of flowering time have significantly improved in recent times, with the development of the 'Chill-overlap model' (Darbyshire et al. 2016, White 2016). The use of these models will improve the ability to predict changes in the timing of flowering in cultivars of apple under future climates.
- Climate analogues (Parkes and White 2016) should be used by the industry to broadly identify climate change impacts on apple and pear production systems and possible options for adaptation. Growers in Manjimup are already successfully managing the impacts of inadequate chill in some years, lessons can be learnt from their knowledge and experience.
- In future, more comprehensive data should be collected on orchards through the use of sensing and mapping technologies. This data should be used to undertake more sophisticated and comprehensive analysis of flowering patterns and variability between and within locations.
- Further research in Australian pears is needed to improve the understanding of flowering in cultivars of this tree crop, and the likely impacts of changing climate.
- In blocks where flowering is becoming increasingly irregular, an important assessment for growers to make of their orchard businesses will be to determine at what point the increased cost of inputs and effort required to produce a consistently high quality crop make a block of trees unprofitable. Ongoing observations of flowering performance and its relationship with chilling, will be necessary for making informed predictions about future block and cultivar profitability.

Scientific research needs

- Better understanding of apple and pear chilling requirements is necessary for making appropriate cultivar selections for particular growing climates. This will require:
 - Research into the genetic basis of progression through the phases of dormancy.
 - Determination of the point when buds enter into true dormancy and become sensitive to chilling temperatures, and when buds exit true dormancy prior to bud burst. Genetic and/or physiological markers of these phase shifts are needed.
 - Improved chill model performance through cultivar specific parameterisation of the dynamic model.
 - Understanding of the effectiveness of early versus late season chill in dormancy breaking.
- Development of chill-overlap models for flowering time of pome fruit cultivars other than 'Cripps Pink'. This will improve the predictability of climate change impacts on flowering timing.
- Determine the potential effects of warming temperatures on leaf area development, floral initiation, flower viability, fruit set and bee activity, as these are likely to have significant impacts for productivity in apple and pear.

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A climate analogue approach to understanding climate change impacts on flowering in Australian pome fruit trees

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Summary

Future changes in climate are predicted to result in reduced winter chill in apple and pear growing regions of Australia. Potential impacts on the pome fruit industry due to effects of reduced chill on bud dormancy release and flowering of fruit trees in these regions are not yet clear. Inadequate winter chill can result in variable and protracted flowering, potentially leading to impacts on fruit set and marketable yield at harvest. Climate analogues are one option for investigation of potential climate change impacts on agricultural production and appropriate adaptation strategies. This study investigated the potential for using the climate analogue concept, together with collected datasets, to predict impacts of climate change on pome fruit flowering in Australia and to identify possible methods for adaptation.

The temperate tree fruit growing regions of Manjimup (WA) and Stanthorpe (QLD) were used as a case study to test this strategy. Based on mean autumn and winter temperatures alone Manjimup was considered to be an appropriate climate analogue for Stanthorpe in 2030. Flowering datasets from commercial apple and pear cultivars were collected at each site in 2013 and 2014. Whole tree field assessments were made of 5% green tip, first open flower and progression of flowering to full bloom using standardised methods across sites. The data show an uneven and protracted pattern of flowering in Manjimup compared with Stanthorpe. Average green tip dates for all cultivars were spread across 32 days in Manjimup compared with 15 days in Stanthorpe. Similarly, average full bloom dates were spread across 19 days in Manjimup and 9 days in Stanthorpe. The duration between the first flower opening and full bloom in Manjimup was more than twice as long as in Stanthorpe (an average of 25 days compared with 10 days) when averaged across years and cultivars. There were no clear differences in yield between the locations. Comparison of grower orchard management practices indicated that 50% of Manjimup growers use dormancy-breaking sprays compared with zero in Stanthorpe.

Results from the climate analogue approach suggested that a more variable and protracted pattern of flowering is likely to exist across many apple cultivars in Stanthorpe in 2030. The more variable flowering will not necessarily have significant impacts on productivity of apple orchards in that timeframe and Stanthorpe growers are likely to be able to manage low chill years with the use of dormancy-breaking sprays. At this stage there is no apparent need to shift to lower chill cultivars (or crops) as Manjimup growers are achieving high levels of productivity with the same variety mix as is currently grown in Stanthorpe.

The climate analogue approach is a valuable tool for providing broad information around potential impacts and adaptation strategies for Australian temperate tree crops and horticulture more generally. There are a number of important details to consider when applying this methodology and these are outlined in this report.

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Introduction

Future changes in climate are predicted to result in reduced winter chill in apple and pear growing regions of Australia (Darbyshire et al. 2013b, Hennessy and Clayton-Greene 1995). Potential impacts on the pome fruit industry in these regions are not yet clear. Inadequate winter chill results in variable and protracted flowering, potentially leading to impacts on fruit set and marketable yield at harvest (Theron 2013, Erez 2000, Saure 1985). Climate analogue analysis involves a detailed comparison between locations, where the current climate of one location is similar to the projected future climate of the location of interest (Nyairo et al. 2014). This is one option for investigation of potential climate change impacts on agricultural production and identification of appropriate adaptation strategies.

Relationships between temperature and flowering in apple and pear trees are complex and poorly understood, making it difficult to determine future impacts of warming climate on flowering in these crops. A number of benefits of applying a climate analogue approach have been identified (Nyairo et al. 2014, Veloz et al. 2012) and suggest that it may be a useful approach in the investigation of this question. Some of the benefits are:

- Ability to analyse climate change impacts, without the need for understanding of complex physiological processes underlying flowering.
- Ability to analyse options and capacity for adaptation. The question can be asked *how do growers in region X respond to a climate that is similar to ours in the future?* Impacts and adaptation can be investigated simultaneously.
- Impacts of climate change on flowering are analysed within the production system as a whole.
- Provision of tangible, practical information for growers to work with and allows for growers at the test location to learn from growers at the analogue location.
- Analogue location can be used as a research site for possible adaptation strategies.
- Improved communication of climate change impacts and options for adaptation to growers.

Although the concept has been around for some time, most studies have focussed broadly on whole farming systems (Nyairo et al. 2014), rather than investigating climate change impacts on a single cropping system or on one physiological aspect of a crop such as flowering.

Study objectives

The aim of this project was to investigate potential for using a climate analogue approach, together with collected data sets, to predict impacts of climate change on pome fruit flowering and to identify possible methods for adaptation.

Methodology

To test the potential of the climate analogue approach, a case study was undertaken in Stanthorpe, Queensland. The following questions were posed:

1. How will flowering of apple and pear trees be impacted by reduced winter chill in Stanthorpe in 2030?
2. Will there be an impact on productivity?
3. What can growers do to adapt?
4. Is the climate analogue approach appropriate in this context and can it be applied more broadly?
5. Are there factors that should be considered when using climate analogues for informing climate change adaptation in horticulture?

There were four parts to the investigation: the identification of an appropriate climate analogue location for Stanthorpe in 2030, comparison of the apple and pear industries in each location to

ensure a meaningful comparison, analysis and comparison of flowering behaviour and productivity in each location, and comparison of relevant orchard management practices to investigate possible climate change adaptations.

Identification of an appropriate climate analogue location

The 'analogues explorer' tool from the Climate change in Australia website¹ was used to identify a broad pool of possible climate analogue locations for Stanthorpe in 2030.

Winter chill projections for Stanthorpe in 2030 were constructed from four Global Climate Models selected from the list of models generated by the Climate Futures Tool at the Climate Change in Australia website¹, for a Representative Concentration Pathway (RCP) of 4.5. The RCP4.5 emissions scenario assumes that lower greenhouse gas emissions are achieved in future due to some mitigation efforts. It is a minimum to medium case climate change scenario.

Historical temperature data from 1986 to 2005 for Manjimup and Stanthorpe was obtained from the SILO climate database². Point data for the years 2012, 2013 and 2014 was obtained from the weather station at Manjimup Horticultural Research Institute (Manjimup), and an on-site temperature logger in the orchard at Applethorpe Research Facility (Stanthorpe).

The Dynamic model (Erez et al. 1990, Fishman et al. 1987)) was used to calculate winter chill from hourly temperature data recorded in the orchard from the beginning of autumn until the end of winter (1 Mar to 31 Aug). This is the current 'best-practice' model and has been shown to perform better than other models for calculating winter chill, particularly in mild winter climates such as Australia (Darbyshire et al. 2013a, Luedeling et al. 2009).

Industry comparison

Comparison of the apple and pear industries in Manjimup and Stanthorpe was made based on information sourced from the Australian Bureau of Statistics, a Shire Council report (Tancred and McGrath 2013), and personal communication with growers and local industry representatives.

Comparison of flowering

The flowering datasets were from orchards in Manjimup and Stanthorpe (Table 1) collected in spring 2013 and 2014 from cultivars of apple and pear, as part of the project AP12029 *Understanding apple and pear production systems in a changing climate* (Table 2).

Table 1. Description of sites used for flowering data observations.

| State | Location | Orchard | Latitude and Longitude | Cultivars |
|-------|------------|--|------------------------|----------------------|
| Qld | Stanthorpe | Department of Agriculture and Fisheries Qld, Applethorpe Research Facility | 28.52 S 151.90 E | All apples and pears |
| WA | Manjimup | Department of Agriculture and Food WA, Manjimup Horticultural research Institute | 34.18 S 116.07 E | All apples |
| | | Newton Brothers Orchards | 34.13 S 116.07 E | All pears |

¹ <http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-analogues/analogues-explorer/>

² <https://www.longpaddock.qld.gov.au/silo/>

Table 2. Description of trees used for flowering observations.

| Study site | Tree crop | Cultivar | Rootstock ¹ | Number of trees (for yearly observation) | Net |
|------------|-----------|-----------------------------|------------------------|---|-----|
| Stanthorpe | Apple | Braeburn | M.26 | 5 | Yes |
| | | Cripps Pink (Pink Lady™) | M.26 MM.106 | 5 3 | Yes |
| | | Cripps Red (Sundowner™) | M.26 MM.106 | 5 5 | Yes |
| | | Fuji | M.26 | 5 | Yes |
| | | Galaxy (Gala) | M.26 | 5 | Yes |
| | | Granny Smith | M.26 MM.106 | 4 5 | Yes |
| | | Hi Early (red delicious) | M.26 | 5 | Yes |
| | Pear | Packham's Triumph | D6 | 5 | No |
| | | Williams' Bon Chrétien | D6 | 5 | No |
| Manjimup | Apple | Braeburn | MM.109 | 2 | No |
| | | Cripps Pink (Pink Lady™) | MM.104 M.26 | 2 2 | No |
| | | Cripps Red (Sundowner™) | MM.104 M.26 | 3 1 | No |
| | | Galaxy (Gala) | MM.104 | 2 | No |
| | | Granny Smith | MM.104 | 2 | No |
| | | Hi Early (red delicious) | MM.104 | 2 | No |
| | | Red Fuji (Fuji) | MM.104 | 2 | No |
| | Pear | Packham's Triumph | D6 | 5 | No |
| | | Williams' Bon Chrétien | D6 | 5 | No |

¹Rootstock effects were not considered in this analysis as previous studies indicated that rootstocks did not significantly impact the timing of green tip and flowering dates in data collected for this study (Darbyshire 2016).

Green tip and flowering data was collected three times per week at the whole tree level. For each tree, the date of green tip, first open flower and full bloom were recorded. A tree was defined as being at 'green tip' when 5% of the buds had observable green tips, corresponding to the 07 stage in the international BBCH code for pome fruit (Meier et al. 1994). A tree was defined as being at 'full bloom' when 80% of the flowers were open, similar to the 65 stage in the international BBCH code for pome fruit (Meier et al. 1994).

Comparison of productivity and orchard management practice

Broad yield data and information on orchard management practices was obtained from the Australian Bureau of Statistics, personal communication with growers and local industry representatives, and from a grower survey performed using digital audience response technology at the AP12029 project

roadshow event held in Manjimup on 1 October 2014. Detailed yield and orchard practice data was not collected as part of this study.

Results and discussion

Identification of an appropriate climate analogue location for Stanthorpe 2030

The Analogues Explorer tool was used to identify a broad pool of possible climate analogue locations for Stanthorpe in 2030. When climates were matched for annual temperature and rainfall, twelve analogue locations were listed including Bega, Manjimup, Mount Barker, Young and Albury-Wodonga.

To ensure that the climate analogue selected could be used to specifically investigate the impacts of reduced chilling on flowering, the Analogues Explorer tool was set-up to identify analogues matched on autumn and winter temperatures only. Spring and summer temperatures were removed from the assessment, along with rainfall. A slightly different set of climate analogues was listed including Nuriootpa, Horsham, Naracoorte, Manjimup, Mount Barker and Sale. From this list, Manjimup, one of Australia's main apple and pear growing regions, was selected as the climate analogue location for Stanthorpe in 2030 (Figure 1).



Figure 1. Map of Australia showing the locations of Stanthorpe and Manjimup. Manjimup was identified as an appropriate climate analogue for Stanthorpe in 2030.

It is worth noting that, when the seasons are considered separately Manjimup is a reasonable analogue for 2030 in Stanthorpe for summer, autumn and winter, but not for the spring. This is because, in the current climate, Stanthorpe has a warmer spring than Manjimup.

Projections of winter chill using global climate models were undertaken to evaluate how well winter chill in Manjimup is likely to match chill received under a 2030 climate in Stanthorpe (Figure 2.). The historical chill portion data for the period 1986 to 2005 in Manjimup is similar to the chill data for Stanthorpe over this same period (Figure 2). However, 2012, 2013 and 2014 were low chill years in Manjimup. If the chill portion data for these years is considered separately, it falls neatly within the range of the projected winter chill results for Stanthorpe in 2030 (Figure 2). Therefore Manjimup in the years 2012 to 2014 was considered to be a good climate analogue for assessing the impacts of reduced winter chill on flowering in Stanthorpe in 2030.

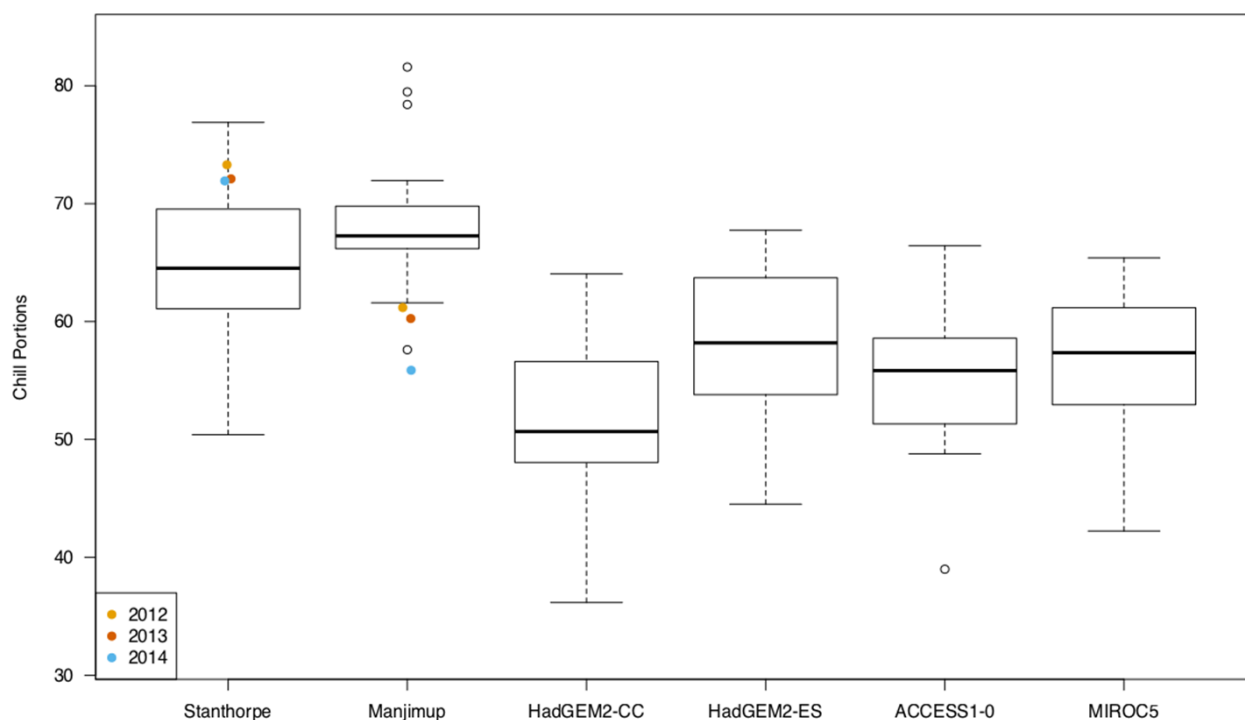


Figure 2. Box plot showing winter chill projections from four climate models for Stanthorpe in 2030, compared with current winter chill in Manjimup. Orange, red and blue dots show winter chill data calculated from hourly temperature data collected on-site from 2012, 2013 and 2014 respectively. Historical boxplot data is for the period from 1986 to 2005.

The apple and pear industries in Manjimup and Stanthorpe

The apple and pear industries in Manjimup and Stanthorpe are comparable on most industry characteristics including gross value, orchard size, variety mix, rootstocks and planting systems (Table 3). One significant difference is in the use of orchard netting, Stanthorpe apples are grown almost entirely under hail netting, while most of the apple orchards in the Manjimup district are un-netted (although this is changing rapidly).

Table 3. Characteristics¹ of the apple industries in Manjimup and Stanthorpe.

| Industry characteristic | Manjimup | Stanthorpe |
|-------------------------|---|--|
| Gross value | \$41M (WA) | \$36M (QLD) |
| Orchard businesses | 35 | 45 |
| Area of production | 650ha | 1,204ha |
| Orchard Size | 22ha | 27ha |
| Varietal mix | Pink Lady; Granny Smith; Gala; Fuji; Jazz | Pink Lady; Granny Smith; Gala; Fuji; Red Del; Jazz |
| Rootstocks | MM.106; M.26 | MM.106; M.26 |
| Planting systems | Central leader on vertical trellis | Central leader on vertical trellis; V-trellis |
| Irrigation | Under tree sprinkler; drip | Drip |
| Proportion under net | 40% of growers with net | 100% |

¹Gross value is the average from the 2002-2003 to 2012-2013 seasons.

Apple and pear tree flowering in Manjimup and Stanthorpe

In 2013 and 2014, Stanthorpe received 72 and 74 chill portions respectively, while Manjimup received 54 chill portions in both years (well below its long-term average) (Figure 3). The low winter chill in Manjimup was associated with a greater spread of green tip and full bloom dates in both years (Figure 3). Average green tip dates for all cultivars were spread across 32 days in Manjimup compared with 15 days in Stanthorpe. Similarly, average full bloom dates were spread across 19 days in Manjimup compared with 9 days in Stanthorpe.

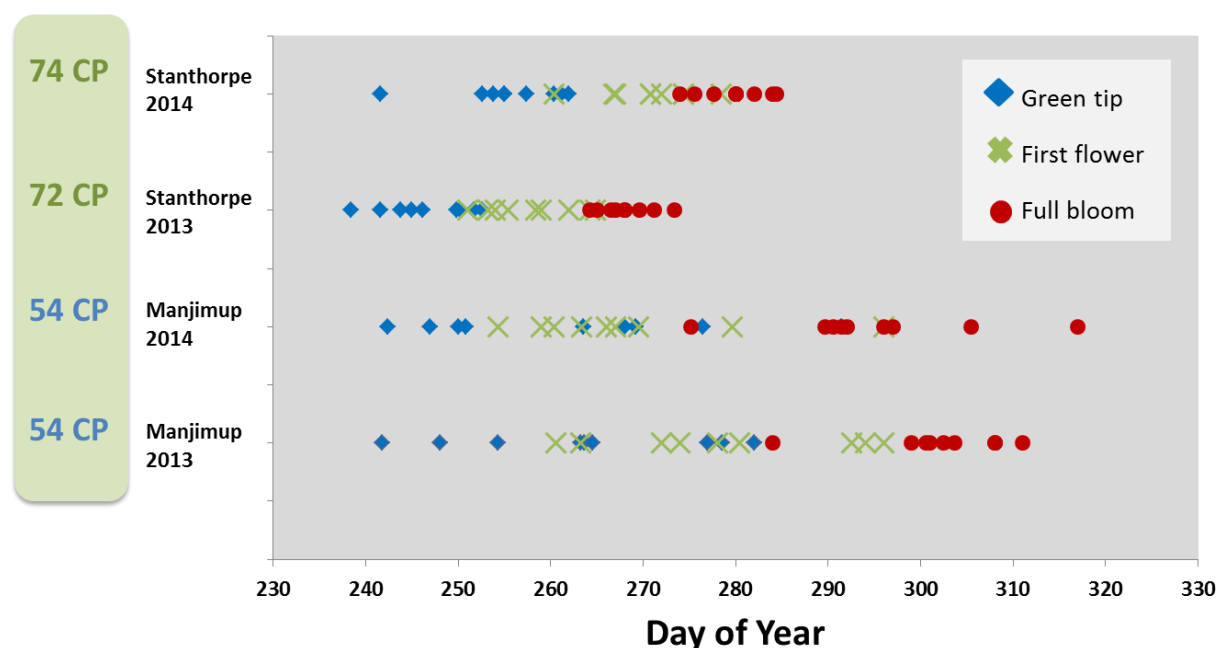


Figure 3. Green tip, first flower and full bloom dates for cultivars of apple and pear in Manjimup and Stanthorpe in 2013 and 2014. Dates are given as the 'day of year', day 260 is 17 September and day 300 is 27 October. Data points are the average of individual tree observations. CP is the total chill portions calculated up to 31 Aug.

The duration between the first flower opening and full bloom in Manjimup was more than twice as long as in Stanthorpe (an average of 25 days compared with 10 days) when averaged across years and cultivars (Figure 4 and Figure 5). This protracted pattern of flowering was consistently observed in Manjimup over the period of the study and was largely the result of irregular and uneven bud movement within individual tree canopies (Figure 6).

A prolonged and irregular period of flowering can be difficult to manage for a number of reasons. Determining an appropriate chemical thinning program is challenging when buds are at multiple stages of green tip and flowering on each tree within the block, at any given time (Theron 2013). Fruitlets are likely to vary greatly in size and development stage, and therefore careful attention is required at the time of hand thinning to ensure that fruitlets are thinned in a manner that optimises crop uniformity and reduces the spread of fruit maturity at harvest (Theron 2013, Erez 2000).

A long drawn out flowering season has other indirect impacts on orchard activities including a longer period for controlling flowering pests such as dimpling bug, and for managing of bee hives. These impacts were not assessed in this study.

Overlap of flowering between a cultivar and its pollinisers is essential for good fruit set (Ramirez and Davenport 2013). Changes in the timing of flowering between seasons or across years that result in

the loss of flowering synchronisation can therefore result in reduced yields. Flowering overlap does not appear to be a problem for either Manjimup or Stanthorpe in the years of study (Figure 5), however, reduced marketable yields can result from the extended period of flowering overlap that is caused by irregular bud movement (Petri and Leite 2004). In this situation, fruit set occurs over an extended period of time, resulting in the significant spread of fruit maturity within individual trees.

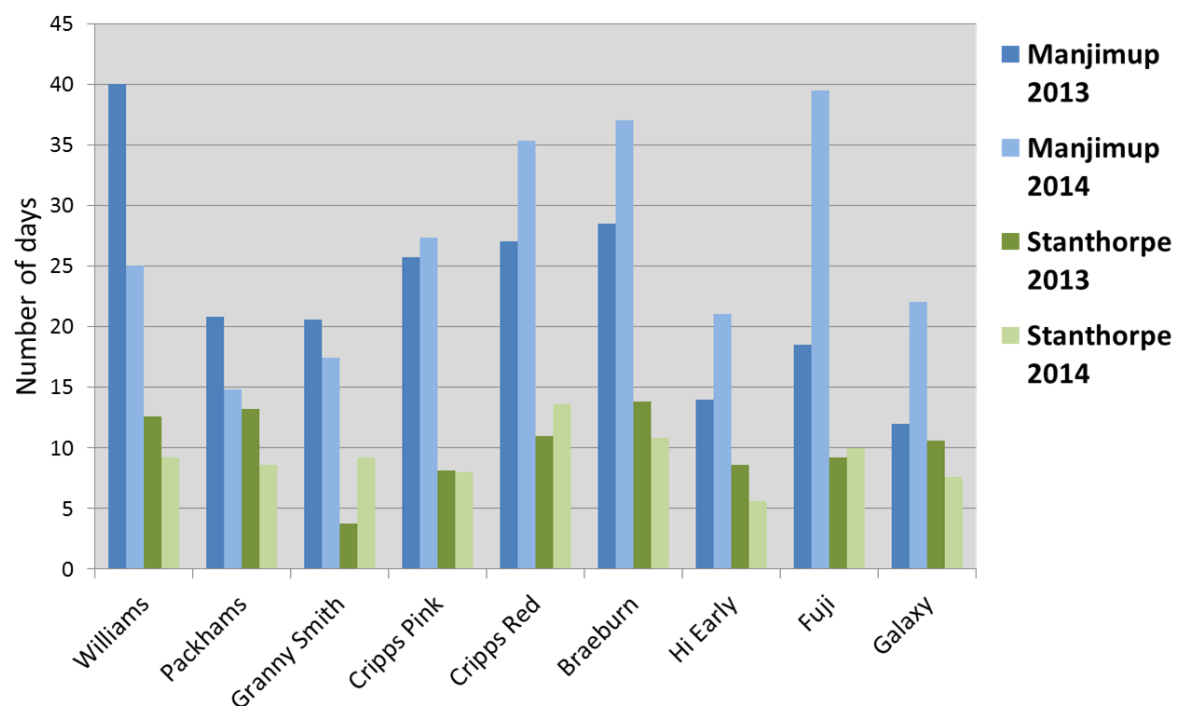


Figure 4. Duration of the flowering period from first flower to full bloom in cultivars of apple and pear grown in Manjimup and Stanthorpe in 2013 and 2014. Results are the average of individual tree observations.

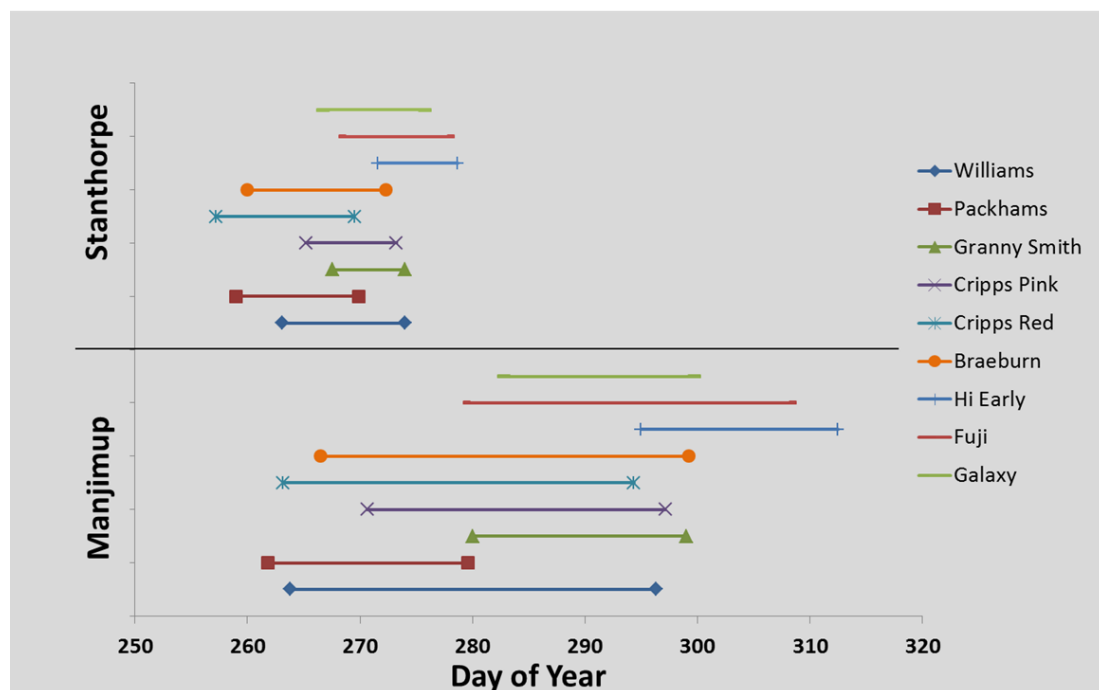


Figure 5. Overlap of flowering periods, from first open flower to full bloom, in cultivars of apple and pear in Manjimup and Stanthorpe. Dates are given as the 'day of year', day 260 is 17 September and day 300 is 27 October. Data points are the average of individual tree observations for 2013 and 2014.



Figure 6. Uneven flowering in 'Cripps Pink', Lyster's Orchard Manjimup, 2014.

Apple and pear productivity in Manjimup and Stanthorpe

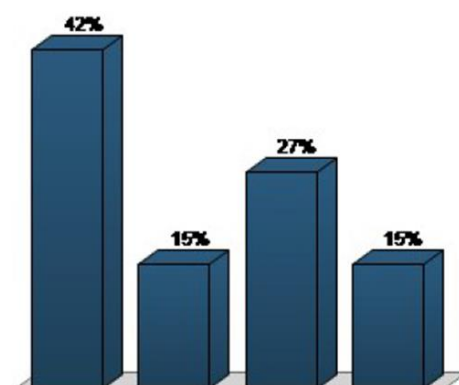
Low winter chill and irregular flowering can reduce productivity through impacts on fruit set and variability of fruit quality at harvest (Petri and Leite 2004, Erez 2000). To investigate any association between irregular and protracted flowering in Manjimup in 2013 and 2014, with productivity in those years, broad assessments of yield were undertaken.

Meaningful comparison of yield data between locations can be problematic, as yield is impacted by the interaction of many complex factors including pests and diseases, irrigation, planting systems, tree canopy management practices, as well as climatic factors. Long-term apple yield data was similar between locations with an average of 37.7 kg per tree in Manjimup and 38.2 kg in Stanthorpe (source: Australian Bureau of Statistics).

There was no evidence of reduced productivity in Manjimup in the low chill year of 2014. In a survey of Manjimup growers, 69% reported an above average or excellent yield in 2014 and 79% reported average or really good fruit quality in 2014 (Figure 7). These results were based on grower perceptions, detailed yield data was not collected as part of this study.

4. How was your 2014 Cripps Pink harvest yield compared to an average year? (Multiple Choice)

| | Responses | |
|----------------------------|-------------|-----------|
| | Percent | Count |
| Above average | 42.31% | 11 |
| Not good enough | 15.38% | 4 |
| Excellent | 26.92% | 7 |
| Pickers ate too much fruit | 15.38% | 4 |
| Totals | 100% | 26 |



5. What was the quality like in the Cripps Pink 2014 harvest compared to an average year ? (Multiple Choice)

| | Responses | |
|-----------------------------|-------------|-----------|
| | Percent | Count |
| Really good | 50% | 12 |
| Poor colour development | 12.5% | 3 |
| Average | 29.17% | 7 |
| Too many bins went to juice | 8.33% | 2 |
| Totals | 100% | 24 |

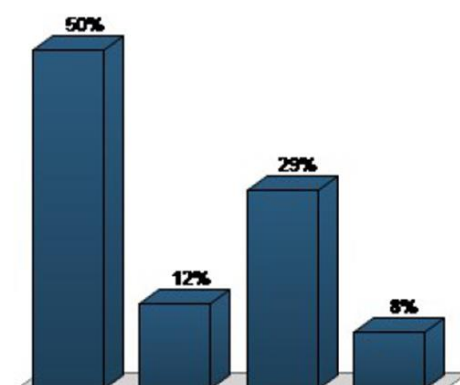


Figure 7. Results from a survey of Manjimup growers on 'Cripps Pink' yields and quality in 2014. The survey was undertaken at a grower roadshow event using digital audience response technology 1 October 2014.

Orchard management practices in Manjimup and Stanthorpe

The lack of evidence for losses in marketable yield as a result of the variable and protracted flowering observed in Manjimup in 2014 could be because, 1) the observed pattern of flowering had no impact on fruit set or fruit quality at harvest, 2) Manjimup growers have adjusted management practices to adapt to low chill years, or 3) impacts on productivity were there, but were not great enough to be picked up in grower yield records.

While it was not possible to distinguish between these alternative explanations with the data collected in this study, it was worth considering whether Manjimup growers have implemented any changes to cultural practices and / or longer term strategies to manage variable and protracted flowering. In the survey of Manjimup growers, 50% indicated that they were using dormancy-breaking sprays on some

cultivars to manage the irregular flowering. This is compared with zero growers in Stanthorpe for that year.

It is not clear whether the use of dormancy-breaking sprays in Manjimup is the reason that there was no clear impact of the variable and protracted flowering on productivity, but it is likely to have helped (Erez 1995, Saure 1985, Petri et al. 2014).

A longer-term strategy for managing the effects of low chill years on flowering is to plant cultivars with lower chilling requirements. The existing variety mix was similar in Stanthorpe and Manjimup and there was no apparent difference in the cultivars under consideration for new plantings (personal communication).

Conclusions

The following conclusions on the impact of reduced winter chill on Stanthorpe's apple industry in 2030 can be drawn from the evaluation of flowering, productivity and orchard management practices in Manjimup.

1. How will flowering of apple and pear trees be impacted by reduced winter chill in Stanthorpe in 2030?

A more variable and protracted pattern of flowering is likely to exist across many apple cultivars in Stanthorpe in 2030.

2. Will there be an impact on productivity?

The more variable flowering will not necessarily have significant impacts on productivity of apple orchards in 2030.

3. What can growers do to adapt?

Stanthorpe growers are likely to be able to manage low chill years with the use of dormancy-breaking sprays. At this stage there is no clear need to shift to lower chill cultivars (or crops) as Manjimup growers are achieving high levels of productivity with the same variety mix as is currently grown in Stanthorpe.

4. Is the climate analogue approach appropriate in this context and can it be applied more broadly?

Yes, the climate analogue approach provided insight into potential impacts of reduced winter chill on flowering in Stanthorpe in 2030, and is likely to be a valuable tool for broadly evaluating climate change impacts and options for adaptation in many horticultural contexts.

5. Are there factors that should be considered when using climate analogues for informing climate change adaptation in horticulture?

Three important factors for consideration were identified during this case study.

Selection of the climate analogue should be undertaken carefully, with consideration given to differences between the analogue and target locations with respect to environment, industry, social factors and so on.

The Analogues Explorer tool comes with the following qualifying statement:

"It is important to note that other potentially important aspects of local climate are not matched when using this approach, such as frost days or other local climate influences. Furthermore, for agricultural applications, solar radiation and soils are not considered. Thus we advise against the analogues being used directly in adaptation planning without considering more detailed information".

A good example of why this is important was identified in this case study. The town of Young was one of the possible climate analogues listed for Stanthorpe in 2030, when the climates were matched on annual temperature and rainfall. In the current climate, Young receives significantly higher winter chill than Stanthorpe, but has a hotter summer. Hence, they might be a good match based on annual temperature, but Young would not have been a useful analogue for evaluating reduced winter chill in Stanthorpe. On the other hand, it might be a good analogue for assessing risk associated with extreme summer heat.

An intrinsic assumption of the climate analogue approach is that the only significant difference between the test site and the analogue location is the climate, however, locations might differ in other ways that could significantly reduce the value of the climate analogue approach. For instance, if comparing crop production in Australia with that of somewhere else in the world, the production systems may be too different to provide meaningful impact and adaptation information.

Relationships between climate and physiology are complex, the details and nuances of climate change impacts may not be fully defined by the climate analogue approach.

This case study concluded that the differences in flowering behaviour observed in Manjimup compared with Stanthorpe were the result of low winter chill in Manjimup in 2013 and 2014. However, it is possible that the variable and protracted flowering in Manjimup was a response to the complex interaction between multiple factors other than total winter chill such as, the pattern of chill accumulation, heat, spring temperatures and day-length factors. This will only be understood through further experimentation, detailed climate data and modelling.

The climate analogue approach is limited to investigation of one possible climate scenario at a time, while a modelling approach enables the testing of many different climate scenarios.

Manjimup was used as a climate analogue for Stanthorpe in 2030. To investigate impacts of reduced winter chill in Stanthorpe in 2050 or 2090, alternative analogue locations would need to be sought as the conclusions from this case study cannot be extended beyond the intended time-frame.

Key messages

- Results from the climate analogue approach suggested that more variable and protracted flowering behaviour is likely in pome fruit trees in Stanthorpe by 2030 without significant impact on productivity. Adaptations will include the use of dormancy-breaking sprays to manage flowering, but there is no evidence for a need to switch to low chill cultivars at this stage.
- The climate analogue approach can provide broad information around potential impacts and adaptation strategies for Australian temperate tree crops and horticulture more generally, however, the details need to be considered cautiously.

Recommendations

- Climate analogues should be used by the industry to broadly identify climate change impacts on apple and pear production systems and possible options for adaptation. Growers in Manjimup are already successfully managing the impacts of inadequate chill in some years, lessons can be learnt from their knowledge and experience.
- This study did not capture the many potential impacts that protracted flowering can have on orchard management including a longer period for flowering pest control such as dimpling bug and for management of bee hives, difficulties in the timing of chemical thinner application, more labour intensive hand thinning and dealing with greater variability of fruit maturity at

harvest. A more detailed grower survey should be undertaken to better understand how growers in Manjimup are managing flowering in low chill years.

- Potential impacts of low winter chill on marketable yield were not adequately addressed in this study and requires further research using a climate analogue and / or modelling approach.
- A global study to investigate the limits of profitable apple production with regards to winter chill would provide valuable information for the Australian industry in climate change adaptation planning. Production areas with very low winter chill accumulation in South Africa and Southern Brazil rely heavily on dormancy-breakers and would be obvious target locations for this research.
- The Australian Apple and Pear Industry's ability to adapt to changing climate will depend not only on basic research, but on its ability to observe and capture data on tree physiology, climate and orchard practice, and interpret it in a meaningful way. Australia's industry is made up of growing regions with diverse climates and much can be learnt about climate change impacts and options for adaptation by sharing of knowledge.

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Dormancy-breaking sprays for low winter chill in apples

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Summary

In the 2015-16 season, trials were undertaken in 'Gala' apple trees at three locations (Queensland, Western Australia and Tasmania) to assess the efficacy of using dormancy-breaking sprays under current Australian climates and, the potential to use these sprays as an orchard management adaptation to inadequate winter chill under future Australian climates. The trials compared the effect of Waiken™, Dormex® and Erger® on the timing of green tip and flowering, the duration of the flowering period, fruit set, yield, harvest time and variability of maturity at harvest. All dormancy-breaking sprays were able to advance flowering time and compact the flowering period in 'Gala' apple, with differences observed between products and sites. Fruit maturity was advanced with dormancy-breakers (again with differences observed between products and sites) and generally reflected differences in flowering dates. There were no differences in fruit set, yield or variability of apple maturity in trees treated with dormancy-breaking sprays despite the compaction of flowering. Dormex® had the most significant impacts on 'Gala' flowering and harvest timing in WA and QLD, when compared with Waiken™ and Erger®. The timing of spray application relative to green tip and winter chill accumulation, impacted the bud burst and flowering response to dormancy-breaking products, and therefore flowering responses are likely to vary between seasons and cultivars. Dormancy-breaking sprays are likely to be an effective tool for managing flowering in 'Gala', and other apple cultivars, in lower chill years in Australia. Benefits from the use of dormancy-breakers would be greater in low chill years when the potential impacts of inadequate chill on flowering are greatest. Therefore, benefits are likely to increase under future warmer climate scenarios. Impacts of dormancy-breaking sprays on fruit quality and length of the harvest window remain unclear.

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Introduction

Dormancy is a phase of the annual cycle of apple trees that allows them to survive unfavourably cold winter conditions (Saure 1985). The minimum accumulation of winter chill needed to break bud dormancy is defined as the chilling requirement, and is thought to be genetically determined (Labuschagne et al. 2002, Samish 1954).

Failure to adequately satisfy the chilling requirement can result in delayed and uneven bud burst and flowering, and extended duration of the flowering period (Saure 1985, Oukabli 2003). An extended flowering period reduces the effectiveness of chemical thinning (Petri and Leite 2004) and can impact on fruit set and yield (Erez 1995). It has also been shown to result in greater variability of fruit size and maturity, which impacts pest and disease management, and harvest efficiency (Petri and Leite 2004).

Efforts are being made to breed lower chill cultivars in some crops to enable commercial production in milder growing regions, however management tools to compensate for insufficient chilling are still required in many temperate tree fruit production systems in warmer climates (Erez 1995). These tools utilise a range of strategies to manipulate bud progression through dormancy including the use of dormancy-breaking sprays to promote bud burst (Erez 1995, Allderman et al. 2011, Saure 1985). The use of dormancy-breaking sprays is perhaps the most widely used and accepted method for managing low chill conditions globally (Erez 2000, Jackson and Bepete 1995, Petri et al. 2014).

Winter chill is predicted to decrease in Australian growing regions under future climate change, with milder districts likely to experience the impacts of inadequate chilling on a more regular basis (Darbyshire et al. 2013, White 2016). The use of dormancy-breaking sprays is a potential adaptation for the apple industry to manage existing commercial cultivars in warmer years, as they have been shown to stimulate earlier, more homogenous bud burst and flowering in a number of crops grown in conditions with insufficient winter chill (Erez et al. 2008, Petri et al. 2012, Saure 1985). Additional benefits such as improved uniformity of fruit maturity and quality with the use of dormancy-breaking sprays have been reported (Petri and Leite 2004).

Different types of products have been shown to have dormancy-breaking action in a range of crops. These include thidiazuron (a compound with cytokinin-like activity) (Wang et al. 1986), dinitro-o-cresol (DNOC-oil) and potassium nitrate (Faust et al. 1997), garlic extract and gibberellic acid (Abd El-Razek et al. 2013), the emulsified vegetable oil compound Waiken™ (Bound and Miller 2006) and hydrogen cyanamide which is better known as Dormex® (Bound and Jones 2004). Dormex® has known risks for plant and human health, and therefore alternatives to the use of this product have been sought (Petri et al. 2014). More recently, Erger®, an inorganic nitrogen compound combined with calcium nitrate, has been shown to cause earlier and more compact flowering in apples (Petri et al. 2014, Petri et al. 2010).

However, with the exception of two studies (Bound and Jones 2004, Bound and Miller 2006), little work has been undertaken in Australia to investigate the efficacy of dormancy-breaking sprays to induce earlier and more uniform flowering in apple cultivars grown under local conditions, and the effects on fruit quality and yield remain unclear.

A survey performed at the WA National Climate Change project Roadshow event in 2014 indicated that half of the growers were currently using Waiken™ and / or Dormex® for the purposes of stimulating uniform bud burst and flowering under conditions of inadequate chill, however there was considerable uncertainty around best practice issues and effectiveness. Questions and discussions with growers in other growing regions also indicated an interest in these products, but highlighted the need for better understanding regarding use and efficacy in low chill years under current climates, and potential as an adaptation strategy for climate change.

Project Objectives

The overarching research question was: *are dormancy-breaking sprays a feasible adaptation option for the Australian apple industry to low chill years in current and future climates?*

The specific research objectives were to determine:

- a. Impact of dormancy-breaking sprays on the timing of bud burst and flowering, and duration of the flowering period in 'Gala' apple grown in diverse Australian climates.
- b. Impact of dormancy-breaking sprays on fruit set, yield and variability of maturity and quality in Australian 'Gala' apple trees.
- c. Comparative effectiveness of using Waiken™, Dormex® and Erger® as dormancy-breaking sprays in apple.
- d. Cost-benefit of using dormancy-breaking sprays.
- e. Issues (actual and potential) associated with using dormancy-breaking sprays for management of, and adaptation to, inadequate winter chill under Australian conditions.
- f. Future research needs towards improving orchard practices around the use of dormancy-breaking products.

To investigate these objectives a study was undertaken in 'Gala' apple tree cultivars in the 2015 / 2016 season at three orchard locations around Australia (QLD, WA and TAS).

Materials and methods

Site description

The study was performed at three commercial orchard sites around Australia in the 2015 to 2016 season (Table 1 and Figure 1). Sites were fully mature 'Gala' blocks and were representative of high-density plantings in Australia. Trees were trained to a dominant central leader and, with the exception of the application of dormancy-breaking sprays as part of this study, were managed by the grower using standard orchard practices.

Table 1. Description of the orchard study sites.

| State | Growing region | Latitude and longitude | 'Gala' strain/ Rootstock | Density trees/ha | Netted |
|------------------------|----------------|------------------------|--------------------------|------------------|--------|
| Queensland (QLD) | Stanthorpe | 28.52 S 151.90 E | Royal Gala/M.26 | 2500 | Yes |
| Western Australia (WA) | Manjimup | 34.16 S 116.70 E | Galaxy/M.26 | 2500 | No |
| Tasmania (TAS) | Huonville | 43.01 S 147.06 E | Alvina Gala/M.26 | 2500 | No |

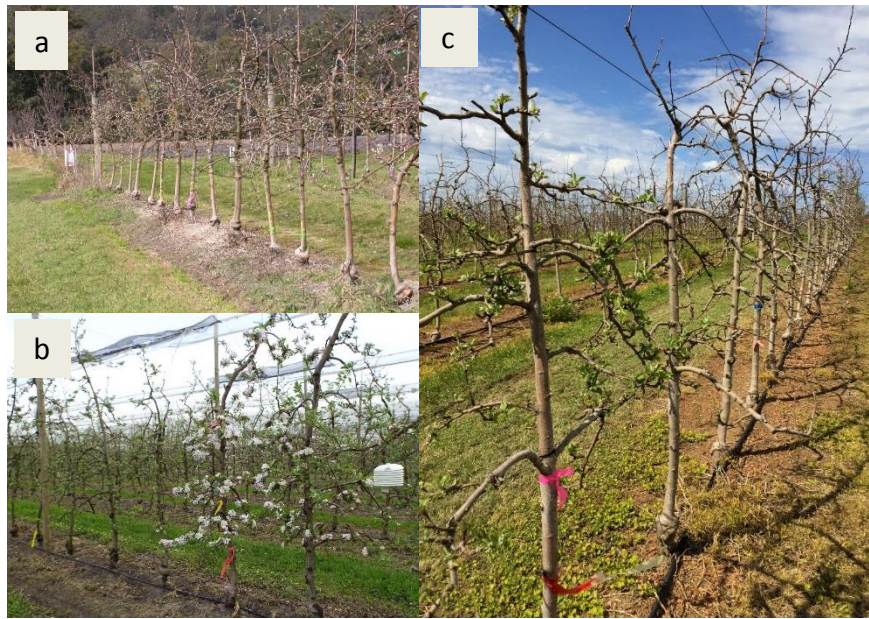


Figure 1. Study sites in Huonville, TAS (a), Stanthorpe, QLD (b) and Manjimup, WA (c) in spring 2015.

Experimental design

The experiment was a randomised complete block design with two treatments (Waiken™ and Dormex®) and an untreated control in WA and TAS, and three treatments (Waiken™, Dormex® and Erger®) and an untreated control in QLD. Replicates were individual trees, with five replicates per treatment. Guard trees were included either side of the datum trees to ensure complete coverage of datum trees and to protect other datum trees in the row from over-spraying. Sprays were applied at one concentration and timing, according to directions on the product label.

Spray application

Dormancy-breaking sprays were applied to the datum trees using a hand lance (Figure 2) as described in Table 2.

Table 2. Details of the dormancy-breaking sprays applied to ‘Gala’ trees in WA, TAS and QLD in winter 2015.

| | Dormex® | Waiken™ | Erger® |
|-----------------------------------|--|--|--|
| Active constituent | 520g/L Cyanamide | 388g/L Methyl esters of fatty acids | 250g/L Decanol alkoxylate (fertiliser adjuvant) |
| Product rate | 3L /100L water (3% v/v) | 4L /100L water (4% v/v) | 5L /100L water (5% v/v) |
| Additives | 50ml/100L Agral or 125ml/100L Kendeen 20 | NA | 10kg/100L Calcium nitrate |
| Application | Applied as a fine spray over entire tree, to the point of run-off. | | |
| Application timing | 35 days before expected green tip (label suggests 30 – 45 days) | 35 before expected green tip (label suggests 35 – 50 days) | 35 days before expected green tip (label suggests 45 days) |
| Determination of application date | Grower records of historical green tip dates were accessed for the study site. Chill accumulation was monitored during the winter and compared with historical chill accumulation data to obtain the best estimate of expected green tip date. | | |



Figure 2. Application of dormancy-breaking sprays using a hand lance in Manjimup, WA.

Table 3. Actual timing of dormancy-breaking spray application on ‘Gala’ trees in QLD, WA and TAS 2015.

| Location | Spray Date | Green tip date* | Spray timing (days before green tip) | Chill Portions at spraying (brackets, % total chill) | Total chill Portions** |
|----------|------------|-----------------|--------------------------------------|--|------------------------|
| TAS | 13 Aug | 8 Sep | 26 | 95 (84%) | 113 |
| QLD | 30 July | 5 Sep | 37 | 60 (75%) | 80 |
| WA | 18 Aug | 23 Sep | 36 | 58 (75%) | 77 |

*In untreated trees. **accumulated from 1 Jan to green tip.

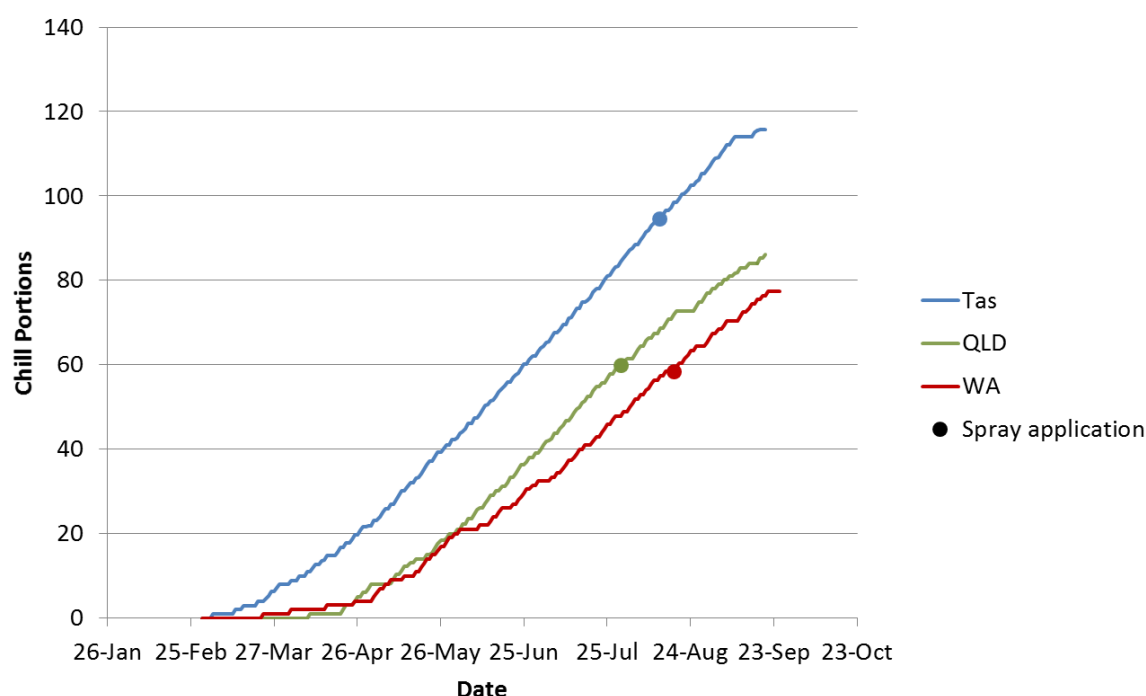


Figure 3. Chill Portion accumulation and dormancy-breaking spray application timing at study sites in TAS, QLD and WA, 2015.

Temperature data and calculation winter chill

Hourly temperature data was recorded in the orchard using temperature data loggers placed inside a miniature Stevenson's screen positioned approximately 1.5 to 2m within the tree row. Winter chill was calculated in Chill Portions using the Dynamic model (Erez et al. 1990, Fishman et al. 1987).

Green tip and flowering

Buds were monitored three times per week (full methods described in appendix 1), from just prior to green tip until the end of flowering. Only spur and terminal buds were assessed, with axillary buds

and long, highly vigorous shoots excluded. Dates were recorded for the day on which each tree reached green tip, 5% flowering and full bloom.

Green tip was defined as the date when 5% of the buds of the tree had observable green tips, corresponding to the 07 stage in the international BBCH code for pome fruit (beginning of bud break: first green leaf tips just visible) (Meier et al. 1994). Full bloom was defined as the date when 80% of the flowers were open, similar to stage 65 in the international BBCH code for pome fruit (full flowering: at least 50% of flowers open, first petals falling) (Meier et al. 1994).

Fruit set

Fruit set measurements were taken from three representative mid-canopy branches per tree. The number of spur and terminal flower clusters were recorded for each limb soon after green tip when flowers were emerging. The number of fruit set per cluster was recorded for each tagged limb after final fruit drop, but before hand-thinning.

Fruit sampling and maturity assessments

A 30 fruit sample was taken per datum tree prior, but as close as possible to, the grower's first harvest. For the purpose of standardisation between treatments, fruit was sampled from the mid-section of each tree on the same side of the row. To ensure the full range of variability was captured, fruit were picked from along the entire length of a branch before moving on to the next branch. This ensured that fruit was not biased towards selection from the outside or inside of the canopy.

The following assessments were made on the 30 fruit sample:

- Starch Pattern Index (SPI) was determined using the starch-iodine test for apples. Each fruit was cut transversely across the equator and the cut surface of one side sprayed with a solution of 1g potassium iodide plus 0.25g iodine per 100ml water (0.1% iodine, 1% potassium iodide). The resulting pattern of starch hydrolysis was compared with the ENZA 0-6 scale.
- Background colour (BGC) was estimated using an ENZA 'Royal Gala' swatch.
- Red blush intensity (RBI) was assessed by comparing the blush/red side of the fruit with the 'Royal Gala' ENZA 11 point colour chart.
- Red blush coverage (RBC) was assessed by estimating the % of the fruit surface covered by greater than or equal to an RBI of 2 (on the ENZA 11 point chart).

Variability in fruit quality at harvest

Variability of fruit maturity and quality at harvest was assessed by calculating the standard deviation of the fruit weight, SPI, BGC, RBI, RBC measurements taken from the 30 fruit sample.

Yield

Yield was calculated per tree by multiplying the total fruit number (counted and recorded prior to harvest) by the average fruit weight (taken from the 30 fruit sample). Trunk cross-sectional area (TCA) was calculated from a trunk circumference measurement taken 20 cm above the graft.

Phytotoxicity

As both Dormex® (Bound and Jones 2004) and Erger® (Hawerth et al. 2010) can cause phytotoxicity, phytotoxicity was assessed and recorded from the date of spray application to flowering using a 0-4 scale (appendix 2)..

Results and discussion

Timing of spray application

The target spray timing was 35 days before green tip. Historical green tip records, together with in-season chill accumulation calculations, were used to predict the estimated date of green tip for 2015. A best estimate of green tip date was determined by comparing the current season's chill accumulation curve with that of the previous few seasons to determine how the season was tracking. The actual spray date was further dictated by the weather, with favourable conditions for spraying required. Actual spray timing was 26, 37 and 36 days before green tip in TAS, QLD and WA respectively (Table 3).

The timing of dormancy-breaking spray application can have considerable impact on product efficacy (Faust et al. 1997, Petri et al. 2010). Spraying too early reduces effectiveness and spraying too close to bud burst can have undesirable effects such as delayed green tip and bud damage (Bound and Jones 2004, Bound and Miller 2006). Getting the timing right can be problematic however, due to difficulties in estimating the date of green tip. Dormancy-breaking sprays are commonly applied according to calendar date in other crops such as grapes (pers. comm.), but this is not recommended in apples as the date of green tip can vary considerably from season to season. The methods described in this study estimated green tip dates successfully in WA and QLD. Green tip timing was more difficult to predict in TAS, primarily due to the exceptionally cold winter conditions.

No bud or flower phytotoxicity was observed in this study with any of the dormancy-breaking spray treatments.

Green tip and flowering

Green tip and flowering responses to dormancy-breaking sprays varied between sites (Figure 4 and Table 4).

In TAS, green tip was delayed by five and six days in Dormex® and Waiken™ sprayed trees respectively (Figure 4 and Table 4). Extended dormancy is not an uncommon response and occurs when dormancy-breaking sprays are sprayed close to bud burst (Bound and Miller 2006). These trees caught up with the untreated control trees and there were no significant differences in the date of full bloom or the duration of the flowering period. A reduction in the length of flowering was observed in trees sprayed with both of the dormancy-breaking products, but this was not statistically significant.

The lack of flowering response to the dormancy-breaking sprays was likely due to the cold 2015 winter in which Huonville received 113 chill portions, well above the long-term average of 88. Under these conditions it was likely that the 'Gala' chilling requirement was satisfied prior to application of the dormancy-breaking sprays, limiting the potential impact. Buds were possibly already sitting in the eco-dormant phase of dormancy waiting for favourable growing conditions. The rapid onset of a warm spring resulted in a short flowering period of just two to three days in all trees.

In QLD, green tip was significantly advanced in trees sprayed with Dormex®, Erger® and Waiken™, by nine, six and five days respectively, when compared with untreated trees (Figure 4 and Table 4). Full bloom was advanced by 12, 5, and 5 days with Dormex®, Erger® and Waiken™ respectively (Figure 5), and the flowering period was condensed with all dormancy-breaking sprays. Green tip and flowering responses to the Dormex® spray were significantly stronger than responses to Waiken™ and Erger®, with no differences observed between the latter two products.

In WA, green tip was significantly advanced by 14 days in trees sprayed with Dormex® and four days in trees sprayed with Waiken™ (Figure 4 and Table 4). Full bloom was advanced by nine days in Dormex® sprayed trees while there was no difference in full bloom dates between trees sprayed with Waiken™ and the untreated trees. The length of the flowering period was reduced by 19% with

Dormex®, while Waiken™ caused a significant increase in the flowering period by 39%. In studies of both time and rate of application across five cultivars, Bound and Miller (2006) reported that Waiken concentrated the flowering period regardless of whether the flowering period was brought forward or delayed. The cause of the lengthening of flowering in this study in the Waiken™ treated trees is unclear and requires further studies to determine if this is a real response to Waiken™ or the result of other experimental factors.

The differences observed in green tip and flowering responses to dormancy-breaking sprays at each site in the 2015-2016 season indicate that responses are likely to vary from season to season, depending on factors including temperatures before and after spraying, and timing of spraying relative to green tip. Petri et al. (2010) described the impact of temperature at spraying, and in the days immediately following spraying, on the response to dormancy-breaking sprays.

In QLD and WA, dormancy-breaking sprays caused large changes to full bloom timing and duration indicating that careful consideration needs to be given to the flowering time of polliniser varieties to ensure fruit set is not impacted. With historical knowledge of cultivar flowering times, dormancy-breaking sprays can be used to improved synchronisation of flowering between cultivars and their pollinisers (Petri et al. 2012).

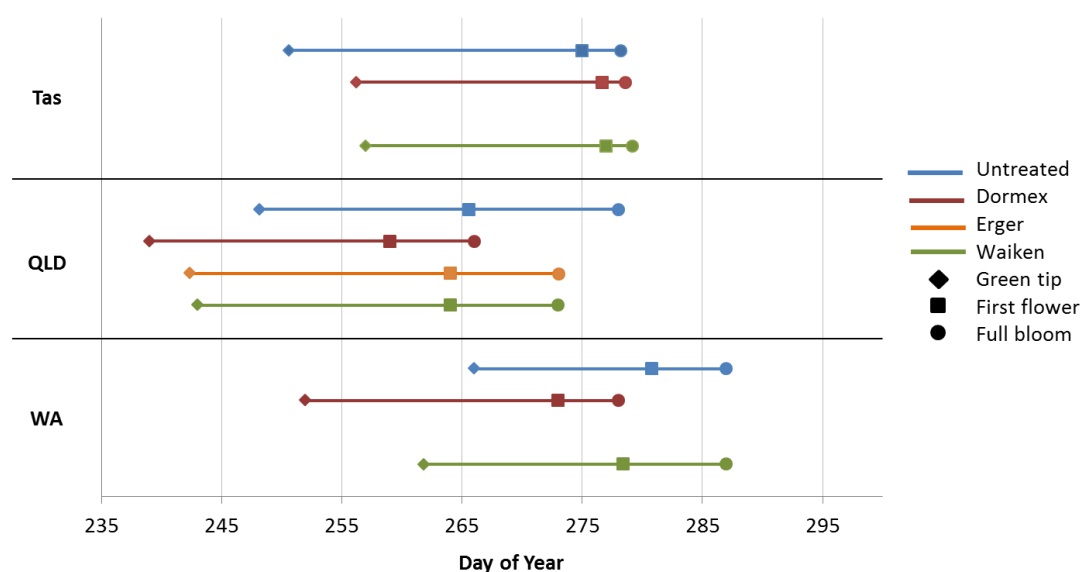


Figure 4. Green tip, first flower and full bloom in Gala apples treated with and without dormancy-breaking sprays in TAS, QLD and WA.

Table 4. Effect of dormancy-breaking sprays on green tip and flowering dates and duration, for ‘Gala’ apple strains grown in TAS, QLD and WA in the 2015 - 2016 season.

| Site | ‘Gala’ strain | Treatment | Green tip (DoY) | First flower (DoY) | Full bloom (DoY) | Green tip to first flower (days) | First flower to full bloom (days) |
|------|---------------|-----------|-----------------|--------------------|------------------|----------------------------------|-----------------------------------|
| Tas | Alvina | Untreated | 251 b | 275 b | 278 | 24 a | 3 |
| | | Dormex® | 256 a | 277 a | 279 | 20 b | 2 |
| | | Waiken™ | 257 a | 277 a | 279 | 20 b | 2 |
| QLD | Royal | Untreated | 248 a | 266 a | 278 | 17 c | 12 a |
| | | Dormex® | 239 c | 259 c | 266 | 20 b | 7 c |
| | | Erger® | 242 b | 264 b | 273 | 22 a | 9 b |
| | | Waiken™ | 243 b | 264 b | 273 | 21 ab | 9 b |
| WA | Galaxy | Untreated | 266 a | 281 a | 287 | 15 b | 6 b |
| | | Dormex® | 252 c | 273 c | 278 | 21 a | 5 c |
| | | Waiken™ | 262 b | 278 b | 287 | 17 b | 9 a |

DoY = Day of year. Within a single and site only, means with different letters are significantly different, $P = 0.05$, LSD test. Full bloom dates did not vary between trees within each treatment and therefore no statistics could be performed.

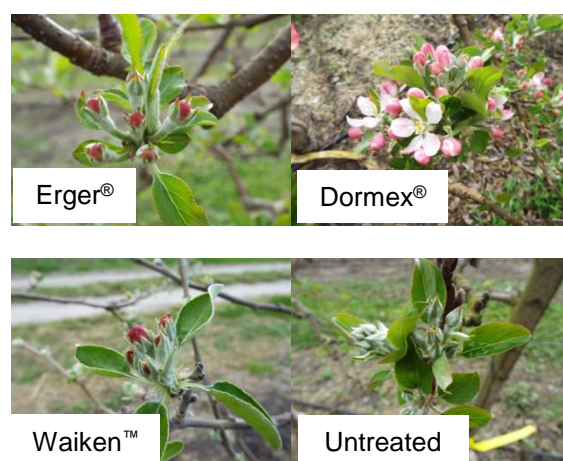


Figure 5. Differences in stages of flowering on 18 September 2015 in QLD ‘Gala’ trees treated with and without dormancy-breakers.

Fruit set and yield

Fruit set, expressed as the percentage of flower clusters that set fruit, was not significantly different between treatments at any location (Figure 6), indicating that compaction of the flowering period, observed most strongly in QLD, did not negatively (or positively) impact the effectiveness of pollination. Similarly, when expressed as the number of fruit set per 100 flower clusters, there was no difference between treatments (data not shown). Dormancy-breaking sprays have been shown to have a slightly negative effect on fruit set in some studies (Hawerorth et al. 2010, Bound and Jones 2004) suggesting that impacts on pollination success are likely to be influenced by factors such as cultivar and season.

Interestingly, the number of fruit set per 100 flower clusters was significantly different between locations, with TAS showing the highest fruit set, followed by WA, and then QLD (data not shown).

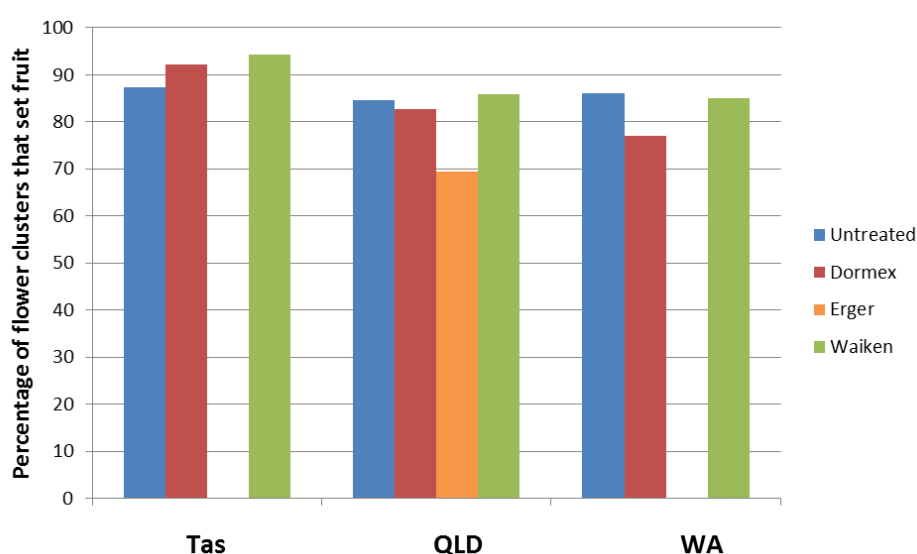


Figure 6. Fruit set in 'Gala' apple trees treated with dormancy-breaking sprays at study sites in TAS, QLD and WA, 2015.

There were no differences in gross apple yields between treatments at any location (Table 5). In TAS, fruit from Waiken™ treated trees had the highest and most marketable mean fruit weight compared with the other treatments, however this was likely a crop load effect and not a result of the treatment per se (Table 5). Yield adjusted for trunk cross sectional area was significantly higher in the control trees compared with both Waiken™ and Dormex® treated trees in TAS. It is unclear whether these differences were a result of the treatment, as flowering density varied widely between trees in the block, and therefore it is possible that any differences in yield were a reflection of flowering density rather than an impact of the treatments.

In QLD, fruit numbers were significantly higher in the Dormex® treated trees, compared with those sprayed with Erger® and Waiken™ (Table 5). Again, it is unclear whether this is the result of the treatments as there were no significant differences in the percentage of flowers setting fruit (Figure 6). In WA, there were no differences in the components of yield between treatments (Table 5).

Dormex® has been shown to significantly improve yields in other studies of apple, including in 'Granny Smith' and 'Golden Delicious' (Jackson and Bepete 1995). Such improvements are likely to be more substantial in very warm growing regions, such as the one used in the Jackson and Bepete (1995)

study, which had less than 300 chill hours, where yields are generally very low to start with. In most Australian growing regions, significant improvements are more likely to be related to fruit quality and marketable yield, rather than gross yield.

Table 5. Effect of dormancy-breaking sprays on gross yield and its components at harvest, for ‘Gala’ apple strains grown in TAS, QLD and WA in the 2015-2016 season.

| Site | ‘Gala’ strain | Treatment | TCA ¹ (cm ²) | Fruit no. / tree | Fruit no. / TCA | Mean fruit weight (g) | Kg/tree | Kg/TCA | T/ha |
|------|---------------|-----------|-------------------------------------|------------------|-----------------|-----------------------|---------|--------|------|
| Tas | Alvina | Untreated | 14.1 | 233 | 16.6 a | 133.2 b | 30.8 | 2.2 a | 77 |
| | | Dormex® | 16.2 | 201 | 12.1 b | 124.8 c | 24.1 | 1.5 b | 60 |
| | | Waiken™ | 15.8 | 118 | 7.7 c | 157.3 a | 18.7 | 1.2 b | 47 |
| QLD | Royal | Untreated | 18.5 | 196 ab | 10.8 a | 128.8 | 25.2 | 1.4 | 63 |
| | | Dormex® | 21.7 | 241 a | 11.1 a | 128.5 | 30.8 | 1.4 | 77 |
| | | Erger® | 21.2 | 167 b | 8.1 b | 139.5 | 23.3 | 1.1 | 58 |
| | | Waiken™ | 20.6 | 187 b | 9.3 ab | 130.3 | 24.2 | 1.2 | 60 |
| WA | Galaxy | Untreated | 17.3 | 162 | 10.5 | 107.0 | 16.6 | 1.1 | 41 |
| | | Dormex® | 18.0 | 161 | 10.2 | 114.1 | 18.4 | 1.1 | 46 |
| | | Waiken™ | 19.6 | 212 | 10.8 | 104.4 | 21.9 | 1.1 | 55 |

¹TCA = trunk cross-sectional area. Within a single and site only, means with different letters are significantly different, *P* = 0.05, LSD test.

Fruit maturity and quality

Results of the effect of dormancy-breaking sprays on fruit maturity and quality are shown in Table 6. In TAS, fruit from trees treated with Waiken™ were the most advanced according to the delta absorbance (DA) meter and background colour, however the starch pattern index results indicate that fruit from untreated trees were the most mature at harvest. Therefore, differences in the timing of maturity with treatments are not clear, but the impacts were not large.

In QLD, fruit was harvested on different dates due to the large differences in maturity between treatments. Fruit from Dormex® trees were more than one week ahead of untreated trees (Table 6). Fruit from Erger® and Waiken™ trees were also ahead by at least two days, however comparison of the background colour and red blush coverage data suggested that fruit on these trees were further advanced (Figure 7). Advances in fruit maturity reflected the differences in flowering dates.

In WA, fruit maturity was slightly advanced in Dormex® trees compared with control but this was not statistically significant (Table 6). The background colour was significantly higher in fruit from Waiken™ treated trees compared with Dormex® and control trees. According to the data there were no differences in red blush coverage between treatments, although grower observation suggested that

the colour was more intense in the trees sprayed with Dormex® compared with other treatments. This may have been due to advanced maturity.

Table 6. Effect of dormancy-breaking sprays on fruit maturity and quality at harvest, for ‘Gala’ apple strains grown in TAS, QLD and WA in the 2015-2016 season.

| Site | ‘Gala’ strain | Treatment | Fruit sample date | Starch pattern index | Background colour | Red blush coverage ² (%) | Red blush intensity ² | DA index ¹ |
|------|---------------|-----------|-------------------|----------------------|-------------------|-------------------------------------|----------------------------------|-----------------------|
| Tas | Alvina | Untreated | 7/3/16 | 0.8 a | 6.4 b | | | 0.45 b |
| | | Dormex® | 7/3/16 | 0.3 b | 6.2 c | | | 0.51 a |
| | | Waiken™ | 7/3/16 | 0.3 b | 6.5 a | | | 0.35 c |
| QLD | Royal | Untreated | 3/2/16 | 2.4 | 3.4 c | 15.6 b | 1.8 | |
| | | Dormex® | 27/1/16 | 3.2 | 4.1 b | 35.6 a | 2.9 | |
| | | Erger® | 1/2/16 | 3.5 | 4.5 a | 36.0 a | 3.1 | |
| | | Waiken™ | 1/2/16 | 3.5 | 4.3 ab | 33.9 a | 3.0 | |
| WA | Galaxy | Untreated | 9/2/16 | 2.1 | 3.4 b | 70.9 | 5.2 | |
| | | Dormex® | 9/2/16 | 3.1 | 3.4 b | 68.2 | 4.6 | |
| | | Waiken™ | 9/2/16 | 2.5 | 4.1 a | 72.6 | 5.0 | |

¹DA index was measured with the Delta Absorbance meter in Tasmania only. ²Red blush coverage and intensity were not measured in Tasmania. Numbers are the average of 30 fruit samples. Within a single and site only, means with different letters are significantly different, $P = 0.05$, LSD test.



Figure 7. Fruit at harvest on 27 January 2016 in ‘Gala’ trees treated with Dormex® and Erger®, QLD (centre tree was sprayed, surrounding trees are untreated).

There was no measurable reduction in the variability of fruit maturity (as assessed by looking at colour, starch pattern index and fruit weight) at harvest with any of the sprays (data not shown), despite the significant effect of the treatments on compaction of flowering at some sites. Similar results were observed by Bound and Jones (2004) who found no consistent trends in impacts on fruit quality with the use of Dormex® even though significant compaction of the flowering period was observed.

Based on the finding that an extended flowering period increases the variability of fruit size at harvest (Petri and Leite 2004), it was hypothesised in this study that a reduction in the spread of flowering would result in a reduction in the spread of maturity, potentially reducing the number of picks and increasing the percentage of fruit picked at optimum maturity.

Failure to observe an improvement in variability could be the result of a number of factors. Firstly, the small experimental scale. Up-scaling the experiment to rows or blocks of trees would provide more scope for identifying differences in fruit variability and potential for improving harvest management. Secondly, other influences impacting on fruit quality may have overshadowed any effects of the more uniform flowering. Factors such as position in the canopy, shading, leaf area associated with individual fruit development and age of wood bearing the fruit, have all been shown to impact on mineral content and quality (Volz et al. 1994).

Cost-benefit analysis

A full cost-benefit analysis was not undertaken here as the size of the study did not enable sufficient collection of data for meaningful analysis of dollar value, however the broad costs and benefits are outlined in **Error! Reference source not found.**

Table 7. Outline of cost and benefits associated with the use of dormancy-breaking sprays to manage low winter chill years in apple.

| | |
|-----------------|---|
| Costs | Direct costs |
| | Product purchase. |
| | Labour to apply product. |
| | Tractor and associated costs to perform one spray during the dormant period. |
| | Potential indirect costs |
| | Inappropriate application timing could result in anything from nil benefit to significant bud damage, resulting in negative impacts on pollination and fruit set. |
| | Human health impacts from inappropriate handling and use of some dormancy-breaking products. |
| Benefits | More compact and uniform flowering resulting in improved efficiency of chemical thinning and management of flowering pests. |
| | More compact flowering potentially resulting in more uniform fruit maturity throughout the canopy and therefore shorter harvest duration (saving on labour costs) and improvements in fruit quality. Also likely to be benefits for the effectiveness of pest and disease management and efficacy of plant growth regulators, such as ReTain®, to manage harvest. |
| | Benefits would be greater in low chill years when the potential impacts of inadequate chill on flowering are greatest. Benefits are likely to increase under future warmer climate scenarios. |
| | Earlier flowering and harvest time: market-price benefits in some cases. |
| | Benefits are likely to vary with cultivar, and block (for example tree structure may effect impact of dormancy-breaking sprays on fruit quality). |

Conclusions

The dormancy-breaking sprays assessed in this study were able to advance flowering time and compact the flowering period in 'Gala' apple, with differences observed between products and sites. A more compact and uniform flowering period has a number of benefits including improved management of bee hives, flowering pests and chemical thinning practices.

Despite the compaction of flowering, there were no clear differences observed in fruit set, yield or variability of apple maturity in trees treated with dormancy-breaking sprays. More work is required to test the potential of these products to improve fruit quality and reduce the length of harvest. Advances in harvest timing were observed with the dormancy-breakers and generally reflected differences in flowering dates. The ability to manipulate harvest timing can be useful in situations where advantage can be taken of a high-price market window.

Dormex® had the most significant impacts on 'Gala' flowering and harvest timing in WA and QLD, when compared with Waiken™ and Erger®. However, Dormex® is considerably more toxic to humans than either Waiken™ or Erger®, and has greater capacity to cause phytotoxicity (Bound and Miller 2006). It has been noted in other studies that a significant advantage of using non-toxic dormancy-breaking products such as Waiken™, is greater flexibility with the timing of application. The product can be applied later in the season (up to when some buds are showing green) without causing damage to buds (Bound and Miller 2006).

Application timing of dormancy-breaking sprays relative to green tip, previous winter chill accumulation and temperatures received after spraying, had considerable impact on product efficacy in this study. As a consequence, flowering responses are likely to vary between seasons and it is important to consider the flowering time of polliniser cultivars to ensure flowering overlap so that fruit set is not affected.

The overarching research question posed at the outset of this study was: *are dormancy-breaking sprays a feasible adaptation option for the Australian apple industry to low chill years in current and future climates?* Results have indicated that dormancy-breaking sprays are likely to be an effective tool for managing flowering in 'Gala' in lower chill years in Australian growing conditions. It seems reasonable to broaden this conclusion to other apple cultivars, when considered in the context of results from previously published research in 'Fuji', 'Granny Smith', 'Cripps Pink' and 'Cripps Red' (Bound and Jones 2004, Bound and Miller 2006, Petri et al. 2014, Erez 2000), However significant research gaps still remain.

How effective will dormancy-breaking sprays be as an adaptation for the Australian apple industry to the climate change in the longer term? Or to phrase the question another way, when will the winter chill received in an orchard fall too far below the chilling requirement for even the use of dormancy-breaking sprays to enable economic production? Only a proportion of the chilling requirement can be compensated for by the use of dormancy-breaking sprays (Faust et al. 1997), but the size of this proportion is unclear. It has been suggested that up to 30% of the chilling requirement can be compensated for with dormancy-breaking sprays (Erez 1995), however compensation closer to 45% has been demonstrated in stone fruit (George et al. 2002).

A global study to investigate the limits of profitable apple production with regards to winter chill would provide valuable information for the Australian industry in climate change adaptation planning. Production areas with very low winter chill accumulation in South Africa and Southern Brazil rely heavily on dormancy-breakers and would be obvious target locations for this research.

A more accurate method for determining dormancy-breaking spray timing is required to improve the consistency and predictability of the flowering response. Difficulties in estimating the green tip date has potential to reduce the product efficacy and cause bud damage in the worst cases. Faust et al.

(1997) suggested that dormancy-breakers are only effective when sprayed during the 's-endodormancy' phase of dormancy, and not before (Figure 8). A biological marker is required to determine when buds are at this stage and therefore responsive to dormancy-breaking sprays. Biochemical changes in water status, cell membrane composition, hormone production and anabolic potential have been identified in buds as they progress through the stages of dormancy (Faust et al. 1997) and could potentially be used as markers of dormancy status. Incidentally, the use of tetrazolium staining (Carvalho et al. 2010) as a simple tool to monitor the status of bud dormancy in apples was assessed as part of this study, but could not reliably track the shift from dormancy to bud burst (data not shown).

The mechanism by which dormancy-breaking sprays act to promote bud burst, particularly in the case of Dormex®, remains unclear. Vergara et al. (2012) suggested that a respiratory stress may be involved in the release of buds from dormancy, and Melke (2015) concluded that oxygen starvation was involved in the dormancy breaking mechanism when applying oils. Understanding the mode of action would enable the development of products with greater efficacy and safety.

The Australian pistachio industry has recommended winter oil application in low chill years to advance bud burst. The recommendation states that winter oil be applied if 57 Chill Portions have not been reached by 15 August (Zhang and Taylor 2011). Defined guidelines for apple varieties on the use of dormancy-breaking sprays are likely to be some way off due to a lack of understanding around cultivar chilling requirements. Investigations should be undertaken, however, into the possibility of determining broad guidelines based on current knowledge.

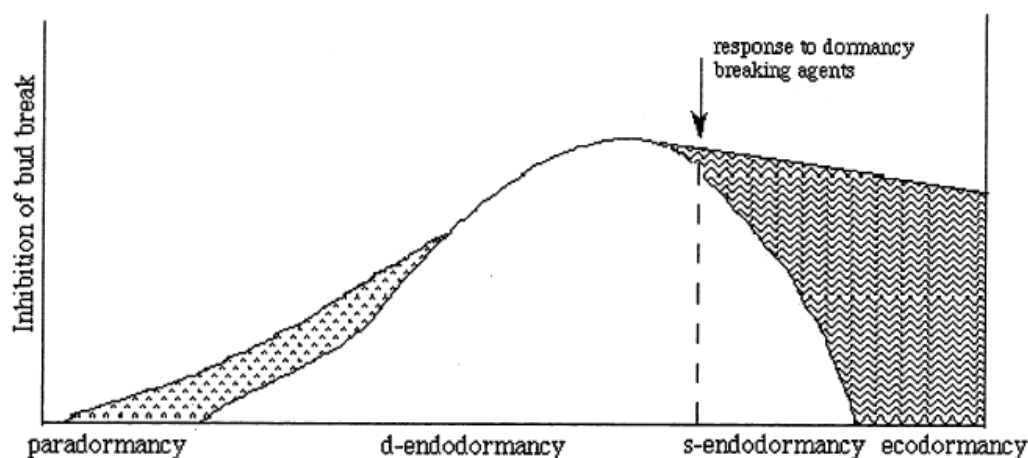


Figure 8. A schematic representation of the progression of buds through dormancy, showing the point at which buds become responsive to the action of dormancy-breaking sprays (Faust et al. 1997).

Key messages

- Dormancy-breaking sprays are likely to be an effective tool for managing flowering in 'Gala', and other apple cultivars, in lower chill years in Australia.
- Impacts of dormancy-breaking sprays on fruit quality and length of the harvest window remain unclear.
- Benefits from the use of dormancy-breakers are likely to be greater in low chill years when the potential impacts of inadequate chill on flowering are greatest. Therefore, benefits are likely to increase under future warmer climate scenarios.
- Dormex®, Waiken™ and Erger® were able to advance flowering time and compact the flowering period in 'Gala' apple, with differences observed between products and sites. Compact and uniform flowering period has benefits for improved management of bee hives, flowering pests and chemical thinning practices.
- Fruit maturity was advanced with dormancy-breakers, with differences observed between products and sites, and generally reflected differences in flowering dates. The ability to manipulate harvest timing can be useful in situations where advantage can be taken of a high-price market window.
- There were no differences in fruit set, yield or variability of apple maturity in trees treated with dormancy-breaking sprays despite the compaction of flowering.
- Dormex® had the most significant impacts on 'Gala' flowering and harvest timing in WA and QLD, when compared with Waiken™ and Erger®.
- The timing of spray application relative to green tip, previous winter chill accumulation and temperatures received after spraying, impacts the bud burst and flowering response to dormancy-breaking products.
- Flowering responses are likely to vary between seasons, cultivars and blocks.
- Flowering time of polliniser cultivars needs to be considered to ensure flowering overlaps so that fruit set is not affected.

Recommendations

- The timing of dormancy-breaking spray application should be carefully considered as inappropriate timing could result in anything from nil benefit to significant bud damage, resulting in negative impacts on pollination and fruit set.
- Application timing should be determined using historical green tip and winter chill records, together with monitoring of in-season chill accumulation. Historical and up-to-date in-season winter chill information will be available from the Australian winter chill website (to be released in March 2017).
- Investigations should be undertaken into the possibility of determining broad guidelines around for the use of dormancy-breaking sprays to manage low chill years in cultivars of apple, based on existing knowledge. Such guidelines should include information on when dormancy-breaking sprays should be used, and in which cultivars and regions.
- Potential benefits of dormancy-breaking sprays on variability of fruit maturity and the length of the harvest window remain unclear. Further research is required to investigate how these products might be used to improve fruit quality and harvest efficiency, particularly in cultivars requiring multiple picks.

- Investigations into alternatives to Dormex® are required. Current research suggests that this product remains the most efficacious dormancy-breaker available in Australia, but its mammalian health impacts may result in de-registration in the future. Research is required to determine the mode of action of Dormex® to enable development of dormancy-breaking products with greater efficacy and safety.
- In considering potential for adaptation to warmer winters, Australian apple growers need to know when the winter chill received in their orchard will fall too far below the chilling requirement for dormancy-breaking sprays to enable economic production of each cultivar. Further research at both the basic and applied levels would be required to provide these guidelines.
- A global study to investigate the limits of profitable apple production with regards to winter chill would provide valuable information for the Australian industry in climate change adaptation planning. Production areas with very low winter chill accumulation in South Africa and Southern Brazil rely heavily on dormancy-breakers and would be obvious target locations for this research.
- Basic research is necessary to identify a biological marker of bud progression through dormancy to facilitate optimal timing for dormancy-breaking spray application.
- Further research to develop phenology models of bud burst timing for apple cultivars is required to enable more accurate estimations of green tip date.

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Appendices

1. Phenology Data Collection Protocols
2. Bud damage scale

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Appendix 1

PHENOLOGY DATA COLLECTION PROTOCOLS

1.1 Phenology Data

Phenology assessments will be performed to determine 5% green tip (apple) and full bloom (80% open flowers) dates for apple varieties. Regular visual assessments (Monday, Wednesday and Friday) will be made from just prior to budburst until flowering is completed. Assessments will be performed on a whole tree basis with only spur and terminal buds and spur and terminal flower clusters assessed (axillary buds on one-year-old pome fruit shoots are not included in the assessments).

1.2 Apple Phenology Collection Methods

Select five trees to monitor for each variety and rootstock (where applicable) under investigation.

Green tip:

- Prior to green tip, count the number of buds (spur and terminal) on one of the five selected trees and record.
- Compare the remaining four trees and estimate up or down the number of buds on each tree. If there is an obvious variation to the counted tree, perform a full count.
- Estimate green tip percentages by counting all buds at the green tip stage. The initial bud count will inform this. For instance if the tree has 500 buds, 25 buds at green tip will indicate the tree is at 5%.
- After the tree has reached 5% green tip, make one more visit to ensure the observation was correct.

Flowering:

- Once flowering commences, initially record the number of open flowers up to 50. This will be easier than calculating small percentages.
- Count the number of flower clusters on one tree. Similarly to the bud count, estimate the number of clusters on the remaining four trees and make adjustments up or down for differences between the trees.
- To estimate flowering percentage, count the number of full clusters open by estimating across clusters. For instance, if two clusters have half the flowers open that equates to one full cluster. Estimate percentage open based on total cluster number previously recorded.
- For very large trees (flower clusters greater than 1000), additional estimates may need to be made to account for the size of the tree. Follow the above

protocol for three representative branches (similar cluster distribution up the branch as the tree) on each tree rather than the whole tree.

- If the tree is less than 50% bloom, counting the number of open clusters will be easiest. If more than 50% of flowers are open, counting the number yet to bloom will be easier.
- As a general rule, round estimates to the nearest 5%.

1.3 Recording Phenology Data

An Excel based data collection pro forma has been developed to ensure data is recorded consistently between sites. Attachment A is an example of the data recording sheet.

Attachment A: Data Recording Template for Phenology Data Collection

| Date | Comments | Tree 1 | | | | Tree 2 | | | | Tree 3 | | | | Tree 4 | | | | Tree 5 | | | |
|------------|---|--------|----|----|----|--------|----|----|----|--------|----|----|----|--------|----|----|----|--------|----|----|----|
| | | %GT | FF | #F | %F | %GT | FF | #F | %F | %GT | FF | #F | %F | %GT | FF | #F | %F | %GT | FF | #F | %F |
| 27/08/2012 | overall - trees are 'dormant', buds are fuzzy/at silver tip | 0 | | | | 0 | | | | 0 | | | | 0 | | | | 0 | | | |
| 29/08/2012 | | 0 | | | | 0 | | | | 5 | | | | 5 | | | | 10 | | | |
| 31/08/2012 | | 10 | | | | 5 | | | | 10 | | | | 10 | | | | 10 | | | |
| 4/09/2012 | | 10 | | | | 25 | | | | 20 | | | | 20 | | | | 15 | | | |
| 7/09/2012 | | | | | | | | | | | | | | | | | | | | | |
| 10/09/2012 | | | | | | | | | | | | | | | | | | | | | |
| 12/09/2012 | | | | | | | | | | | | | | | | | | | | | |
| 14/09/2012 | | | | | | | FF | 1 | | | FF | 3 | | | | | | | FF | 1 | |
| 17/09/2012 | | | | | | | | 2 | | | | 9 | | | FF | 2 | | | | 7 | |
| 19/09/2012 | | | FF | 2 | | | | 12 | | | | 20 | | | | 6 | | | | 17 | |
| 21/09/2012 | | | | 33 | | | | 30 | | | | 34 | | | | 18 | | | | 30 | |

Note: Sample data is for demonstration only

%GT: Approximate percentage of the tree showing green tip

FF: First flower appearance

#F: number of flowers on the tree (up to approximately 50)

%F: Approximate percentage of the tree in flower

Bud damage scale

Scale

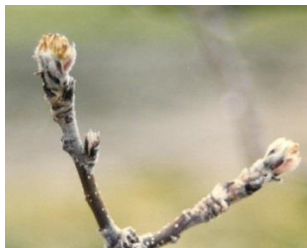
0

No damage



1

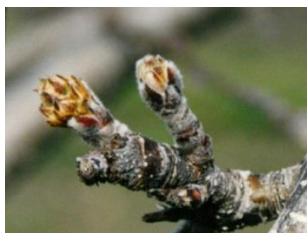
Mild burning



Mild burning of bud scales, but buds normally recover

2

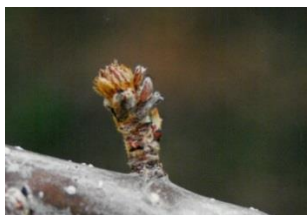
Moderate damage



Buds likely to develop, but some flowers too burnt to open; some flowers undamaged

3

Severe burning



Buds do not develop, usually results in bud death



Sun damage risk of Royal Gala apple in fruit-growing districts in Australia

R Darbyshire, L McClymont & I Goodwin

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RESEARCH ARTICLE

Sun damage risk of Royal Gala apple in fruit-growing districts in Australia

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This study estimated minimum air temperatures for potential sun damage for sunburn browning (non-netted and netted) and sunburn necrosis (non-netted) for Royal Gala apple in Australia. The approach estimated when conditions may be conducive to the development of sun damage in some fruit. The approach provides a measure of potential damage. This allows for more flexible analyses of potential sun damage which current models are unable to produce due to data limitations. The air temperature thresholds determined were 34.1 and 38.7 °C, respectively, for browning and necrosis for non-netted fruit and 37.9 °C for browning under netting. These air temperature thresholds were applied across southern Australia from 1911–2013 demonstrating different risk profiles between sites, inter-annual variability and the benefit of installing netting via a reduction in potential damage days. The results can be further extended to estimate impacts from climate change and assess the benefit of installing netting to adapt to increasingly extreme hot weather.

Keywords: browning; necrosis; shade net; sunburn; sunscald

Introduction

Sun damage in apple occurs as the result of exposure to high radiation loads (Schrader et al. 2003a,b) and can reduce market yield by downgrading quality and increasing cullage. Regions with summers characterised by clear skies and high temperatures, such as southern Australia, have high sun damage risk. A heat wave event in January 2009 in the Goulburn Valley in southeast Australia provides an example with large yield losses incurred due to sun damage, approximated at 30%–70% (Thomson et al. 2014).

Sun damage can manifest in many forms. Sunburn necrosis (henceforth referred to as necrosis) appears as a dark penetrative burn and is a thermal response with a fruit surface temperature (FST) of 52 ± 1 °C for 10 min sufficient to induce necrosis of several apple varieties including Gala (Schrader et al. 2001). Sunburn browning (henceforth referred to as browning) is characterised by a

yellow, brown, bronze or dark tan spot on the sun-exposed side of the fruit (Schrader et al. 2003a; Racsko & Schrader 2012) and results from a combination of high FST and light exposure. For attached Gala apples fully exposed to sunlight on a clear day, Schrader et al. (2001) reported a threshold FST of 47.8 °C for browning damage when FST was maintained at constant temperature for 60 min.

In the context of future climate change and associated rising summertime temperatures, increased risk of sunburn damage is highly likely. Predictions regarding changes to sun damage risk and evaluation of adaptation options are therefore important for future planning. This is particularly pertinent for Australia. Currently, in many of Australia's pome fruit-growing regions, extreme heat events are common with incidences of extreme heat days increasing historically (Alexander et al. 2007). Further, it is expected that such events will continue to increase in both frequency and severity

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due to anthropogenically induced climate change (Alexander & Arblaster 2009). Given the backdrop of increasingly extreme climate conditions, this research aimed to develop potential sun damage incidences for Royal Gala apple using air temperature information for netted and non-netted fruit.

Few studies have scaled up analyses of sun damage beyond the experimental unit due to complexities in determining precise climate and growing conditions that lead to sunburn damage on individual fruit. Schrader et al. (2003b) considered the influence of several factors on FST including air temperature, radiation, wind speed and relative humidity. Of these, air temperature was found to be most highly correlated to FST. In a predictive model developed later, Schrader (2014) added cultivar, fruit diameter and canopy density as additional factors that influence the FST of apple.

Developing a method to use air temperature as a proxy for potential sun damage provides a flexible platform for broader analyses both temporally and spatially. Daily maximum temperatures are commonly recorded by meteorological organisations and are available for long historical periods and with large spatial coverage. Other climate variables, such as relative humidity, are much less available. Furthermore, climate projection information for temperature is more reliable and readily available than for other climate variables (CSIRO 2007). Restrictions in the application of an existing FST model (Schrader 2014) due to data availability are already apparent (Racsko & Schrader 2012), supporting the need for a simplified but considered approach.

The objective of this study was to identify air temperature thresholds that have the potential to lead to sunburn damage. To determine these thresholds, two aspects must be known. First, the FST threshold that induces damage: for this study, Royal Gala apple was used and threshold values of 52 °C for necrosis and 47.8 °C for browning were utilised following previous findings (Schrader et al. 2001). Second, estimates of air temperatures required to reach FST thresholds need to be determined. This aspect is the focus of this study.

Materials and methods

Fruit surface temperature data

Two adjacent Royal Gala apple blocks, one non-netted and one netted, situated at Shepparton (36.42°S, 145.46°E) in southeast Australia (Fig. 1) were used for the experiment. The trees were planted on MM106 rootstock using a central leader trellis system with 2.0 × 4.5 m tree spacing. The experiment was conducted in January 2013. In this region, Royal Gala is usually harvested late January to early February. The nets (Grey Quad 14; NetPro, Stanthorpe, Queensland, Australia) were installed at a height of 6 m above ground with open sides. These nets provided an 18% reduction in incident radiation and are in common use in parts of Australia.

Ten trees in each of the non-netted and netted blocks were selected. Of these, four trees in the non-netted block and five trees (due to some smaller tree sizes) in the netted block were used to measure FST. Thermocouple sensors (Type T thermocouples; Tranzflo NZ, Palmerston North, New Zealand) were placed under the skin of 60 fruit in both the non-netted and netted blocks (i.e. a total of 120 sensors). The sensors were distributed across the selected trees such that 20 sensors were located in each of the upper, middle and

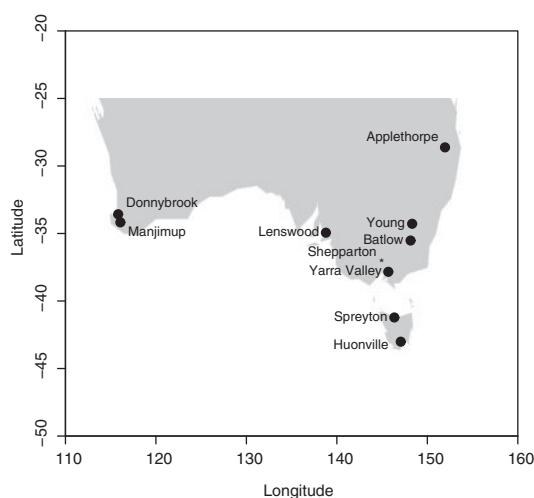


Figure 1 Spatial area investigated and sites used for analyses. * marks the study site for observations (Shepparton).

lower parts of the canopy for both the netted and non-netted blocks. Sensors were positioned towards the western side of the tree to increase the likelihood of reaching FST damage thresholds. FST was logged at 1 min intervals (CR1000; Campbell Scientific, Logan, Utah, USA). Average air temperatures were concurrently measured (HMP155; Vaisala, Vantaa, Finland) and logged at 1 min intervals (Datataker DT80M; Thermo Fisher Scientific, Yokohama, Japan) in both the non-netted and netted blocks. Air temperature sensors were shielded and positioned 1.5 m above the ground surface. Both FST and air temperature data were logged from 8–29 January 2013.

Observations of sun damage were conducted for fruit on the 10 trees in the non-netted and netted blocks. Damage was classified at harvest, between 24 January and 4 February 2013, as browning or necrosis, following descriptions by Schrader et al. (2003a).

Air temperature threshold analysis

A conservative approach was taken to determine minimum air temperature thresholds for potential sun damage. Air temperatures at FST for browning (47.8 °C) and necrosis (52 °C) thresholds (Schrader et al. 2001) were initially extracted for fruit in the non-netted and netted blocks. To accommodate FST that did not fall precisely on the threshold value, a buffer of +0.2 °C was applied. Specifically, air temperatures for FST between 47.8–48.0 °C

and 52.0–52.2 °C were extracted to represent browning and necrosis, respectively.

The 10th percentile of the air temperatures at these FST threshold ranges was then calculated. This value was used to represent the minimum air temperature threshold required for fruit to reach an FST that can cause damage, i.e. a conservatively low air temperature threshold that can cause sun damage. It was assumed that at the 10th percentile, other conditions that moderate damage were acting to increase the potential of damage rather than dampen. For instance, low wind conditions. This was performed for browning and necrosis FST thresholds and for non-netted and netted data.

Spatial analysis

Analysis of the total number of days in January where daily maximum temperatures crossed the minimum air temperature threshold for potential damage was conducted using historical spatial gridded data (0.05 × 0.05 °) for southern Australia from 1911–2013, sourced from the Australian Bureau of Meteorology. These surfaces were produced through a combination of empirical interpolation and function fitting applied to Australia’s network of quality controlled weather stations (Jones et al. 2009). Within the spatial data sets, 10 locations situated in important Australian pome fruit-growing districts were identified for individual site analyses (Fig. 1 and Table 1).

Table 1 Location information. January maximum temperature data (1911–2013) calculated using AWAP data set.

| Location | Latitude (°S) | Longitude (°E) | Mean January maximum temperature (°C) | SD January maximum temperature (°C) |
|--------------|---------------|----------------|---------------------------------------|-------------------------------------|
| Applethorpe | 28.62 | 151.95 | 26.3 | 3.4 |
| Batlow | 35.52 | 148.14 | 26.1 | 4.5 |
| Donnybrook | 33.58 | 115.83 | 30.2 | 4.5 |
| Huonville | 43.01 | 147.06 | 21.9 | 4.4 |
| Lenswood | 34.94 | 138.79 | 25.4 | 5.8 |
| Manjimup | 34.18 | 116.07 | 27.4 | 4.7 |
| Spreyton | 41.22 | 146.35 | 21.0 | 2.6 |
| Shepparton | 36.33 | 145.40 | 29.4 | 5.0 |
| Yarra Valley | 37.84 | 145.68 | 25.2 | 5.5 |

AWAP, Australian Water Availability Project; SD, standard deviation.

Across the historical data set, variation in the total number of potential sun damage days in January was assessed for southern Australia. Differences in the number of potential damage days between non-netted and netted results were compared.

Results

Air temperature thresholds

Prior to analysis, exploration of FST data from the 120 fruit was conducted. Fruit were inspected every 2–3 days to ensure that the sensors were in place. In the event that a sensor had dislodged, the sensor was reinstalled and the data for that sensor was removed back to the time of the previous inspection. Results from one thermocouple in the lower canopy from the non-netted block were excluded due to readings consistent with regular wetting from an irrigation emitter. The numbers of data points available for analysis were 1,330,588 and 1,587,606 for non-netted and netted fruit, respectively.

Using these data, air temperatures as related to FST for non-netted and netted fruit were considered (Fig. 2). A close relationship between FST and air temperatures can be seen for cooler air

temperatures. At higher FSTs, greater variation in air temperatures was observed, that is, a widening of the air temperature range at a particular FST.

Non-netted and netted air temperatures that related to necrosis (52.0–52.2 °C) and browning (47.8–48.0 °C) FST thresholds were extracted. The distribution of air temperatures along these FST thresholds are shown in Fig. 3. No fruit recorded an FST above 52 °C under netting (Fig. 2) and hence no estimates of air temperature thresholds were evaluated for necrosis damage under netting.

The 10th percentile of the extracted air temperatures was calculated, providing a minimum air temperature threshold at which sun damage may occur. For browning in the non-netted and netted blocks these values were 34.1 and 37.9 °C, respectively. For non-netted necrosis damage, the air temperature threshold was 38.7 °C.

In January 2013 at Shepparton, each of the air temperature thresholds for potential damage was surpassed several times (Table 2). Note that the five necrosis damage days were also incorporated in the potential browning days as the browning threshold must be surpassed to reach the necrosis threshold. In comparing the total potential for damage between netted and non-netted fruit, the relative risk of damage under netting was 54% of that for the non-netted fruit.

Observations of sun damage at the study site recorded differences between non-netted and netted trees (Table 3) with lower levels of damage recorded for fruit under netting (Table 3). A 50% reduction of damage was found for fruit under netting.

Historical potential damage analysis

To further investigate the number of potential sun damage days historically and to provide visualisation of risk across Australia's pome fruit-growing regions, the air temperature thresholds (Table 2) were applied to southern Australia (Fig. 4). Increasing risk is observed from the south of the country to the north. A lowering of risk along the eastern seaboard reflects the higher elevation in that part of Australia. Notable variation across the historical data set was found (panels left to right in Fig. 4),

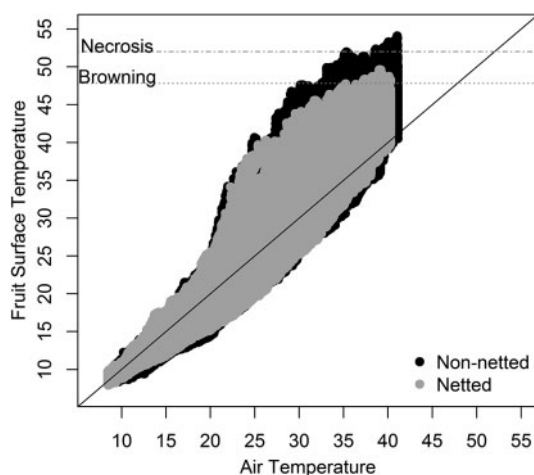


Figure 2 Fruit surface temperature (°C) recordings and related air temperatures (°C). Necrosis and browning FST thresholds represent 52 and 47.8 °C, respectively.

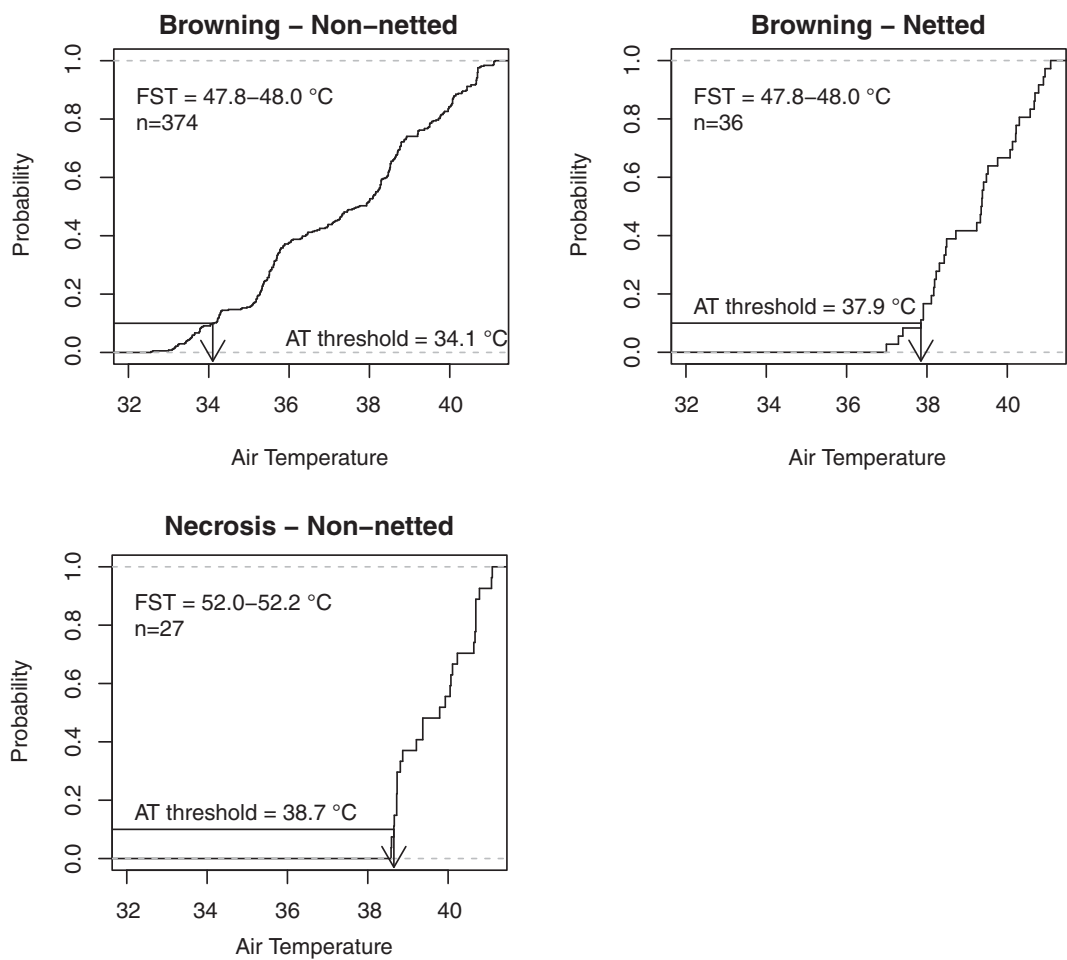


Figure 3 Air temperature (AT) for FST, which relates to browning in the open and under nets and for necrosis in the open. The 10th percentile of the AT data is shown by the arrow. n = sample size.

representing the inter-annual variability in the number of potential damage days in January.

The percentile levels can be taken to represent different risk likelihoods, assuming the climate data are sourced from a normal distribution. In this analysis, the 10th and the 90th percentiles represent the low and high ends of the distribution of the data while the 50th percentile is the median. For example, the 10th percentile value was 2 days for browning in the non-netted orchard at Shepparton (Table 4). This can be interpreted as a 1 in 10 year event that 2 or fewer damage days will be experienced. Equally, this indicates there is a 9 in 10

year chance of 2 or more damage days occurring. Using the upper end of the distribution, the 90th percentile, indicates that receiving 12 or more damage days is a 1 in 10 year event.

Locations in cooler regions (Huonville, Spreyton, Applethorpe, Batlow) rarely crossed the air temperature thresholds required for potential sun damage. The data indicate that none of these cooler sites recorded a day above the air temperature threshold for browning under netting or necrosis for non-netted fruit even at the 90th percentile of the data. Batlow did record 4 days in January that may lead to browning in non-netted blocks at the

Table 2 Summary of total number of days for which daily maximum temperature exceeded each air temperature threshold for potential damage in January 2013 at Shepparton.

| Damage | Air temperature threshold (°C) | Number of days in January 2013 |
|-----------------------|--------------------------------|--------------------------------|
| Browning (non-netted) | 34.1 | 13 |
| Browning (netted) | 37.9 | 7 |
| Necrosis (non-netted) | 38.7 | 5 |

Table 3 Percentage of fruit affected by sun damage for non-netted and netted fruit harvest from 10 trees each.

| | Browning (%) | Necrosis (%) | Total (%) |
|------------|--------------|--------------|-----------|
| Non-netted | 13.0 | 3.0 | 16.0 |
| Netted | 8.1 | 0.1 | 8.1 |

90th percentile, which can be translated as a 1 in 10 year event.

Conversely, other pome fruit-growing regions recorded consistent potential for sun damage. For instance, Donnybrook, Shepparton and Young all recorded potential damage days for browning in non-netted blocks for each percentile level. This can be interpreted, for Donnybrook, as a 9 in 10 chance of at least 3 days in January reaching temperatures that could lead to browning of non-netted fruit.

The wide range in potential damage days at some sites demonstrates strong inter-annual variability in the historical data. For instance, at Shepparton it can be expected that 2–12 days (capturing 80% of the historical data) in January could lead to browning damage for non-netted fruit.

The benefit of netting in terms of reducing the total number of potential damage days for browning is shown in Fig. 5. Note, this was not considered for necrosis as an air temperature threshold for necrosis under netting could not be defined.

Again variability is present with a minimal benefit noted in some years (10th percentile), whereas other years indicated great benefit (90th percentile).

The benefit of netting is clear when individual sites within Australia's fruit-growing regions were considered (Table 5). For sites with few instances of potential browning, these episodes were reduced to nil with netting (Batlow, Huonville). For locations with greater potential for browning damage, substantial decreases in the total number of potential damage days recorded (Young, Donnybrook, Shepparton). For these sites, particularly notable gains for the more extreme of the historical data (90th percentile) were found (Table 5).

Discussion

Using previously established FST thresholds for Gala apple (Schrader et al. 2001), air temperatures that relate to potential browning and necrosis damage for non-netted and netted fruit were recorded at a site in southeastern Australia. A wide range of air temperatures were found at the specified FST thresholds (Figs 2–3). This range in air temperatures for a given FST was expected and represents a combination of different factors. These include different microclimate conditions surrounding the fruit such as fluxes in relative humidity and wind speed, variation in radiation received due to fruit positioning and leaf shading, and fruit characteristics such as size.

Appreciating this variability in air temperature for a given FST, this study estimated minimum air temperature thresholds for potential damage. This was achieved by taking the 10th percentile of air temperatures at two FST thresholds that represent browning and necrosis. By taking this approach it was assumed that other climate effects and fruit characteristics were combining to cause damage at these lower air temperatures. Therefore, the air temperature thresholds determined were conservatively low and are indicative of when damage may begin to occur on some fruit, primarily the more vulnerable fruit. The air temperature thresholds calculated should not be regarded as deterministic or a reflection of damage for a particular fruit or for all fruit in the orchard. Rather, the

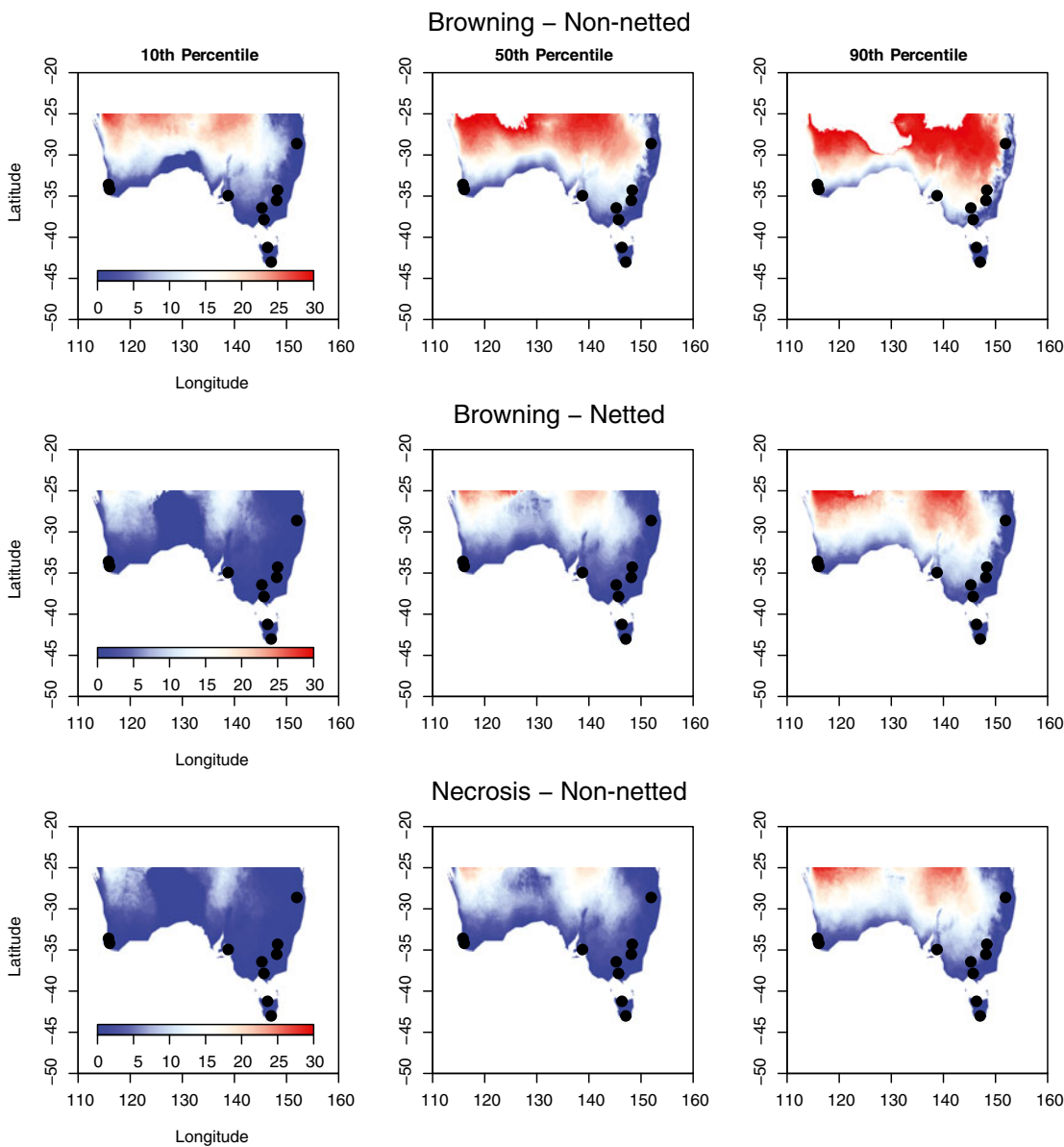


Figure 4 Number of potential sun damage days in January for browning non-netted, browning netted and necrosis non-netted air temperature thresholds. The 10th, 50th and 90th percentiles of the data (1911–2013) are displayed left to right. The colour-bar legend is measured in number of days.

thresholds are an indication of minimum air temperatures at which sun damage may begin to develop.

Analyses of the minimum air temperature thresholds were expanded across southern Australia for

1911–2013 to demonstrate the flexibility of the approach. Spatial patterns in the number of days of potential damage follow a north-south gradient and vary with topography. These analyses provide insight into relative sun damage risk in opening of

Table 4 Distribution of potential damage days in January for sites in Australia's growing regions for 10th, 50th and 90th percentiles of the data.

| Site | Browning, non-netted | | | Browning, netted | | | Necrosis, non-netted | | |
|--------------|----------------------|------|------|------------------|------|------|----------------------|------|------|
| | 10th | 50th | 90th | 10th | 50th | 90th | 10th | 50th | 90th |
| Spreyton | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Huonville | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Applethorpe | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 |
| Batlow | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Yarra Valley | 0 | 2 | 5 | 0 | 0 | 1 | 0 | 0 | 1 |
| Manjimup | 0 | 3 | 5 | 0 | 0 | 2 | 0 | 0 | 1 |
| Lenswood | 0 | 3 | 6 | 0 | 0 | 2 | 0 | 0 | 1 |
| Young | 1 | 7 | 16 | 0 | 1 | 5 | 0 | 0.5 | 4 |
| Shepparton | 2 | 6 | 12 | 0 | 1 | 5 | 0 | 1 | 4 |
| Donnybrook | 3 | 7 | 11 | 0 | 1 | 3 | 0 | 0.5 | 2 |

new areas for production or shifts in varietal mixes at established growing regions.

For selected fruit-growing regions, it was found that some sites are more exposed to potential sun damage risk than others. This was expected, with cooler regions (Spreyton, Huonville, Applethorpe) illustrating very little risk. For warmer regions (Donnybrook, Shepparton, Young), greater potential risk—that is, total number of potential damage days—was accompanied by substantial inter-annual variability. Considering potential browning for non-netted fruit at Young, there is a 1 in 10 year chance that 16 days or more in January will be

conducive to browning (90th percentile), equally there is a 1 in 10 year chance of 1 day or less in January being conducive to browning (10th percentile). Managing this variability in potential risk is important to maintain yield and quality.

These broader analyses, both historically and spatially, illustrate the flexibility for investigative analyses of sun damage using the air temperature thresholds determined to estimate conditions that are conducive to damage. This approach overcomes the data access limitations of more detailed models that require greater data inputs (Thorpe 1974; Evans 2004; Schrader 2014). The methods

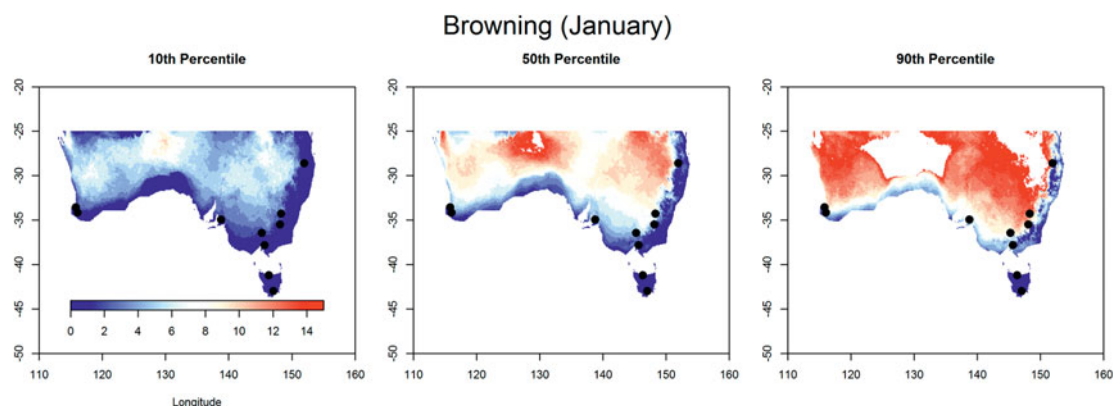
**Figure 5** Reduction in the number of potential browning damage days for January across 1911–2013 due to netting. The colour-bar legend is measured in number of days.

Table 5 Difference in total number of potential browning days between open and netted fruit. Bracketed is the percentage reduction from open values.

| Site | 10th percentile | 50th percentile | 90th percentile |
|--------------|-----------------|-----------------|-----------------|
| Spreyton | 0 (NA) | 0 (NA) | 0 (NA) |
| Huonville | 0 (NA) | 0 (NA) | 1 (100%) |
| Applethorpe | 0 (NA) | 0 (NA) | 1 (53%) |
| Batlow | 0 (NA) | 0 (NA) | 4 (100%) |
| Yarra Valley | 0 (NA) | 2 (100%) | 4 (80%) |
| Manjimup | 0 (NA) | 2 (67%) | 4 (80%) |
| Lenswood | 0 (NA) | 2 (67%) | 5 (83%) |
| Young | 1 (100%) | 5 (71%) | 11 (68%) |
| Shepparton | 2 (85%) | 4 (67%) | 7 (60%) |
| Donnybrook | 2 (67%) | 5 (71%) | 9 (82%) |

NA indicates no browning events for fruit in the open.

used here prioritised generalisation rather than specificity. As such, only general remarks about changes in potential conditions for damage can be made. To interpret damage to individual fruit, use of multivariate models is still required.

These thresholds could be used to consider the risk of sunburn damage under future climates as only maximum temperatures are required to estimate conditions that may lead to damage. Assessments considering netted and non-netted thresholds could be conducted to highlight any increasing protection offered by shade netting. Note this would only be possible for browning damage as this study was unable to determine a necrosis air temperature threshold as fruit did not reach the required FST for damage. Finally, the air temperature thresholds can be used by growers as a guide for when to use overhead sprinklers for evaporative cooling in efforts to minimise potential damage.

These results have illustrated the benefit of shade netting in lowering sun damage risk (Table 5 and Fig. 5). Previous investigations have shown that shade nets are effective in decreasing sun damage by reducing incident solar radiation (Iglesias & Alegre 2006; Gindaba & Wand 2008). In this study, a reduction in the number of days of potential browning was quantified across Australia (Fig. 5). Using Young as an example, a decrease of 1–11 days of potential damage (for 80% of the

historical data) was found, reducing the number of potential damage days by 68%–100%.

This benefit of netting needs to be balanced against other possible drawbacks. For instance, Do Amarante et al. (2011) found a reduction in red coloration and lower firmness values of Royal Gala under netting. Changes to management practices, such as use of reflective mulch, would assist in combating some of these implications. An important limitation of installing netting is the expense. In Australia, the initial capital cost of erecting netting has been estimated at AU\$40,000 per hectare (Lolicato 2011). For sites with minimal reduction in sun damage with the installation of netting (Applethorpe, Batlow), investing in netting may not be practical, although the other benefits that netting provides, such as a reduction in hail and bird damage, should be considered in decision-making processes.

Assessments of sun damage rates on the experimental trees (Table 3) provide support for the air temperature thresholds. Using the estimated air temperature thresholds, it was determined that for January 2013 there were 13 and 7 days (Table 2) with potential for damage for non-netted and netted fruit, respectively. Therefore the potential for damage under the nets was predicted to be 46% lower than for non-netted fruit. This was broadly supported in the damage assessments, with a 50% reduction found in browning of fruit under nets. Other effects may have influenced the observed damage rates, including temperatures experienced during December, which were not included in the analysis. Additionally, the total predicted potential damage days may have identified individual days as damage days that did not lead to any observed fruit damage. As damage assessments occurred at harvest, this cannot be determined.

In interpreting these results, appreciation of the assumptions in the methodology is needed. FST thresholds used in this study were determined in North America (Schrader et al. 2003b). Higher ultraviolet radiation conditions are experienced in Australia compared with the northern hemisphere due to lower ozone protection. For this reason, the transferability of FST thresholds between hemispheres was questioned by Racsko & Schrader

(2012). Further research following Schrader et al. (2003b) is required to assess if there are differences in FST thresholds between the northern and southern hemispheres.

In order to extend the results of this study, the air temperature threshold values found for Shepparton were expanded across southern Australia. Other sites may have weather conditions that combine differently than those at Shepparton to determine FST. The conservative approach taken here should act to minimise potential underestimates of damage rates with field observations needed for verification of transferability of these air thresholds.

Conclusion

This study determined the minimum air temperature thresholds that represent potential for sun damage for Royal Gala apple in non-netted (browning and necrosis) and netted (browning) blocks. Results were constructed using a conservative approach indicating when damage may start to occur for some fruit in the orchard. Application of the approach spatially and temporally was demonstrated, providing historical context for sunburn damage risk and assessment of relative risk between locations. Such an analysis has not been previously possible due to data limitations of more detailed sun damage models. The protection offered by netting was interpreted and the relative benefits of installation demonstrated. Using the methods in this study to determine air temperature thresholds, further research is possible including expansion to other varieties, assessments of climate change impacts and the use of shade netting as an adaptation strategy.

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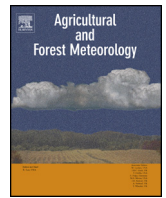
Disclosure statement

No potential conflict of interest was reported by the authors.

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How hail netting reduces apple fruit surface temperature: A microclimate and modelling study

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ABSTRACT

High fruit temperatures compromise fruit quality and cause production losses in the apple industry. In south-eastern Australia, orchardists have begun investing in netting because of empirical evidence that it reduces these losses, but the magnitude of its effect and mechanisms responsible have not yet been quantified. Models of fruit temperature based on meteorological conditions could inform the design of netting structures, and improve tactical management to reduce sun damage through treatments such as protective sprays and the use of overhead irrigation to cool fruit. The objectives of this study were firstly to measure the effect of netting on fruit surface temperature, and secondly to test the thermodynamic Smart-Sinclair model. The study was conducted near Shepparton, Victoria, in an orchard where there were adjacent netted and non-netted sections. During late afternoon when sun damage normally occurs, netting was able to reduce the median fruit surface temperature by 1.5–2.0 °C, but there was a greater reduction in maximum fruit surface temperature of 4.0 °C. The model required calibration to account for turbulence in the transfer of heat from fruit to the surrounding air. The optimised model was able to predict fruit surface temperature with a root mean square error of 2–4 °C. The mechanism for the reduction in fruit surface temperature was by reducing the intensity of the solar beam in the late afternoon by interception and scattering, which more than offset the potential fruit heating effect of netting that occurs through a reduction in internal orchard wind speed.

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1. Introduction

Fruit exposed to high temperatures while growing on the tree suffers reduced quality, particularly in apples (*Malus domestica* (L.)). Reports from South Africa, USA, Australia and New Zealand suggest that pack-house culls of 10% could be expected in typical seasons (Bergh et al., 1980; Schrader et al., 2004; Wünsche et al., 2001) but losses can be much higher as these estimates do not include severely damaged fruit that is not picked. In Australia, apple growers estimate typical losses to vary from 6 to 30%, depending on season and fruit variety (Lolicato, 2011). Following some years of high losses, orchardists have begun investing in netting

as a risk reduction strategy because of empirical evidence that it reduces these losses, but the magnitude of its effect and mechanisms responsible have not yet been quantified.

Schrader et al. (2003) identified fruit surface temperature thresholds at which two types of damage occurs. At a threshold of between 46 and 49 °C sunburn browning occurs, which consists of discolouration of the sun-exposed peel that reduces the saleability and storage life of the fruit. The threshold is cultivar-dependent, and requires a combination of both high temperatures and solar radiation. Protecting fruit from exposure to ultraviolet radiation greatly reduces the occurrence of sunburn browning (Schrader, 2011). At a threshold of 52 °C sunburn necrosis occurs, in which epidermal and subepidermal cells die leaving a necrotic spot on the sun-exposed side of the fruit. This type of damage can occur in the absence of solar radiation if the temperature threshold is reached. Fruit surface temperatures are dependent not only on the air temperature, but also solar radiation that heats the sun-exposed fruit surface, and wind that removes heat from the surface. Under conditions of high solar radiation and low wind speeds, the sun-exposed

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surface of fruit can be up to 15 °C warmer than air temperature (Schrader et al., 2003).

Several thermodynamic models have been developed to calculate temperatures in spherical fruit such as apples. Internally, these models use similar parameters and equations. Thorpe (1974) described a thermodynamic model of apple surface temperature, which included the effects of solar radiation, wind and the conduction of heat to the shaded side of the fruit. This model developed further by Smart and Sinclair (1976), who presented a series of equations that solve for the temperature of the most sun-exposed surface of spherical fruit, known as the “hot-spot”. Since excessive hot-spot temperatures are sufficient to downgrade the entire apple, this is the most useful parameter to model. Later, Evans (2004) described a model that calculated the surface temperature of apples under evaporative cooling. Sauderau et al. (2007) presented a 3-dimensional model that calculated temperatures at all parts of ellipsoid fruit. Cola et al. (2009) described a model of grape temperature, which was validated at several sites in Italy, while Li et al. (2014) built on previous models and tested it on apples in Washington State, USA. Apart from Cola et al. (2009) and Li et al. (2014), these models have only had limited field validation, and none have been tested under netting. Potential uses of a validated model include both tactical and strategic management. Tactically, fruit surface temperature could be calculated from numerical weather forecasts so protective sprays can be applied prior to heat events, or evaporative cooling used when fruit surface temperature reaches a damage threshold. Strategically, the value of investment in infrastructure, such as netting or evaporative cooling systems, could be investigated with consideration of future climate change scenarios.

The objectives of this study were firstly to measure the effect of hail netting on fruit surface temperature and orchard microclimate, secondly to test the thermodynamic Smart-Sinclair model, and thirdly to quantify the mechanisms by which netting reduces sun damage.

2. Material and methods

Briefly, fruit surface temperatures were measured in adjacent netted and non-netted areas of a commercial orchard. Simulated fruit surface temperature was calculated using a modified version of the thermodynamic model developed by Smart and Sinclair (1976) using either microclimate measurements taken within the orchard, or surrogates derived from standard weather data measured external to the orchard. Table 1 summarises parameters used in the model and symbols used in this paper.

2.1. Field measurements

Fruit surface temperatures of Royal Gala apples were monitored at two sites (“netted” and “non-netted”) within a commercial orchard located north of Shepparton Australia. The majority of the orchard was covered by permanent hail netting, except for five rows in the eastern side. The netting (Grey Quad 14, NetPro Pty Ltd, Stanthorpe, Qld, Australia) had a 10% shade rating and was installed 6 m above the ground with open sides. We refer to the product as “hail netting” because its primary purpose is to protect from hail, and to distinguish it from shade-cloth that has shade ratings of 16–80% (NetPro, 2010). Fruit surface temperatures were monitored from 8 January 2013 until the first fruit were harvested on 24 January 2013. At each site, 60 fruit were selected from 4 trees; 20 fruit were in the upper canopy, 20 in the middle and 20 in the lower canopy. Monitored fruit were selected from fruit on the western sides of trees that would be exposed to direct radiation in the afternoon, in the expectation that maximum daily fruit surface temperatures normally occur in the mid-afternoon between 1430 and 1645 h

(Schrader et al., 2003). Copper-constantan thermocouples (Type T, Tranzflo NZ Ltd, Palmerston North, New Zealand) were inserted under the fruit skin on the sun-exposed face. Data were logged by four data loggers (CR1000, Campbell Scientific, Logan, Utah, USA), at each site at 1 min intervals. The target of 60 monitored fruit was sometimes not achieved because of datalogger difficulties, some sensors becoming dislodged from the fruit and because two loggers were not installed until 15 January. On the 2 hottest days (for which detailed data are reported later in the paper), 44 fruit were monitored under netting and 38 in the non-netted orchard on 11 January, while the equivalent numbers were 59 and 58 respectively on 17 January. The diameters of the monitored fruit were recorded on 11, 16 and 23 January 2013. Fruit were harvested, counted and weighted between 24 January and 4 February 2013 from 10 trees each in the netted and non-netted sites including the 4 trees logged for temperature. Fruit harvested from the 4 trees logged for temperature were visually assessed for sunburn damage. Damage was classified as (i) minor sunburn browning, (ii) major sunburn browning, (iii) necrosis, or (iv) photo-oxidative sunburn (Racsko and Schrader, 2012).

The microclimate was monitored at the netted and non-netted sites and data logged (DataTaker DT80M, Thermo Fisher Scientific Inc., Yokohama, Japan) at 1 min intervals. Air temperature (T_{air} , °C) and humidity (HMP155, Vaisala Oyj, Vantaa, Finland) were measured at 1.5 m height with the sensor mounted in a cylindrical white aluminium screen. Wind speed (v , m/s) was measured by cup anemometers (PA2 Wittich and Visser, Rijswijk, Netherlands) in the lower, middle and upper canopy at heights of 1, 2, and 3 m. Diffuse and total radiation (R_{df} and R_s , W/m²) and ultraviolet-B (UV-B, W/m², 280–315 nm) were monitored above the canopy at 3 m height (SPN1, Delta T Devices, Cambridge, UK; SKU430, Skye Instruments, Llandrindod, Wales). Adjacent to the orchard the external environment was logged (6004C-21 STARLOG; Unidata, O'Connor, Australia) at 10 min intervals. Humidity and T_{air} (HMP 45A-T, Vaisala, Oyj, Vantaa, Finland) were measured at 1.5 m height with the sensor mounted in a cylindrical white aluminium screen. A cup anemometer (Wind sensor compact, Thies Clima, Gottingen, Germany) was used to measure v at 2 m height. Data from the external weather station were only available 8–29 January, whereas data from the orchard weather stations were available 1–31 January. Potential evapotranspiration (ET_o , mm) was calculated on a 10 min timestep from weather data measured in the netted and non-netted orchards by the FAO56 equations of Allen et al. (1998).

At both the netted and non-netted sites, trees were irrigated by microjet sprinklers spaced midway between trees and approximately 0.3 m above the soil surface. Trees were 1.5 m apart trained on a central leader system in rows 4.8 m apart, and rows were oriented NNW-SSE (345°). Tree age, variety, rootstock and management did not differ between the netted and non-netted sites, with the exception of increased irrigation flow rates in the non-netted area. All management activities (irrigation, fertilisation, and weed and pest control) were undertaken by staff of the commercial orchard.

2.2. Fruit temperature modelling

Smart and Sinclair (1976) proposed the following algebraic solution to calculate the instantaneous temperature increment above T_{air} on the sun-exposed surface of the fruit (ΔT_{max} , °C) as

$$\Delta T_{max} = \frac{I_0(1 - \alpha)(k_s + 4h.r)}{(r.h + k_s)4h} \quad (1)$$

where I_0 is incident solar radiation received by a fruit surface perpendicular to the solar beam (W/m²), α the reflectance of the fruit surface (albedo), k_s the thermal conductivity of the fruit (W/(m °C)), h the heat transfer coefficient from the fruit surface to the atmo-

Table 1

Symbols used in this paper, and source of the values used.

| Symbol | Units | Explanation | Values/source |
|------------------|-----------------------|--|--|
| α | Unitless fraction | Reflectance of the fruit surface | 0.4, Merzlyak et al. (2003) |
| d | Days | Day number (1 Jan = 1) | Calculated |
| d_r | Relative units | Relative inverse distance between the earth and sun (range 0.967–1.033) | Calculated according to equation 23 of Allen et al. (1998) |
| D | m | Fruit diameter | Measured |
| δ | m | Thickness of the boundary layer of still air at the fruit surface | Equation 5 of this paper, based on Nobel (1975) |
| ET_o | mm | Potential evapotranspiration | Calculated according to Equation 6 of Allen et al. (1998) |
| f | Unitless factor | Calibration factor | Fitted |
| G_{sc} | W/m ² | Solar constant | 1367 W/m ² , Allen et al. (1998) |
| h | W/(m ² °C) | Heat transfer coefficient | Equation 5b of Smart and Sinclair (1976) |
| I_o | W/m ² | Solar radiation received on a fruit surface normal to the solar beam | Equation 2 of this paper, based on Smart and Sinclair (1976) |
| k_a | W/(m °C) | Thermal conductivity of air, 2.55 W/(m °C) | Smart and Sinclair (1976) |
| k_s | W/(m °C) | Thermal conductivity of the fruit | Equation 9 of Smart and Sinclair (1976) |
| r | m | Fruit radius | Measured |
| R_a | W/m ² | Extraterrestrial solar radiation on a plane horizontal to the earth's surface | Calculated by equation 28 of Allen et al. (1998) |
| R_s | W/m ² | Total solar radiation measured on a plane horizontal to the earth's surface | Measured |
| R_{df} | W/m ² | Indirect solar radiation measured on a plane horizontal to the earth's surface | Measured |
| R_{UVB} | W/m ² | Solar radiation in the ultraviolet-B band, 280–315 nm | Measured |
| T_{air} | °C | Air temperature | Measured |
| $T_{fr, mx}$ | °C | Temperature of the hottest face of sun-exposed fruit in the orchard | Measured |
| ΔT_{max} | °C | Difference between fruit surface temperature and air temperature | Calculated from measurements and equation 1 of Smart and Sinclair (1976) |
| v | m/s | Wind speed | Measured |
| z_d | degrees | Zenith angle of the sun (degrees from vertical) | Calculated according to Jacobson (2005) |
| z_r | radians | Zenith angle of the sun (radians from vertical) | Calculated according to Jacobson (2005) |

sphere (W/(m² °C)), and r the radius of the fruit (m). In our study, I_o was calculated as

$$I_o = G_{sc} d_r \frac{R_s - R_{df}}{R_a} + R_{df} / 2 \quad (2)$$

where G_{sc} (W/m²) is the solar constant, d_r the inverse relative distance between the earth and the sun, R_s total radiation measured above the canopy on a horizontal plane, R_a (W/m²) extra-terrestrial radiation on a horizontal plane, and R_{df} diffuse radiation measured on a horizontal plane above the canopy. In Eq. (2) it is assumed that the sunlit fruit face was exposed to only half the R_{df} measured on a horizontal plane ([Smart and Sinclair, 1976](#)). The terms G_{sc} , d_r and R_a were calculated according to [Allen et al. \(1998\)](#). Reflectance (α) was set at 0.4 based on data from [Merzlyak et al. \(2003\)](#), who reported a range from 0.35 for dark red fruit to 0.45 for pale fruit. Thermal conductivity of fruit (k_s) is related to apple temperature and was calculated as

$$k_s = 0.297 + 0.0024 T_{fr, mx} \quad (3)$$

based on [Lisowa et al. \(2002\)](#), where $T_{fr, mx}$ is the temperature of the hottest face of sun-exposed fruit in the orchard calculated in the previous iteration (see Eq. (7) below). The heat transfer coefficient h was calculated as

$$h = \frac{k_a}{\delta} + 2k_a / D \quad (4)$$

where k_a is the thermal conductivity of the air 0.0257 W/(m² °C), δ the thickness of the boundary layer of still air at the surface of the hot-spot of the fruit (m), and D the fruit diameter (m); δ was estimated from v and D by an equation based on [Nobel \(1975\)](#),

$$\delta = f \left(0.28 \sqrt{\frac{D}{v}} + \frac{2.5}{v} \right) \quad (5)$$

where f is a calibration factor. Values of v were set to a minimum value of 0.5 m/s to avoid division by zero. D was calculated from measurements of fruit diameter interpolated by a linear regression relationship between measurement dates,

$$D = \frac{(57.84 + 0.2133d)}{100} \quad (6)$$

where d is the day number (1 January = 1). Preliminary runs of the model indicated that without a calibration factor, δ was too high resulting in insufficient heat transfer from the fruit surface to the surrounding air, and simulated fruit surface temperatures were much higher than observed. The model was calibrated using a range of values of f from 0.1 to 1.0 in increments of 0.05, and calculating the root mean square error (RMSE) of differences between calculated fruit surface temperatures and the maximum fruit surface temperature in each 10 min period. The optimum value of f was that with the lowest RMSE. A similar approach was used by [Cola et al. \(2009\)](#) in calibrating aerodynamic roughness to measured fruit temperature in grapevines from wind speeds measured at a weather station external to the vineyard. Separate values of f were sought for the netted and non-netted sites, with v measured either at 3 m height within each orchard or at the weather station external to the orchard. The first half of the data set from 9 to 15 January 2013 was used for model calibration, and the remaining data was used for validation. Since the monitored fruit were only exposed to the afternoon sun, only data from 1400 to 1700 h were used for calibration and validation.

The temperature of the hottest face of sun-exposed fruit in the orchard ($T_{fr, mx}$, °C) was then calculated as

$$T_{fr, mx} = \Delta T_{max} + T_{air} \quad (7)$$

where T_{air} (°C) is the measured air temperature, and ΔT_{max} the simulated difference between air temperature and fruit surface temperature. Calculations were performed on a 10 min timestep,

Table 2

Harvested yield, fruit weight and sunburn damage from the netted and non-netted sites in the orchard, and the statistical significance of differences.

| | Netted | Non-netted | Significance |
|---------------------------------------|--------|------------|--------------|
| Total fruit yield (t/ha) | 34.6 | 37.3 | 0.564 |
| Fruit weight (g/fruit) | 153 | 125 | <0.001 |
| Minor sunburn browning (% by weight) | 7.7 | 10.4 | 0.014 |
| Major sunburn browning (% by weight) | 0.4 | 2.6 | 0.007 |
| Necrosis (% by weight) | 0.1 | 3.0 | 0.003 |
| Photo-oxidative sunburn (% by weight) | 0.2 | 0.7 | 0.135 |
| Total damage (% by weight) | 8.3 | 16.7 | 0.002 |
| Yield of undamaged fruit (t/ha) | 31.7 | 31.1 | 0.282 |

but final output was calculated as a moving average of the previous 30 min to compensate for the lack of thermal mass in the equations.

2.3. Supplementary site

To test its structure and calibration, modelled $T_{fr, mx}$ was compared with measurements taken at a supplementary site east of Shepparton. Measurements were made in a commercial Royal Gala orchard without netting, in which trees were planted at 2.5 m spacing in rows 5.0 m apart and irrigated at the tree base by microjet sprinklers. This site was part of a larger study of evaporative cooling (Green et al., 2011), and data reported here are for 3 apples without cooling on the north-west side near the top of the canopy where protective foliage had been removed. Copper-constantan thermocouples were inserted beneath the north-west facing surface of sun-exposed apples on 27 January 2011 and temperatures monitored until harvest on 10 February. Temperatures were measured at 10-s intervals and logged (CR1000, Campbell Scientific, Logan, Utah, USA) at a 1-min frequency. Fruit diameter was measured on 25 January and 7 February. In a nearby clearing surrounded by orchards, an automatic weather station recorded air temperature, solar radiation and wind speed at a 2 m height at a 15-min frequency. Solar radiation was measured at 2 m height using a silicon photodiode pyranometer (SK01D; Carter-Scott Design, Brunswick, Australia). PAR was measured at 2 m height using a silicon photodiode quantum sensor (PAR sensor; Tranzflow, Palmerston North, New Zealand). Air temperature and humidity were measured at a 1.5 m height (HMP 45A-T; Vaisala, Vantaa, Finland) mounted in a cylindrical white aluminium screen. Wind speed was measured using a 3-cup anemometer at 2-m height (AN2; Monitor Sensors, Caboolture, Australia). Measurements were taken every 30 s and the average calculated and stored at 15-min intervals in a data logger (DT500; Datataker, Scoresby, Australia). Supplementary wind measurements were also taken from the Irrigation network (<http://awsdata.it.csiro.au:8000/id/station/TATR>). These measurements were taken at a 2 m height on an exposed site at the Tatura Research Station operated by the Department of Economic Development, Jobs, Transport and Resources.

2.4. Statistical analysis

Fruit yield and sunburn damage data from each tree were compared by one-way analysis of variance. Residuals were checked for normality and homogeneity of variance. No transformations were required on any of the variables. Solar radiation observations in the netted orchard were compared with the non-netted orchard by means and descriptive linear regression, with a focus on the afternoon (1400–1700 h) when the risk of sun damage is greatest. Data for T_{air} , relative humidity and v from the netted and non-netted orchards were compared with the weather station external to the orchard using a combined linear regression with the site (netted or non-netted) as a factor. This enabled the orchard microclimate to be estimated from weather data external to the orchard.

Since the model requires some non-standard weather data parameters, relationships were sought to predict these from standard parameters. Prediction equations of these non-standard parameters – R_{df} in the non-netted orchard, and both R_{df} and R_s under netting – were sought by linear regression from 10 min weather data collected between 1 and 15 January 2013 using relationships of the form

$$\frac{R_{df}}{R_s} = a + b \frac{R_s}{R_a} + c \frac{1}{AM} + d \left(\frac{R_s}{R_a} \right) \left(\frac{1}{AM} \right); \frac{R_s}{R_a} > e \quad (8)$$

where the coefficients a , b , c , d , and e are derived from the regression, and AM the air mass number, to account for solar angle effects. The R_s/R_a component of this function was based on Spitters et al. (1986), who recommended a series of split line relationships to estimate R_{df}/R_s from R_s/R_a . According to these relationships, under heavy cloud (low R_s/R_a), the proportion of total radiation that is diffuse (R_{df}/R_s) is not influenced by R_s/R_a up to a break point, after which there is a linear relationship with R_s/R_a . The term AM is used in astronomy and the solar power industry to describe the path length of the solar beam in the atmosphere relative to a direct vertical path, and was calculated by an empirical function of Kasten and Young (1989),

$$AM = 1/(\cos z_r + 0.050572(6.07995 + 90 - z_d)^{-1.6364}) \quad (9)$$

where z_r and z_d are the zenith angle of the sun in radians and degrees respectively. The value of AM ranges from close to 1 when the sun is overhead to over 10 at dawn or dusk. The inverse of AM was used in the regression analyses because the attenuation of the solar beam through scattering and absorption would be expected to follow an inverse relationship with path length. Similar effects would be expected as the solar beam passes through netting. To determine parameters, the Genstat split line regression procedure was first used to estimate e independent of AM . This set a break point for the split line relationship, and below this threshold the break point value of R_{df}/R_s was used. Values of R_s/R_a in excess of e were then selected to determine the other parameters using generalised linear regression. A similar approach was used to estimate netted R_s/R_a from non-netted R_s/R_a , but no break point was required. Since the intent was to develop estimates at times of risk of sun damage, input values were constrained to times when R_a exceeded 380 W/m^2 to avoid refractive effects that occur close to dawn and dusk when the sun is near the horizon. This constraint limited data to 0640–1800 h in mid-January. Another required constraint was to remove 10 min periods when R_s exceeded clear-sky radiation, which was assumed to be $0.8 R_a$. These periods occurred when R_s included radiation reflected from clouds, and could at times predict negative values of R_{df} . Statistical analyses were conducted using Genstat (14th Edition, VSN International, Hemel Hempstead, UK). Model predictions were compared with measurements by the root mean square error (RMSE).

2.5. Sensitivity analysis

Sensitivity of the model to its inputs was tested by varying individual parameters by either the range reported in the literature, or for weather parameters the range measured in our study between 1400 and 1700 h. The range for α was from 0.1 (Sauderau et al., 2007) to 0.6 (Evans 2004), k_s from 0.28 to $0.54 \text{ W/(m}^2\text{ }^\circ\text{C)}$ (Smart and Sinclair, 1976; Donsi et al., 1996; Lisowa et al., 2002), v from 0.1 to 3.4 m/s , R_s $60\text{--}1040 \text{ W/m}^2$, R_{df} $50\text{--}580 \text{ W/m}^2$, and T_{air} $15\text{--}42 \text{ }^\circ\text{C}$, while D was varied from 0.049 to 0.080 m based on measurements of individual fruit. The parameters not varied were taken from the time of maximal $T_{fr, mx}$ during the study, which was from the non-netted orchard from 1610 to 1620 h on 17 January 2013.

3. Results

3.1. Sunburn damage and fruit yield

Fruit in the non-netted orchard had twice the rate of sunburn damage as that in the netted orchard (17 vs 8%) (Table 2). The greatest differences were in the major sunburn browning and necrosis categories. Total fruit yield in the non-netted orchard was 8% higher than with netting, but the yield of undamaged fruit was 2% lower. These differences in fruit yield were not statistically significant because of a relatively high coefficient of variation between individual trees of 29%. Fruit harvested from the non-netted orchard were smaller than those with netting (125 vs 153 g).

3.2. Fruit surface temperatures

Measured $T_{fr, mx}$ were up to 14.4 °C higher than T_{air} with netting during the afternoon, and up to 16.7 °C without netting, but at night the differences were small (Fig. 1). The two days with the highest $T_{fr, mx}$ were the 11th of January (a clear day) and the 17th of January (a partly cloudy day). As the days with the greatest risk of sun damage, these were examined in greater detail. The probability distribution of the maximum temperature achieved in each monitored fruit for these days shows that with netting the median temperature was 1.5–2.3 °C cooler with netting than without, but that the maximum temperature was 4.0 °C cooler (Fig. 2). On the clear day (11 January) 45% of non-netted fruit exceeded the threshold of 46 °C at which sunburn browning occurs (Schrader, 2011), compared with only 9% under netting. However, on the partly cloudy day (17 January) the proportions exceeding the threshold were much higher at 79% without netting and 32% with netting. Measured $T_{fr, mx}$ on the clear day showed a broad peak in the late afternoon, whereas on the partly cloudy day there was a series of sharp peaks (Fig. 3). These peaks coincided with short periods of high solar radiation between clouds. The upper quartile of fruit surface temperature peaked late in the afternoon at 1600–1700 h.

3.3. Netted vs non-netted microclimates

Microclimate differences between the netted and non-netted orchards are addressed here, first for the entire month of January, then in greater detail for the two days when the highest fruit surface temperatures were recorded. Averaged across all afternoons in January 2013, the netted orchard had 15% less total radiation than the non-netted orchard, 32% lower UV-B and a 13% lower potential evapotranspiration, but 20% more diffuse radiation (Table 3). For the whole month of January 2013, potential evapotranspiration was also 13% lower under netting than without (159 vs 183 mm/month).

Descriptive linear regressions of radiation parameters during the afternoon between the netted and non-netted orchards showed a high level of correlation, with R^2 values of between 0.881 and 0.987 (Table 3). All slopes and intercepts were statistically significant ($P < 0.001$), indicating that there were significant differences in radiation parameters between the environments.

Table 3
Summary of differences in afternoon radiation and ET_o (1400 and 1700 h Eastern Australian Standard Time) between netted and non-netted environments 1–31 January 2013, compared by their arithmetic mean, and linear regression as $y = a + bx$ where y is the parameter under netting, a the intercept, b the slope, and x the parameter without netting.

| Parameter | Means | | | Regression | | |
|---|--------|------------|----------------|------------|-------|-------|
| | Netted | Non-netted | Difference (%) | Intercept | Slope | R^2 |
| Global radiation (R_s , W/m ²) | 616 | 726 | –15 | –67.7 | 0.941 | 0.982 |
| Diffuse radiation (R_{df} , W/m ²) | 141 | 117 | 20 | 63.1 | 0.666 | 0.881 |
| Ultraviolet radiation-B (UV-B, W/m ²) | 1.26 | 1.84 | –32 | –0.0734 | 0.723 | 0.997 |
| Reference evapotranspiration (ET_o , mm/hr) | 0.47 | 0.54 | –13 | –0.0046 | 0.924 | 0.987 |

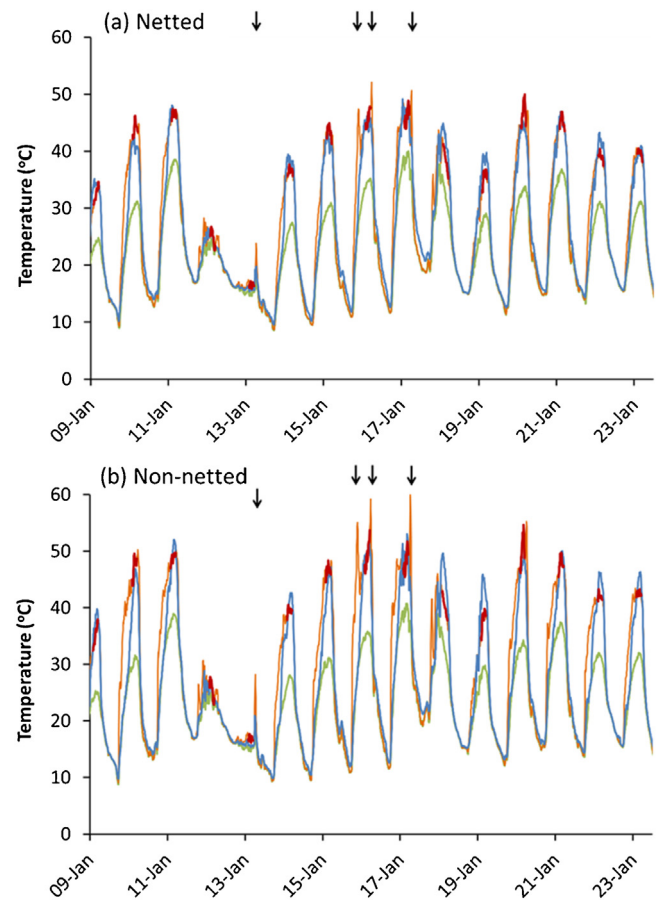


Fig. 1. Measured (blue) and simulated (red and orange) fruit surface temperature of the hottest face of sun-exposed fruit ($T_{fr, mx}$) and orchard air temperature (T_{air}) at (a) netted, and (b) non-netted, with simulated $T_{fr, mx}$ calculated from wind speeds measured external to the orchard. Simulated temperatures are shown in red between 1400 and 1700 h, and orange at other times. Arrows show spikes in simulated values at times of low wind speed and high direct radiation before 1000 and after 1700 h. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the afternoon v at the netted site was lower (22–24%) at a 3 m measurement height, but there were no significant differences in T_{air} (Tables 4 and 5). At night the netted orchard was more humid than the non-netted orchard and had lower v .

Predictive relationships for R_{df} and R_s under netting based on Eq. (8) showed root mean square errors of between 17 and 71 W/m² (Table 6). In each case all the slopes and intercepts were statistically significant ($P < 0.001$). Using these relationships for a theoretical clear day (defined as $R_s/R_a = 0.75$) in mid-January, netting reduced R_s by 10% at 1230 h, but by 20% at 1620 h. Equivalent reductions in I_o were 22% and 26% respectively.

On the clear day, R_s closely followed the pattern of R_a , but on the cloudy day the pattern was spikey with short periods when R_s was up to 13% greater than at the same time on the clear day

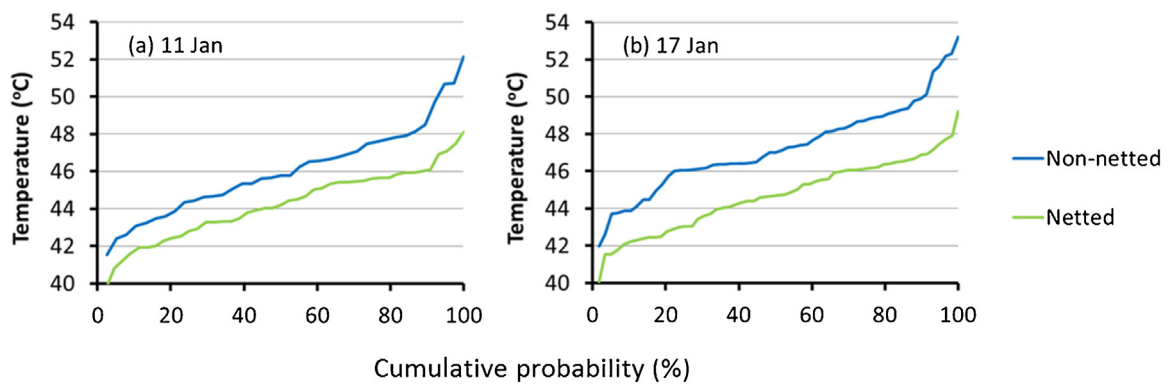


Fig. 2. Cumulative probability distribution of the maximum fruit surface temperature measured in non-netted and netted sections of the orchard on (a) a clear day (11 January 2013) and (b) a partly cloudy day (17 January 2013).

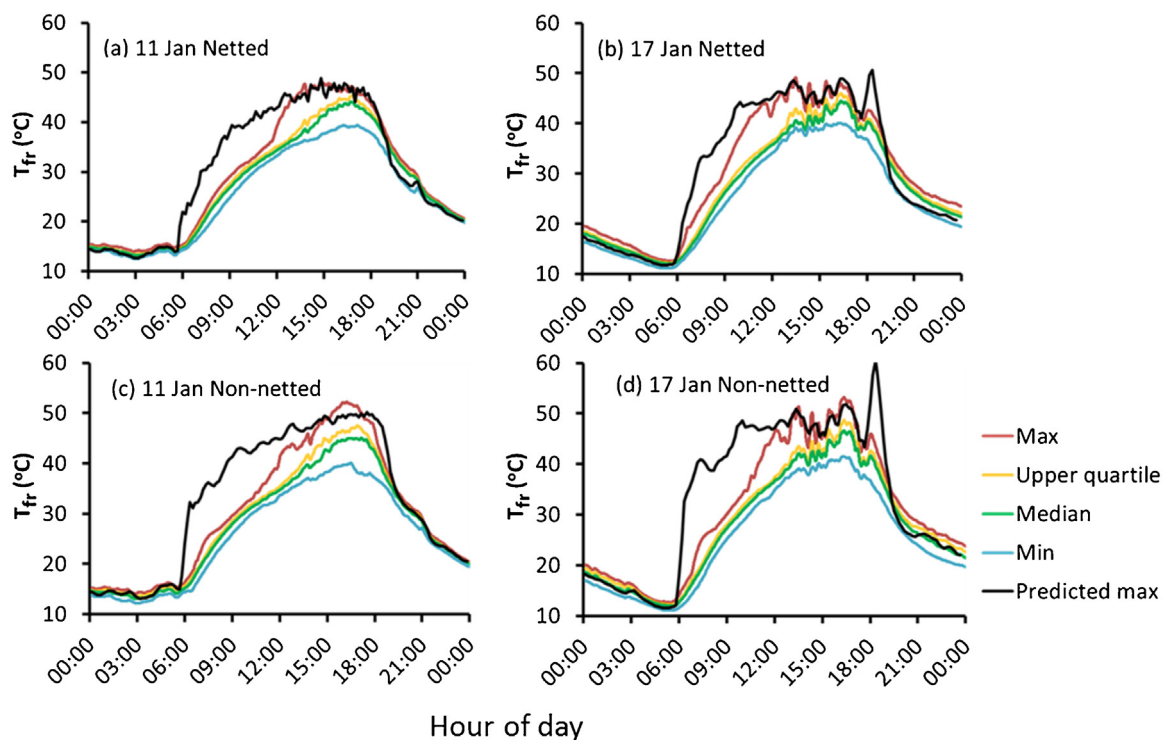


Fig. 3. Fruit surface temperature (T_{fr}) measured in the netted and non-netted sections of the orchard, showing the maximum, upper quartile, median and minimum, and the simulated orchard maximum modelled from weather data according to Eq. (7) for a clear day (11 January) and a partly cloudy day (17 January).

Table 4

Summary of air temperature, humidity and wind speed during afternoons (1400–1700 h Eastern Australian Standard Time) and nights (2000–0500 h) in the netted orchard, non-netted orchard and external environment 8–29 January 2013.

| Parameter | Afternoon | | | Night | | |
|-----------------------|-----------|------------|----------|--------|------------|----------|
| | Netted | Non-netted | External | Netted | Non-netted | External |
| Air temperature (°C) | 31.7 | 32.2 | 30.1 | 17.1 | 17.3 | 17.9 |
| Relative humidity (%) | 29.3 | 27.5 | 26.3 | 69.8 | 66.0 | 62.2 |
| Wind speed (m/s) | | | | | | |
| 3 m | 1.22 | 1.56 | | 0.55 | 0.84 | |
| 2 m | 0.80 | 0.74 | 2.66 | 0.30 | 0.23 | 1.70 |
| 1 m | 0.20 | 0.35 | | 0.04 | 0.06 | |

(Fig. 4). On the clear day without netting about 10% of radiation was in the diffuse form, whereas under netting it was 17%. The percentage of R_s transmitted through the net was similar on both days, and ranged from 89% at midday to about 60% close to dawn or dusk. Estimated I_0 reached a broad maximum around the middle of the day, after which it declined more rapidly under netting than in

the non-netted orchard. At a height of 3 m v was about 20% lower under netting, but there was little difference in T_{air} (Fig. 5). At both sites there were low wind speeds in the evening and night. On 17 January these nearly calm conditions had started by 1725 h. Differences between the netted and non-netted environments close to the time of maximum fruit surface temperature are summarised in

Table 5
Microclimate in the netted and non-netted sites expressed as a linear function of readings at the weather station external to the orchard, where environment (netted or non-netted) was a factor in the analysis. Significance of differences between netted and non-netted in intercept or slope are shown as *** for $P < 0.001$, ** for $P < 0.01$, * for $P < 0.05$, – for $P < 0.1$, ns for not significant.

| | Afternoon (1400–1700 h) | | | Night (2000–0500 h) | | | All hours | | |
|----------------------------|-------------------------|--------|----------------|---------------------|--------|----------------|-----------|--------|----------------|
| | Intercept | Slope | R ² | Intercept | Slope | R ² | Intercept | Slope | R ² |
| Air temperature (°C) | | | | | | | | | |
| Netted | 1.09 | 0.967 | 0.987 | –0.24 | 0.938 | 0.962 | –1.33 | 1.024 | 0.978 |
| Non-netted | 1.58 | 0.968 | | –1.24 | 1.009 | | –1.39 | 1.047 | |
| Difference | 0.49 | 0.001 | | –1.01 | 0.070 | | –0.06 | 0.022 | |
| Significance of difference | – | ns | | *** | *** | | ns | *** | |
| Relative humidity (%) | | | | | | | | | |
| Netted | 6.85 | 0.953 | 0.987 | 10.50 | 0.956 | 0.86 | 7.83 | 0.983 | 0.951 |
| Non-netted | 4.82 | 0.959 | | –0.14 | 1.075 | | 3.44 | 1.003 | |
| Difference | –2.03 | 0.005 | | –10.64 | 0.119 | | –4.39 | 0.020 | |
| Significance of difference | *** | ns | | *** | *** | | *** | *** | |
| Wind speed (m/s) | | | | | | | | | |
| Netted 3 m | –0.12 | 0.477 | 0.912 | –0.18 | 0.468 | 0.918 | –0.18 | 0.476 | 0.917 |
| Non-netted 3 m | –0.18 | 0.627 | | –0.16 | 0.642 | | –0.16 | 0.633 | |
| Difference | –0.05 | 0.150 | | 0.02 | 0.174 | | 0.02 | 0.157 | |
| Significance of difference | ns | *** | | ns | *** | | – | *** | |
| Netted 2 m | –0.24 | 0.370 | 0.824 | –0.18 | 0.307 | 0.832 | –0.21 | 0.337 | 0.800 |
| Non-netted 2 m | –0.02 | 0.254 | | –0.12 | 0.220 | | –0.12 | 0.267 | |
| Difference | 0.23 | –0.116 | | 0.07 | –0.088 | | 0.09 | –0.069 | |
| Significance of difference | *** | *** | | *** | *** | | *** | *** | |
| Netted 1 m | –0.02 | 0.072 | 0.476 | –0.04 | 0.049 | 0.622 | –0.05 | 0.069 | 0.486 |
| Non-netted 1 m | 0.08 | 0.083 | | –0.05 | 0.069 | | –0.05 | 0.105 | |
| Difference | 0.11 | 0.011 | | –0.01 | 0.019 | | 0.00 | 0.036 | |
| Significance of difference | *** | ns | | ** | *** | | ns | *** | |

Table 6
Predictive relationships calculated from the calibration period (1–15 January) based on Eq. (8) to estimate global radiation under netting as a proportion of extraterrestrial (R_s/R_a), diffuse radiation as a proportion of global (R_{df}/R_s) in netted and non-netted environments, and the root mean square error (RMSE) and predictive error of the relationships in estimating R_s and R_{df} between 0700 and 1800 h for the validation period (16–31 January 2013).

| Parameter or coefficient in Eq. (7) | Global radiation as a proportion of extraterrestrial (R_s/R_a) | | Diffuse radiation as a proportion of global radiation (R_{df}/R_s) | |
|--|--|--|--|------------|
| | Netted | | Netted | Non-netted |
| Split line regression | | | | |
| e | | | 0.396 | 0.391 |
| R_{df}/R_s at breakpoint | | | 0.830 | 0.855 |
| No. of observations | | | 1017 | 1017 |
| R^2 | | | 0.918 | 0.932 |
| Generalised linear model | | | | |
| a | 0.049 | | 0.715 | 0.506 |
| b | 0.546 | | –0.507 | –0.391 |
| c | –0.079 | | 1.088 | 1.515 |
| d | 0.400 | | –1.684 | –2.17 |
| No. of observations | 1016 | | 896 | 896 |
| R^2 | 0.982 | | 0.761 | 0.754 |
| Overall relationship (validation period) | | | | |
| RMSE (W/m ²) | 17.1 | | 50.6 | 71.2 |
| Predictive error (W/m ²) | 13.1 | | 24.1 | 35.1 |

Table 7. On both days between 1610 and 1620 h, netting reduced I_0 by 26%.

3.4. Calibration of the model

Without calibration the model consistently over-predicted $T_{fs, mx}$ by an average of 6.6 °C, but the calculated values were highly correlated with measurements ($R^2 = 0.87$; data not shown). To correct this over-prediction, a calibration factor (f) was applied to v (wind speed), because the relationship between wind speed and heat transfer to the atmosphere was the least well-defined component of the model. The model was first fitted to v measured at 3 m height at each site within the orchard. This achieved minimum RMSE's of 2.1 and 2.6 °C (Fig. 6a) for netted and non-netted orchards respectively. Secondly, the model was fitted to measurements of v measured at a height of 2 m external to the orchard, which achieved slightly lower RMSE's (2.0 and 2.3 °C respectively), and optimised

at the same calibration factor for both the netted and non-netted orchards (Fig. 6b). Since the second option fitted the data more closely and could be calculated from wind speeds from external to the orchard, which are more commonly measured than internal orchard wind speeds, this option was used for most simulations reported in this paper.

Measured and simulated $T_{fr, mx}$ showed close agreement on most days during the afternoon between 1400 and 1700 h, but before and after these times there were short term spikes in simulated $T_{fr, mx}$ that were not observed in the measured data (Fig. 1). These spikes occurred before 1000 h and after 1700 h during periods of low wind speed, high direct solar radiation, and a high angle of incidence of the sun's rays ($z_d > 36^\circ$ from zenith before 1000 h, and $z_d > 76^\circ$ after 1700 h).

Simulated and measured $T_{fr, mx}$ were closely matched between 1400 h and 1700 h, when fruit were exposed to direct sunlight (Fig. 3). However simulated temperatures exceeded measurements

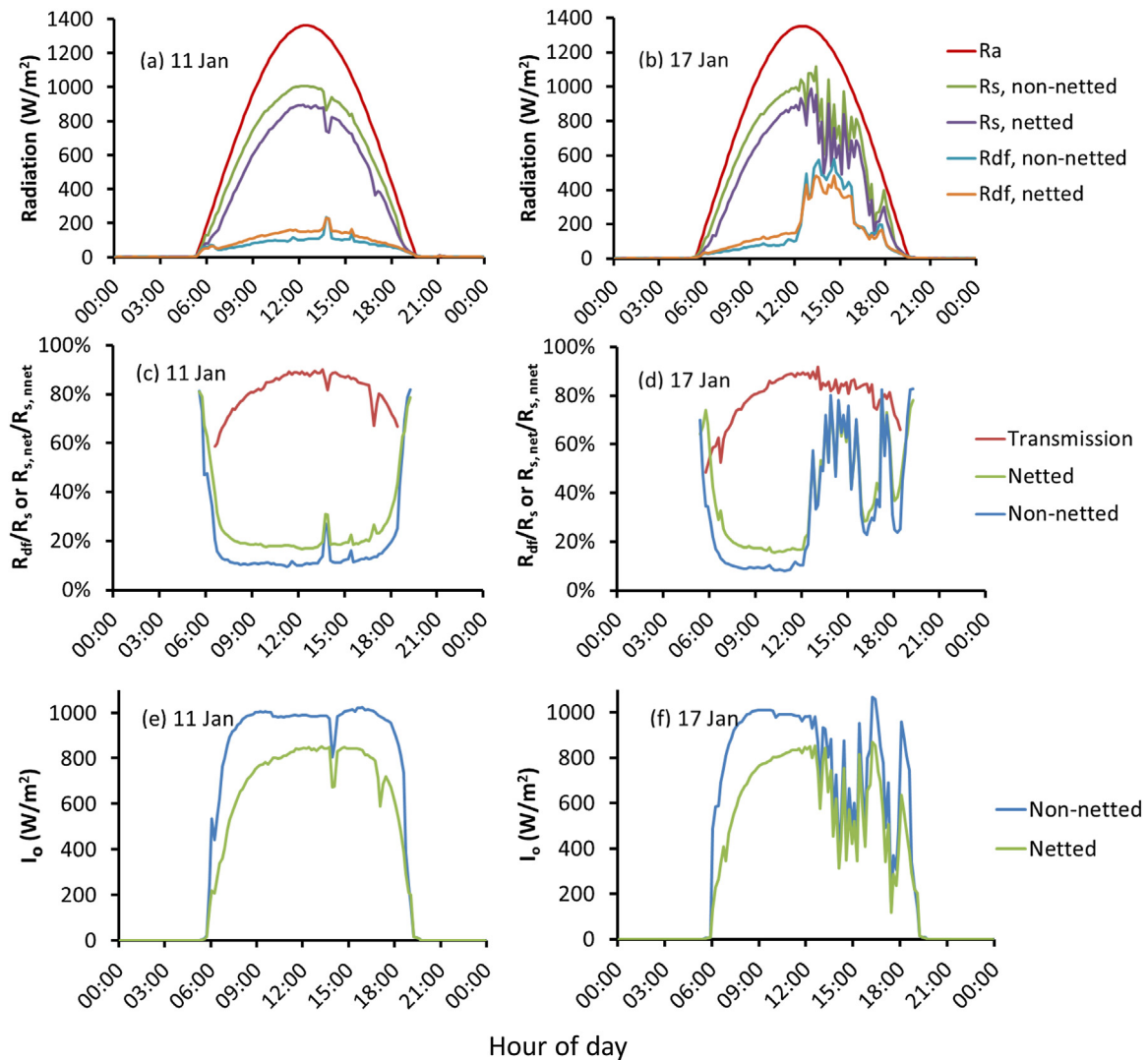


Fig. 4. Solar radiation on a clear day (11 January 2013) and a cloudy day (17 January 2013), showing calculated extraterrestrial radiation (R_a), global radiation measured above the plant canopies of netted and non-netted sites ($R_{s,net}$), and diffuse radiation ($R_{df,net}$ and R_{df}) (a, b). Also shown is the percentage of global radiation recorded above the plant canopy of the non-netted and netted orchards that was in the diffuse form (R_{df}/R_s), the percentage of global radiation that was transmitted through the net ($R_{s,net}/R_{s,net}$) (c, d), and the estimated intensity of the solar energy received on a fruit surface perpendicular to the solar beam (I_o) (e, f).

in the morning and early evening, when the measured fruit were shaded.

3.5. Model validation from standard weather data

Since in-orchard weather data are rarely available for long-term modelling studies, $T_{fr,mx}$ was also calculated for validation purposes from standard weather data using the coefficients in Tables 5 and 6 to estimate T_{air} , R_{df} and R_s in the netted orchard. The external weather station was used for T_{air} and v , but it was assumed that global radiation measured above the canopy at the non-netted site was equivalent to that measured outside the orchard. Using these surrogates there was only a small increase (0.2–0.6 °C) in RMSE relative to in-orchard weather data (Table 8). This applied to both the calibration and validation periods.

3.6. Supplementary site

The model was run using weather data from the supplementary site and compared $T_{fr,mx}$ measured at this site between 1400 and 1700 h (Fig. 7a) ($f = 0.45$, optimised for the main site). The model tended to over-predict early in the data set followed by

under-prediction later, and achieved an overall RMSE of 6.3 °C. Over-prediction occurred on afternoons with low wind speed, and under-prediction on afternoons of high wind speed, a relationship that accounted for 67% of variation (data not shown). Optimising f to this data set reduced the RMSE to 5.7 °C ($f = 0.33$), but there was still a strong relationship between over-prediction or under-prediction and wind speed. The closest fit between predicted and measured was achieved using wind speed data from Tatura, which achieved an RMSE of 3.8 °C ($f = 0.92$) (Fig. 7b).

3.7. Sensitivity analysis

The sensitivity analysis showed that among plant parameters $T_{fr,mx}$ was most strongly affected by α , followed by much smaller effects of D and k_s (Table 9). Among weather parameters $T_{fr,mx}$ was most affected by T_{air} followed by R_s , v and R_{df} . The sensitivity analysis was also used to test the impact of the reduction in v associated with netting and potential offsets. A 25% decrease in v increased fruit surface temperatures by 2.2 °C, but this increase could be offset by either a 16% reduction in total radiation or a 58% increase in the proportion of total radiation in the diffuse form (data not shown).

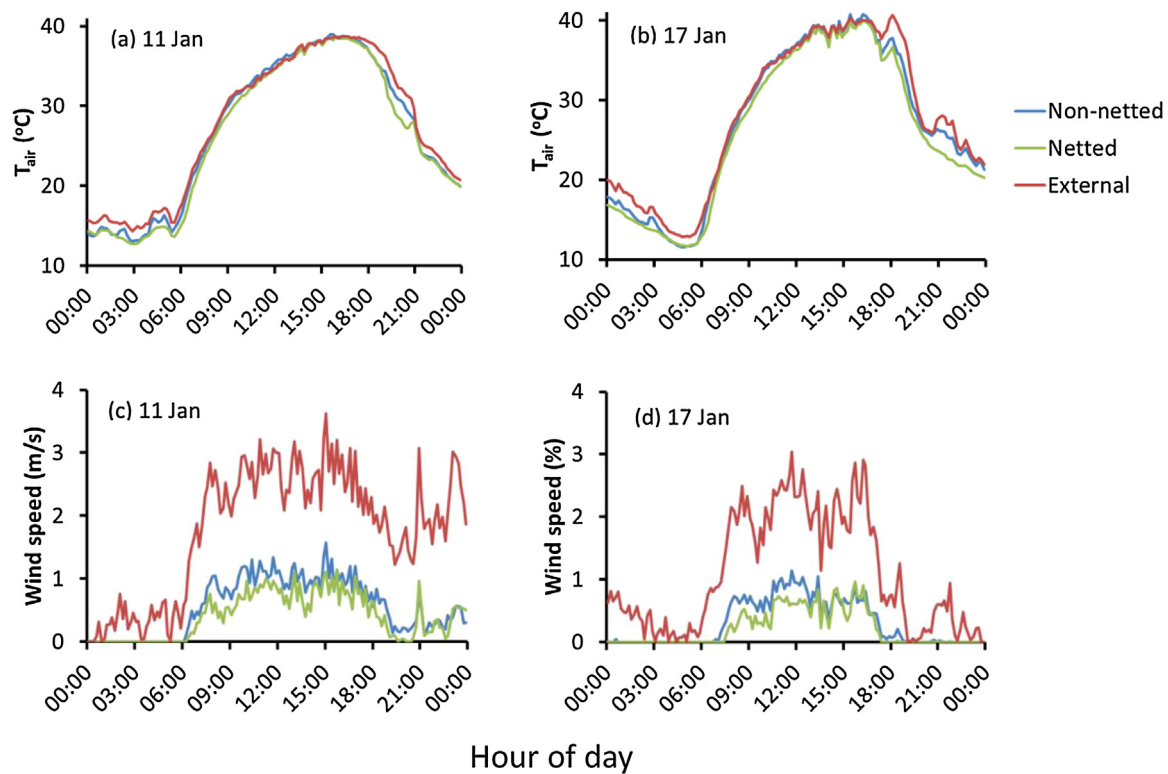


Fig. 5. Air temperature (a, b) and wind speeds (c, d) at the netted and non-netted sites, and at a weather station external to the orchard on 11 and 17 January 2013.

Table 7

Summary of differences between the non-netted and netted environments and external to the orchard close to the time of maximum fruit surface temperature, between 1610 and 1620 on 11 and 17 January 2013. Values are the mean of 1 min readings.

| | 11 Jan (clear day) | | | | 17 Jan (cloudy day) | | | |
|--|--------------------|--------------------|----------------|----------------|---------------------|--------------------|----------------|----------------|
| | External | Non-netted orchard | Netted orchard | Difference (%) | External | Non-netted orchard | Netted orchard | Difference (%) |
| Extraterrestrial radiation, R_a (W/m^2) | 883 | 883 | 883 | | 861 | 861 | 861 | |
| Total measured solar radiation, R_s (W/m^2) | | 679 | 572 | −16 | | 769 | 652 | −15 |
| Diffuse radiation, R_{df} (W/m^2) | | 87 | 114 | 31 | | 175 | 187 | 7 |
| Direct radiation (W/m^2) | | 572 | 425 | −26 | | 592 | 441 | −25 |
| Radiation perpendicular to the sunlit face of fruit, I_o (W/m^2) | | 967 | 749 | −26 | | 971 | 761 | −26 |
| Diffuse radiation relative to global (%) | | 13 | 20 | 56 | | 23 | 29 | 26 |
| Ultraviolet B radiation, UV-B (W/m^2) | | 1.46 | 1.00 | −31 | | 1.58 | 1.04 | −34 |
| Relative humidity (%) | 10 | 13 | 15 | | 10 | 14 | 14 | |
| Wind speed at 3 m (m/s) | | 1.6 | 1.1 | −28 | | 1.2 | 1.3 | 13 |
| Wind speed at 2 m (m/s) | 2.38 | 0.9 | 0.7 | −17 | 2.91 | 0.7 | 0.9 | 37 |
| Wind speed at 1 m (m/s) | | 0.6 | 0.3 | −56 | | 0.4 | 0.2 | −39 |
| Fruit surface temperature (°C) | | | | | | | | |
| Simulated | | 49.6 | 47.2 | −2.4 | | 51.6 | 48.8 | −2.8 |
| Measured maximum | | 52.0 | 46.7 | −5.3 | | 53.1 | 47.9 | −5.2 |
| Measured upper quartile | | 46.3 | 44.7 | −1.7 | | 48.5 | 46.0 | −2.6 |
| Measured median | | 45.0 | 43.7 | −1.3 | | 46.5 | 44.4 | −2.2 |
| Measured lower quartile | | 42.5 | 41.8 | −0.7 | | 45.0 | 42.7 | −2.3 |
| Measured minimum | | 39.9 | 39.3 | −0.6 | | 41.5 | 40.1 | −1.4 |
| Air temperature (°C) | 38.7 | 38.7 | 38.4 | −0.3 | 40 | 40.7 | 40.0 | −0.7 |

4. Discussion

4.1. Fruit damage and yield

A higher fruit yield in the non-netted orchard was offset by a much higher percentage of sunburn damage than in the netted

orchard (17 vs 8%), leading to a 2% reduction in the yield of undamaged fruit. This difference in yield was not statistically significant and would require confirmation through studies with a larger sample size. The 2-fold difference in the percentage of fruit affected by sunburn was consistent with the difference in the percentage of monitored fruit that exceeded the sunburn browning threshold of

Table 8

Root mean square error ($^{\circ}\text{C}$) for fruit surface temperature calculated using the optimum value of the calibration factor (f) for each data set for 3 combinations of weather data with and without netting, for the calibration period (9–15 January) and validation period (16–29 January).

| | Source of weather data | | | | | Data period | |
|---|------------------------|-------------------|-----------------|------------|------|-------------|------------|
| | Total radiation | Diffuse radiation | Air temperature | Wind speed | f | Calibration | Validation |
| RMSE (°C) | | | | | | | |
| Netted orchard | | | | | | | |
| in-orchard weather station | Netted | Netted | Netted | Netted | 0.2 | 2.10 | 3.55 |
| in-orchard and external weather station | Netted | Netted | Netted | External | 0.45 | 2.01 | 3.10 |
| standard weather data | External ^a | External | External | External | 0.45 | 2.24 | 3.43 |
| difference between in-orchard and standard weather data | | | | | | 0.23 | 0.33 |
| Non-netted orchard | | | | | | | |
| in-orchard weather station | Non-netted | Non-netted | Non-netted | Non-netted | 0.25 | 2.60 | 3.67 |
| in-orchard and external weather station | Non-netted | Non-netted | Non-netted | External | 0.45 | 2.27 | 3.09 |
| standard weather data | External ^a | External | External | External | 0.45 | 2.88 | 3.53 |
| difference between in-orchard and standard weather data | | | | | | 0.61 | 0.44 |

^a The source data for total radiation (R_s) were made above the canopy in the non-netted orchard, and assumed to be equivalent to that measured externally.

Table 9

Sensitivity analysis of predicted fruit surface temperature, calculated from in-orchard weather readings, based on standard weather data values between 1610 and 1620 h on 17th of January 2013.

| | Values | | | Change in $T_{fr, mx}$ ($^{\circ}\text{C}$) | |
|---|--------|----------|-------|---|------------------|
| | Low | Standard | High | Low | High |
| Apple reflectance (α) | 0.1 | 0.4 | 0.6 | 6.23 $^{\circ}$ | −4.19 $^{\circ}$ |
| Apple thermal conductivity (k_s) (W/m^2) | 0.28 | 0.42 | 0.54 | 0.83 $^{\circ}$ | −0.57 $^{\circ}$ |
| Fruit diameter (D) (m) | 0.049 | 0.060 | 0.080 | −0.80 $^{\circ}$ | 0.96 $^{\circ}$ |
| Wind speed (v) (m/s) | 0.1 | 1.2 | 3.4 | 9.52 $^{\circ}$ | −6.92 $^{\circ}$ |
| Total radiation (R_s) (W/m^2) | 60 | 768 | 1040 | −14.61 $^{\circ}$ | 5.23 $^{\circ}$ |
| Diffuse radiation (R_{df}) (W/m^2) (R_s held constant) | 50 | 175 | 580 | 1.68 $^{\circ}$ | −5.48 $^{\circ}$ |
| Air temperature (T_{air}) ($^{\circ}\text{C}$) | 15.0 | 40.7 | 42.0 | −25.39 $^{\circ}$ | 1.26 $^{\circ}$ |

46 $^{\circ}\text{C}$ on the hottest day of the study, 17 January 2013 (79 vs 32%). Monitored fruit were only on the west-facing side of the rows that would be exposed to the afternoon sun, and were representative of the half of the apple crop at risk of sun damage. An unexpected difference was that fruit from the non-netted orchard were smaller (125 vs 153 g), most likely due to differences in crop load (fruit number per tree). The Gala variety used in this study is intermediate in its susceptibility to sunburn relative to other cultivars (Schrader et al., 2001; Schrader et al., 2008). A more comprehensive sampling regime during harvest would be required to quantify the effects of netting on yield and sunburn damage for each cultivar.

4.2. Model performance

The model fitted measured $T_{fr, mx}$ at both the netted and non-netted sites with an RMSE of $\sim 2^{\circ}\text{C}$ in the calibration period and $\sim 3^{\circ}\text{C}$ in the validation period, which is similar to previously reported models in orchards or vineyards without netting (Evans, 2004; Cola et al., 2009; Li et al., 2014). While a physically-based model would ideally require no calibration and be based on quantities that are directly measureable, this was not the case here. The most imprecisely defined process is the transfer of heat from the fruit surface to the air through a boundary layer of still air adjacent to the fruit surface. The thickness of this boundary layer (δ) has never been directly measured, but has either been back-calculated from heat transfer characteristics, or estimated from measurements of v by semi-empirical relationships (e.g. Cola et al., 2009; Li et al., 2014). The equations used by Smart and Sinclair (1976) were based on an experiment of Nobel (1975) in which fruit were heated by artificial radiation under laminar air flow, and δ inferred from heat transfer characteristics at various wind speeds. Under field conditions, turbulent air flow alters these relationships, and Nobel (1975) recommended empirical modifications suited to vineyards. However, trellised apple orchards have taller rows of trees, and would be expected to have greater turbulence relative to horizon-

tal wind flow than vineyards. Although wind flow in the horizontal plane was measured by anemometers within the orchard, these data produced a poorer fit to observed fruit surface temperature than those measured at an exposed site adjacent to the orchard. Further resolution of the physics of heat transfer from the fruit surface to the air would require sensors such as sonic anemometers, which measure air flow in 3 dimensions. However for use in a semi-empirical model it appears $T_{fr, mx}$ was more strongly related to wind measurements taken at the more exposed measurement site external to the orchard than those taken with cup anemometers close to the monitored fruit. Likewise at the second site, a closer fit to fruit temperature measurements was achieved using wind data from an exposed site 18 km away at Tatura than a relatively sheltered site close to the orchard. A similar calibration approach was undertaken by Cola et al. (2009) in a study of vineyard temperatures in Italy. It is therefore simpler to calibrate directly between fruit temperature and v measured by a cup anemometer at a standardised weather station location.

The model produced short-term “spikes” of high fruit surface temperature in the morning before 1000 and in the late afternoon after 1700 h. This occurred during short periods of nearly calm conditions when the model calculated a low value of h in Eq. (2). These spikes occurred outside the times when sun damage would normally be expected (1430–1645 h, Schrader et al., 2003), and could cause spurious results should the model be run on long-term or automated weather data. To avoid such problems we suggest the use of a time-based filter that only utilises $T_{fr, mx}$ between 1000 and 1700 h for the following reasons. Firstly, the sun angle after 1700 h ($>60^{\circ}$ from zenith) means most fruit are becoming fully or partially shaded by leaves, while those fully exposed to the sun's rays are unlikely to receive the direct beam of the sun long enough to cause damage. According to Schrader et al. (2001), sunburn browning requires exposure to temperatures exceeding the varietal threshold for 30–60 min for its full development. Secondly, spikes after 1700 h were over-predicted relative to measurements (e.g. Fig. 4).

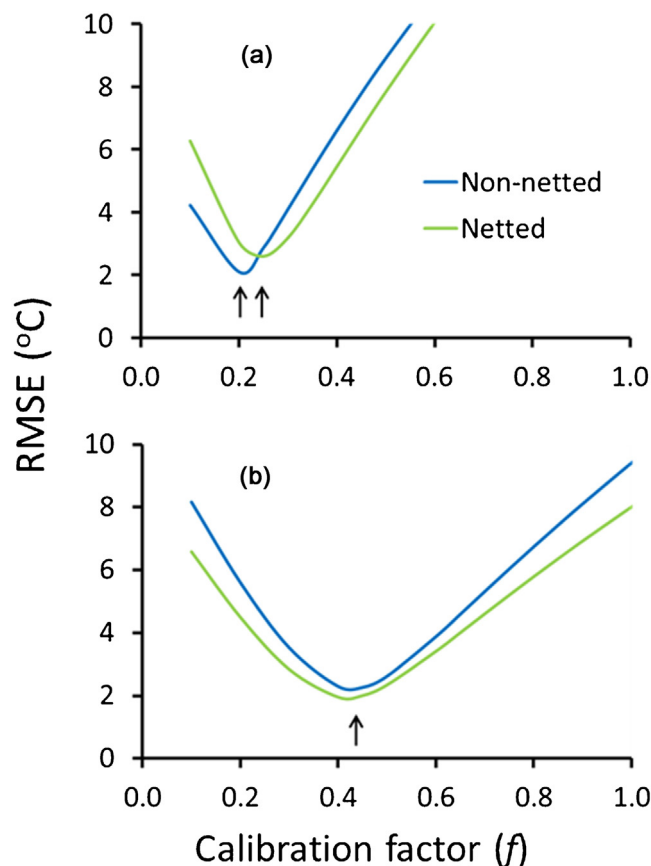


Fig. 6. Root mean square error of fruit surface temperature ($^{\circ}\text{C}$) during afternoons (1400–1700 h) between 9 and 15 January 2013 in response to the calibration factor (f) calculated from wind speed measured (a) within the orchard at a height of 3 m, and (b) adjacent to the orchard at a height of 2 m. Arrows show optimum values.

This could be because the thermocouples were not installed on the face perpendicular to the sun at this time of day, or because Eq. (2) overestimates the strength of the solar beam at high solar zenith angles. Thirdly, UV-B levels are low and likely to cause much less damage at the same fruit temperature than earlier in the afternoon, because after 1700 h UV-B levels declined to less than 25% of that at midday. Morning spikes in simulated $T_{fr, mx}$ were noted until 1000 h, after which wind speeds tended to increase and spikes no longer occurred. Sun damaged apples were observed on the eastern side of the row, but we were unable to determine the time this damage occurred because our equipment was installed on the western side of the row. It is unlikely temperatures above the damage thresholds would occur prior to 1000 h or after 1700 h without also occurring between these times. Since predicted $T_{fr, mx}$ in the early morning or late afternoon and evening is poorly validated and less likely to be damaging, we suggest that only values between 1000 and 1700 h should be used in long term modelling.

It should be noted that these times are in Eastern Australian Standard Time, and that solar noon at this site occurred at 1230 h because it is 4.74° west of the centre of the time zone. Appropriate adjustments would need to be made for other sites, such as outlined by Allen et al. (1998).

The sensitivity analysis showed that among plant parameters α had the largest effect on $T_{fr, mx}$. Most previous studies that reported α did not indicate how the value was measured. The only source that reported methods was Merzlyak et al. (2003), who undertook measurements post-harvest. Across the visible range α averaged 0.35 for dark coloured apples to 0.45 for pale apples. Commercially-available clay sprays reduce $T_{fr, mx}$ by increasing α , particularly at

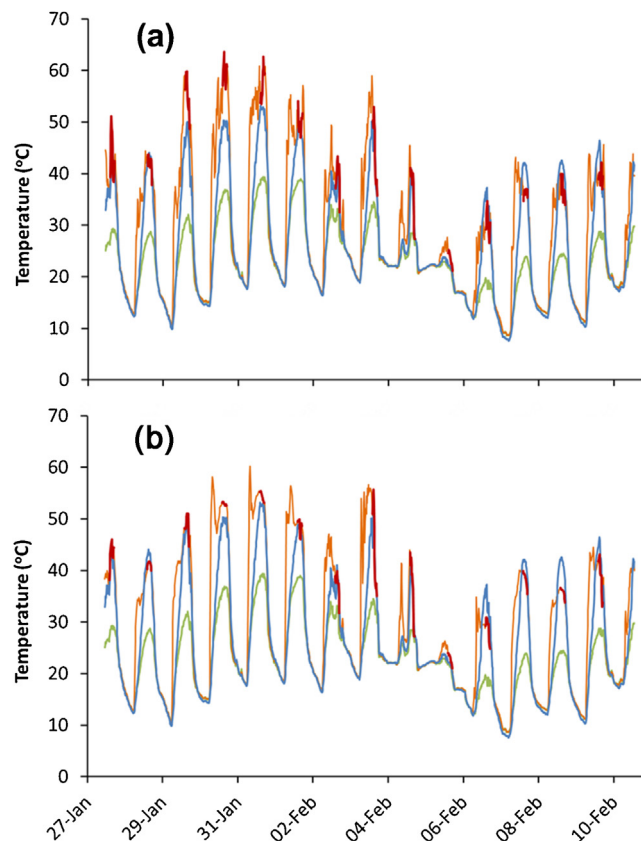


Fig. 7. Supplementary site: measured (blue) and simulated (red and orange) fruit surface temperature of the hottest face of sun-exposed fruit ($T_{fr, mx}$) and orchard air temperature (green). Simulated $T_{fr, mx}$ calculated from wind speeds (a) in a clearing surrounded by orchards and $f = 0.45$ (optimised to the main site) and (b) at an exposed site at Tatura and $f = 0.92$ (optimised to this data set). Simulated temperatures are shown in red between 1400 and 1700 h, and orange at other times. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shorter wavelengths that are more damaging to the skin (Gindaba and Wand, 2005). In our study we initially used an α value of 0.55, which resulted in an optimum f value of 0.7, whereas using a more defensible value of 0.4 resulted in an optimum f value of 0.45. While in a semi-empirical model an inappropriate value of one parameter is resolved by a compensating calibration factor, there are risks that the model performs poorly under conditions that differ from its calibration because the physical processes are not simulated correctly. To resolve this area of uncertainty there is need to undertake more comprehensive measurements of α during fruit development, and over a wider range of wavelengths.

4.3. Effects of hail netting

Hail netting reduced the fruit temperature by $1.5\text{--}3.0^{\circ}\text{C}$ across most of the probability distribution, but for the hottest fruit at each site within the orchard the difference was 4.0°C . The mechanism for this effect of netting was by reducing the intensity of the solar beam by interception and scattering, while allowing good air flow to enable transfer of heat from the fruit surface to the air. The netting structure at the study site represented an ideal design for minimising sun damage because it was installed high above the tree canopy and had open sides, minimising interference to air circulation within the orchard and air exchange with the outside. Despite this design, the netted orchard had internal wind speeds that averaged 22–24% lower than the non-netted site averaged across all afternoons in January 2013 (Tables 4 and 5). A

wide range of designs are used commercially, including temporary nets placed over the trees, retractable netting installed on structures above the tree canopy, and fixed netting with closed or open sides (Lolicato, 2011). Some designs could potentially exacerbate rather than reduce sun damage if wind is substantially reduced. The sensitivity analysis showed that if netting caused a 25% reduction in wind speeds, this could, without other changes to the heat balance, increase fruit temperatures by 2.2 °C. To maintain fruit surface temperatures equivalent to the non-netted orchard would require either a decrease in total radiation of 16%, or if total radiation is unchanged the proportion in the diffuse form needs to increase by 58%. Until recently, hail protection has been the primary rationale for investment in netting, followed by protection from fruit bats and birds. Where the latter is required, the sides would need to be closed, but this could reduce internal v leading to increased fruit temperatures. From principles developed in this study, a design that uses a more open netting on the sides would minimise these problems.

While the netting intercepted only 10–11% of R_s at solar noon, this is not the time maximum protection is required for two reasons. Firstly, the NNW-SSE row orientation and training structure meant that a high proportion of fruit were shaded by leaves at this time of the day. Secondly, air and fruit temperatures on hot days tend to peak in the late afternoon. Our study showed that peak fruit surface temperatures occurred between 1600 and 1700 h, at which time netting intercepted and scattered a greater proportion of R_s than at midday. Protection from radiation at solar noon was consistent with its 10% shade rating, but at 1620 h when the solar angle was 52° its shading effect was greater (15–20%), and there was an even greater reduction in radiation perpendicular to the fruit surface at the hot spot (26%). Excessive shading needs to be avoided because it reduces the development of red colour in the fruit (Gindaba and Wand, 2005). The main protection from sun damage is therefore required between approximately 1600 and 1700 h when netting is over twice as effective in controlling the surface heating effect of the sun than would be expected from its shade specifications. For this reason, hail netting with a 10% shade rating represents a good compromise between protection from hail and sun damage, while minimising its effects on fruit colour development.

Our data are a comprehensive comparison of microclimate with and without netting. From it we were able to develop equations to predict the netted microclimate from external measurements, but these are only directly applicable to the particular design, colour and weave type at the study site. Predictive equations could be obtained over a relatively short period (two weeks) through the use of 10 min data, which for radiation were based on measured R_s relative to R_a (as recommended by Spitters et al. (1986)), and the air mass number as a representation of the sun angle. The sound physical basis of these equations means the approach should be applicable to developing relationships for other structures and weave types from relatively short periods of data. However, the physical nature of this modelling approach is also a weakness, because a large amount of weather data must be assembled at time scales of at least hourly, in addition to site-specific relationships between wind measurement locations and fruit surface temperature. The role of this level of modelling is in understanding processes and quantifying the effects of various netting structures, which can differ in weave type, colour, height and the presence or absence of side netting. For many applications, a simpler approach would be more suitable. For example, Darbyshire et al. (2015) used data from our study to identify the external air temperature at which fruit surface temperature exceeded a sunburn browning threshold in 10% of monitored fruit. This was determined as 37.9 °C with netting and 34.1 °C without netting. These thresholds were then used to assess the benefits of netting in Australia's apple grow-

ing regions for a range of climate change scenarios (Darbyshire et al., 2015; Webb et al., 2016). Their findings are, however, specific to the netting design used in our study, and the approach is limited in investigating the effects of other management options such as canopy architecture, row orientation, leaf density and their interaction with netting design.

Netting was associated with other changes to the agro-ecological environment, including reduced ET_o , higher humidity and lower wind speeds. Under netting ET_o was 13% lower than at the non-netted site, which would lead to a reduced irrigation requirement. The combination of higher humidity and lower v is a potential disbenefit, because it is associated with a longer duration of leaf wetness (Kim et al., 2002), which in turn leads to a higher disease risk. The most economically significant disease of apples is apple scab (*Venturia inaequalis*), which is a fungus that for light infection requires at least 12 h of continuous leaf wetness at 13 °C, and longer periods at lower temperatures (Vaillancourt and Hartman, 2000). The netted environment therefore had a benefit through a lower irrigation requirement, but there was also a disbenefit through a greater risk of fungal diseases that may require more frequent control measures.

5. Conclusions

This study found that netting was able to reduce the median fruit surface temperatures by 1.5–2.0 °C. The mechanism for this effect of netting was by reducing the intensity of the solar beam by interception and scattering, while allowing sufficient air flow to enable transfer of heat from the fruit surface to the air. An adaptation of a previously published thermodynamic model was able to account for these differences with an RMSE of 2–3 °C in the afternoon when sun damage most commonly occurs, but in the morning or early evening it appeared to over predict fruit temperatures during times of low wind speed.

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

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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

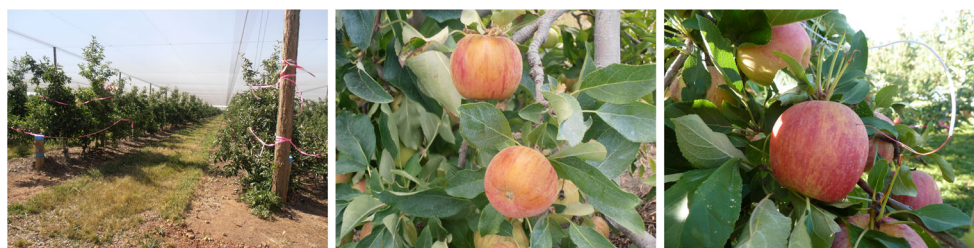


Fig. 1 A netted ‘Royal Gala’ apple orchard in Shepparton, Victoria (*left*), Royal Gala apples with evidence of sunburn browning damage (*centre*) and a thermocouple sensor placed under the fruit skin of a Royal Gala apple to measure fruit surface temperature (*right*)

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.

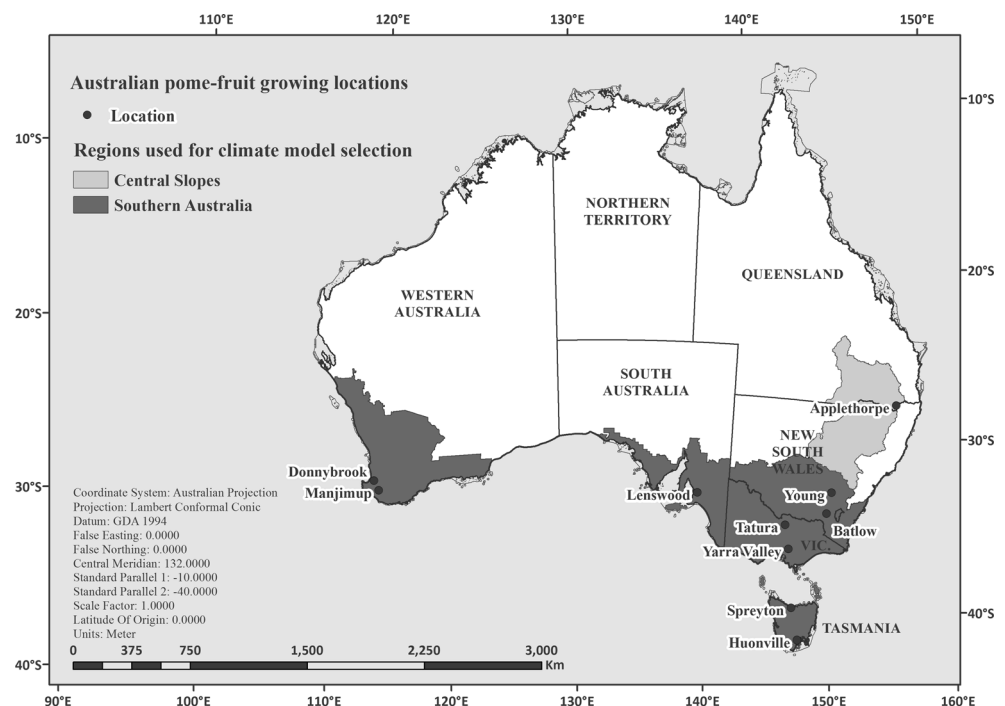
Future daily Tmax conditions were assessed in the study, with the aim to capture the range of climate projections resulting from the future range of RCPs and corresponding range of CMIP5 GCM output. To achieve this, a subset of RCPs and GCMs were identified and combined to create ‘best-case’ and ‘worse-case’ 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 (CO₂) emissions peak around 2040 and strong mitigation of emissions occurs in the latter half of the century, CO₂ 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 CO₂ concentration continues to rapidly rise, reaching 940 ppm by 2100. Current CO₂ 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 Tmax for the two regions (Fig. 2). These were selected by analysing summer (harvest season) Tmax 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 Tmax 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 Tmax 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 Tmax time series

To create future daily Tmax time series, projected average monthly January Tmax change values centred on 2030, 2050 and 2090 for the best-case and worst-case scenarios were added to the AWAP observed January daily Tmax time series (1981 to 2010). To capture the most reliable estimate of location-specific natural climate variability, the baseline Tmax 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 Tmax 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 Tmax 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 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.

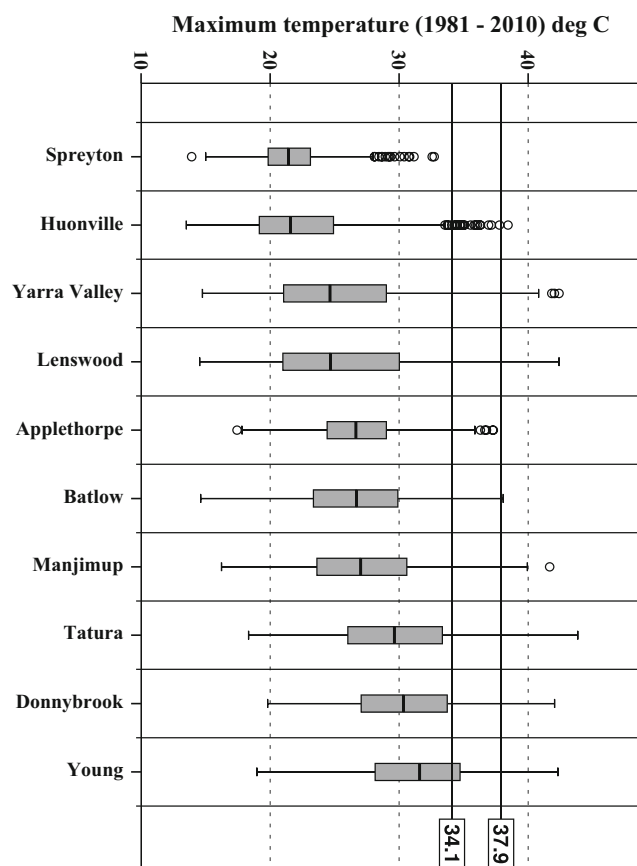


Fig. 3 Boxplot showing daily January maximum temperature (°C) for 1981–2010 for the ten locations in the study (also see Fig. 2 map). The interquartile range (IQR) of the sample is indicated by the height of the box, the sample median (the horizontal bar) and 1.5 times IQR (the whiskers), with outliers (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.

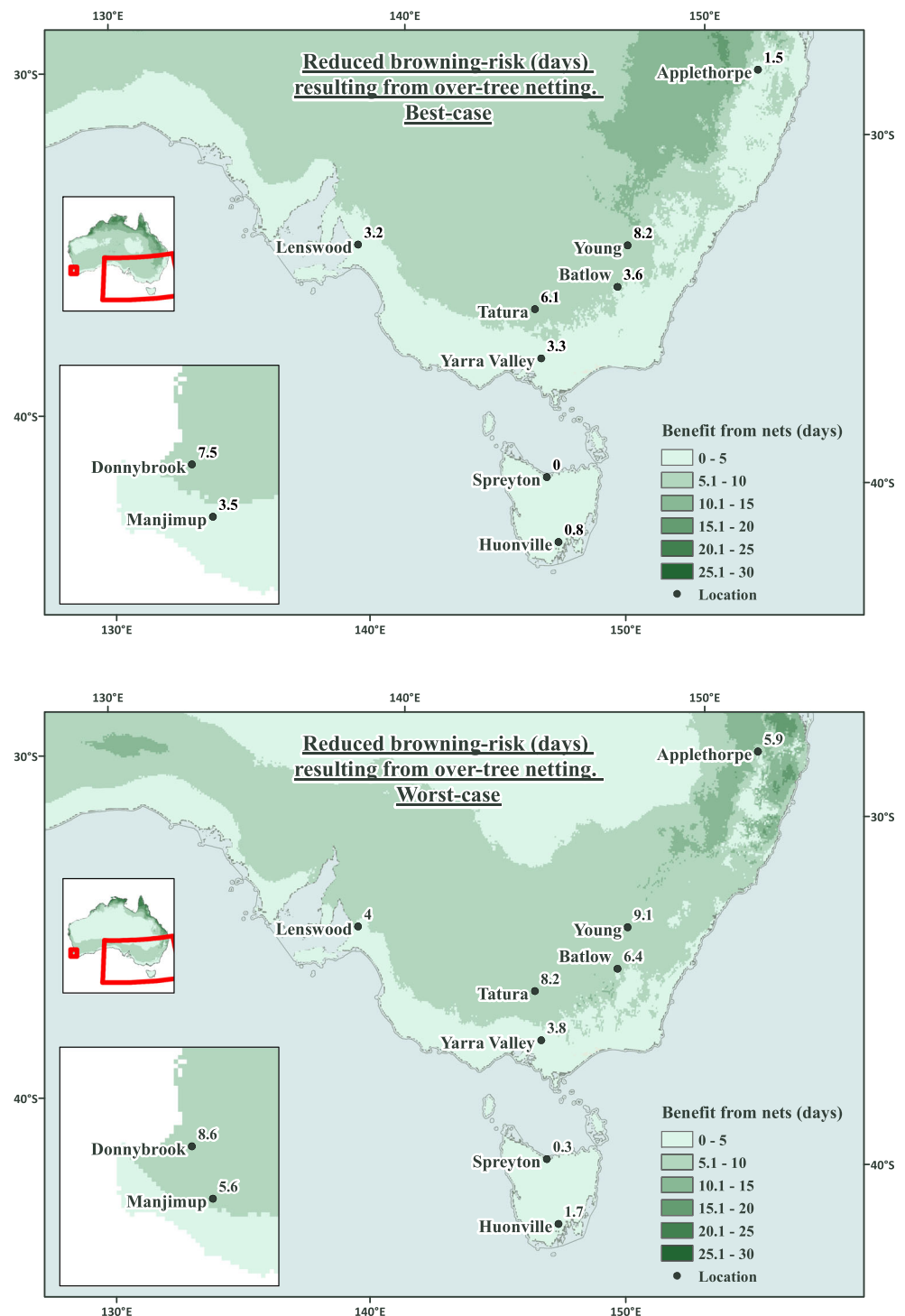
Over-tree netting is an effective option for reducing sunburn browning risk (Smit 2007; Smit et al. 2008; Solomakhin and Blanke 2010) and was found in this study to notably reduce sunburn browning risk for most growing districts. Adaptation planning to determine the time period in which nets could be 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.

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Compliance with ethical standards

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Western Australian Apple Netting Demonstration Site

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Introduction

Climate predictions for the future include reduced winter chilling, less rainfall and more extreme high temperature incidents across the South West of Western Australia (Sudmeyer et al., 2016 and Reid 2010). Over tree netting (hail, shade or bird netting) has been identified as a potential climate change adaptation strategy due to the moderating effect of adverse climate conditions (Lolicato 2011). Netting reduces solar radiation and therefore a reduction in the amount of sun damaged fruit. The installation of over tree netting is one adaptation to climate change that can reduce the impact of browning on apples (Darbyshire et al., 2015). Protection from hail events can be achieved by netting pome fruit orchards enabling the protection of fruit and trees (Middleton and McWaters 2002). The Pome fruit industry is already responding with significant investment in netting infrastructure despite remaining practical questions on the use of hail netting, particularly in warm growing regions, including the effect of different types of netting on temperature, fruit quality and yield (Bosco et al., 2014 and Iglesias and Alegre 2006). The effectiveness of netting as a climate change adaptation strategy, in reducing fruit surface temperature under predicted climate change is unknown.

Data collected at the Western Australian netting demonstration site was set up to expand on existing studies on the effects of netting on air temperature, relative humidity, wind and solar radiation (Middleton and McWaters 2002 and Darbyshire et al., 2015). The Western Australian netting demonstration site aims to compare the effect of different coloured net on fruit yield, quality and environmental conditions under black and white net.

The Western Australian netting demonstration site at Lyster Orchards, Manjimup, was constructed in 2013 to demonstrate the benefits of netting under Western Australian conditions. This demonstration site was part of two nationally funded projects; Crossing the Threshold: Adaptation tipping points for Australian Fruit Trees funded by Department of Agriculture and Water Resources and Understanding Apple and Pear production systems in a changing climate funded by Horticulture Innovation Australia.

The site was set up as demonstration site with one replication of each treatment type; 0.25 hectares of black net, 0.25 hectares white net and no net (figure 1). There were 10 random trees monitored under each treatment from 2 rows.



Figure 1. Western Australian netting demonstration site at Lyster Matijari Orchard.

The aim of the project was to demonstrate the value of hail, bird or shade netting as a means to improve orchard productivity, in high density production systems. Particular attention was given to assessing the impact of netting on fruit quality (sunburn, wind burn and colour). The effects of black and white netting on fruit quality (particularly colour), tree growth and chill accrual in the orchard were compared to the no net treatment.

Materials and Methods

The demonstration site, Lyster's Matijari Orchard, is located 3km south of Manjimup on the South West Highway, Western Australia (34.16°S and 116.07°E). Half a hectare of a 1.2 ha commercial Cripps Pink apple crop has been covered with 16mm quad netting to provide full exclusion to birds plus shade and hail protection.

Construction of the netting started in August 2013 and was completed by 28th October 2013. 0.25ha of black net provides a 23 percent reduction of both shade and UV radiation while 0.25ha of white net provides a 20 percent reduction. The white and black net area was compared to no net areas. The three treatment sites have been monitored from 8th November 2013 through to 29th April 2016. The environmental conditions were monitored during this period and the fruit quality and yield for two harvest seasons. Under each treatment 10 monitoring trees were selected 5 in each row (figure 2).

A fourth site with 'Frustar' net was expected to be constructed after harvest 2014, but was not completed during this project.

The Cripps Pink apple trees, planted in 2004 on a north/south orientation, are on M26 rootstock trained on a central axis. Trees are spaced at 1m with 4m between rows giving a planting density of 2500 trees per ha. The soil type includes sandy clay loam with varying gravel content over medium clay that starts from between 50 to 70cm depth. The grower undertook all management of the trees during the demonstration period.

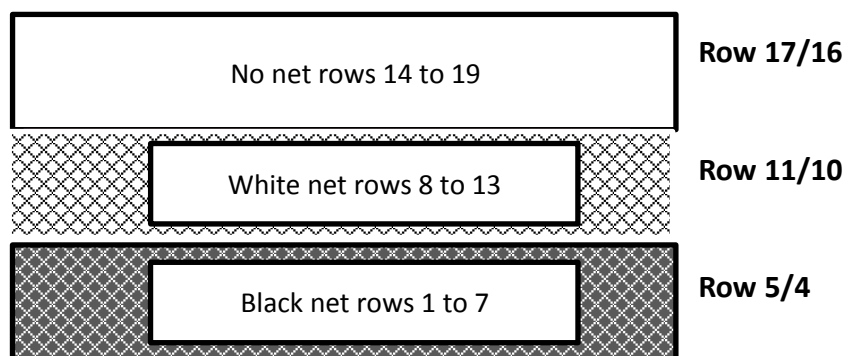


Figure 2. Netting treatment layout at Matijari, 5 trees monitored in each row, 10 trees monitored in each block.

Weather stations were located in the centre of row 4 (black net), 10 (white net) and 16 (no net). Measurements taken every minute are averaged and reported each 15 minutes. Weather observations measured include; solar radiation, UVB radiation, mid canopy air temperature, relative humidity, wind speed and rainfall.

The light interception was calculated by measuring Photosynthetically Active Radiation (PAR) on a clear sky day in March 2014 and February 2015 using a hand held ceptometer. Several measurements were taken throughout each section at morning, solar noon and afternoon to measure the extent and density of the shade created by the tree.

Phenology assessments were performed to determine the beginning of green tip and full bloom timing. Regular visual assessments (Monday, Wednesday, Friday) were made from just prior to budburst until flowering was completed. Assessments were performed on a whole tree basis on only spur and terminal buds and spur and terminal flower clusters assessed (axillary buds on one-year-old pome fruit shoots were not included in the assessments) for the 10 Cripps Pink monitoring trees under black, white and no net treatments.

Fruit Surface Temperature (FST) was measured using thermocouples inserted into the surface of 10 Cripps Pink apples. Sensors were inserted into apples evenly spaced (upper, mid and lower canopy) on 4 trees in row 4 (black), 10 (white) and 16 (no net). Fruit Surface Temperature (FST) readings were taken every 15 minutes from end of January until early March over 3 seasons; 2014, 2015 and 2016.

Yield assessments were undertaken in 2014 and 2015. Each of the 10 monitoring trees from the black, white and no net treatments were strip pick approximately one week prior to the growers first pick. The number of apples from each tree was recorded then graded according to the Pink Lady™ standards then a random sample of 40 was selected. During the grading process the number of bird damage apples and sun damaged apples were recorded from each monitoring tree. The grower bin numbers have been recorded to get the commercial pick data from all Cripps Pink rows under the black, white and no net treatments.

From the sample of 40 apples from each of the monitoring trees the colour was assessed using the Pink Lady™ Europe Ctifl colour charts (**Centre technique interprofessionnel des fruits et legumes (Ctifl)** Pink Lady™ Eurofru colour charts). Each apple was given a score for background colour (F1-F7), a score for blush intensity (R1-R8) and a percentage of blush intensity when the blush was over R3.

The maturity of the apples was tested from a sample of 10 apples randomly selected from the rows monitored, from early April until harvest. With the final maturity test completed from the sample of 40 apples. The maturity tests included starch conversion using the 1-6 scale (Portman and Sutton 2003), total soluble sugars measured using a refractometer, flesh firmness measuring the pressure from each side of the apple using a 11mm plunger and acid titration (McAlpine et al., 1995).

Results and Discussion

Environmental

A summary of the winter chill conditions during the data collection years was compiled. Flowering phenology is influenced by winter chill accumulation, with low chill years due to warm winter conditions potentially delaying flowering. Conversely, warmer spring conditions may advance flowering timing.

Winter temperature conditions must be converted into chill portions. For this project, the Dynamic chill model was used to calculate chill conditions under each net colour. This model estimates winter chill in chill portions and is currently the most robust and reliable chill model available (Luedeling 2012 and Darbyshire et al., 2016). Winter chill was calculated from 1st March through until 31st August 2014 and 2015 from hourly temperature readings collected in the orchard.

There is very little difference in chill accumulation under black net, white net or no net area (figure 3). The nets do not reduce the amount of chill accumulated as there is minimal impact on the temperatures recorded under the black or white net or no net (table 1).

Use of netting to increase winter chill is unlikely to be an effective adaptation option, however these results do show that netting, established for other management outcomes, does not influence winter chill accumulation in a meaningful way.

Table 1. Mean monthly temperatures (°C) from March to October and total chill portions accumulated from 1st March until 31st August under black, white and no net.

| Treatment | Season | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | CP |
|-----------|--------|------|------|------|------|------|------|------|------|----|
| Black | 2015 | 17.9 | 15.1 | 12 | 12.7 | 11.5 | 11.7 | 13 | 16.6 | 66 |
| White | 2015 | 17.9 | 15.1 | 12.1 | 12.8 | 11.7 | 11.9 | 12.9 | 16.6 | 63 |
| No Net | 2015 | 17.9 | 15.2 | 12 | 12.6 | 11.1 | 11.4 | 12.6 | 16.3 | 66 |
| Black | 2014 | 18.5 | 16.2 | 13.9 | 11.8 | 11.1 | 12.8 | 13.2 | 14.7 | 55 |
| White | 2014 | 18.6 | 16.3 | 13.9 | 11.8 | 11.2 | 12.9 | 13.2 | 14.7 | 54 |
| No Net | 2014 | 18.7 | 16.4 | 14 | 11.9 | 11.2 | 12.9 | 13.2 | 14.8 | 52 |

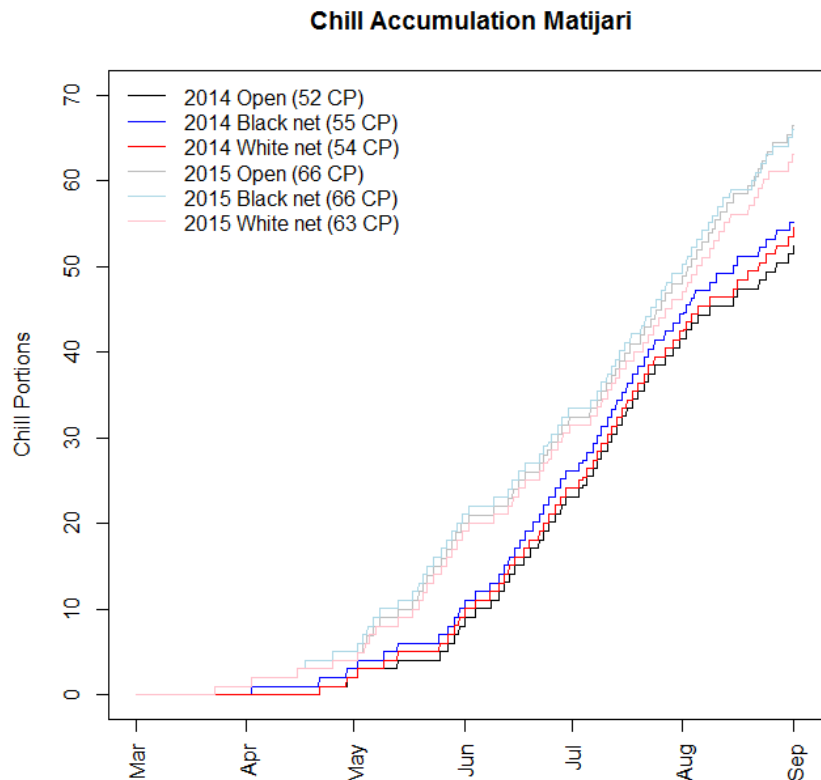


Figure 3. Chill accumulation under the black net, white net and no net at Matijari in 2014 and 2015.

Bud break and flowering data was collected from 10 trees under black, white and no net rows. Observations were made three times a week from 20 August to 30 October 2014 and 2015 (Parkes et al., 2016). Whole tree assessments were made to determine the dates of bud break, occurrence of first flower and full bloom and to monitor progression of flowering (table 2). There is minimal difference in flowering progression between the netted trees to the no net trees. Rootstock shows a greater difference with the MM.106 trees under no net reaching bud break a week before M.26. All trees still came into full bloom at the same time in 2014 (figure 4).

Table 2. Summary of apple bud break and flowering data for 2014 at Matijari based on whole tree assessments. Average dates of bud break (5 percent of buds at green tip or beyond), first flower and full bloom (80 percent of individual flowers open) for ten randomly selected trees.

| Cultivar | Root Stock | Bud break | First Flower | Full Bloom |
|-----------------------|-------------------|------------------|---------------------|-------------------|
| 2014/15 | | | | |
| No Net Cripps Pink | M.26 | 15/9/14 | 26/9/14 | 17/10/14 |
| White Net Cripps Pink | M.26 | 12/9/14 | 22/9/14 | 17/10/14 |
| Black Net Cripps Pink | M.26 | 15/9/14 | 22/9/14 | 17/10/14 |
| No Net Cripps Pink | MM.106 | 8/9/14 | 15/9/14 | 17/10/14 |
| 2015/16 | | | | |
| No Net Cripps Pink | M.26 | 18/9/15 | 25/9/15 | 15/10/15 |
| White Net Cripps Pink | M.26 | 16/9/15 | 25/9/15 | 15/10/15 |
| Black Net Cripps Pink | M.26 | 11/9/15 | 25/9/15 | 12/10/15 |
| No Net Cripps Pink | MM.106 | 23/9/15 | 30/9/15 | 14/10/15 |

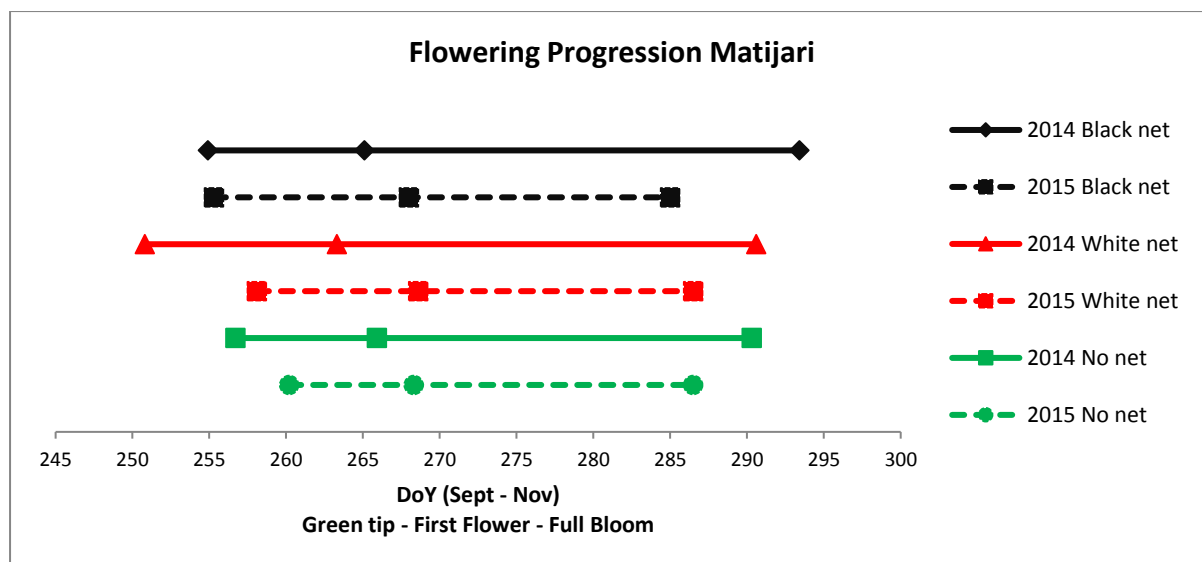


Figure 4. Flowering progression at Matijari for Cripps Pink apples on M26 rootstock under black, white and no net. The first symbol represents green tip, the second first flower and the last full bloom.

Mean daily temperatures rarely varied more than 0.5 to 1 degree (figure 5). The netting led to small increases in minimum temperatures and dampening of maximum temperatures. This action is similar to a cloud cover effect which reduces radiant heat loss overnight and reflects a portion of incoming daytime radiation reducing maximum temperatures.

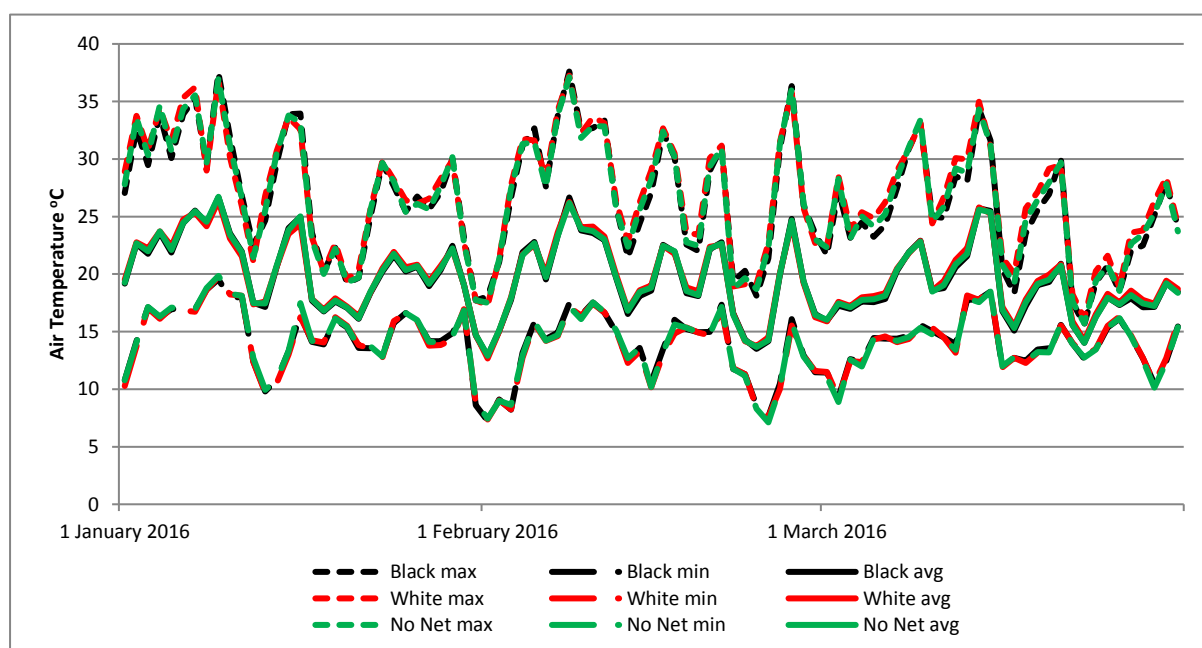


Figure 5. Daily maximum (upper), average (centre) and minimum (lower) air temperatures for black, white and no net treatments for summer 2016.

The daily maximum air temperature for the summer autumn months (December – April 2014, 2015 and 2016) the relationship between the white and no net (figure 6) and black and no net (figure 7) show no effect on air temperature. There is a wide range of air temperatures from 14°C to 37°C

over a 5 month period of the growing season that demonstrating there is no effect on air temperature. Under the nets feels cooler as the solar radiation lower.

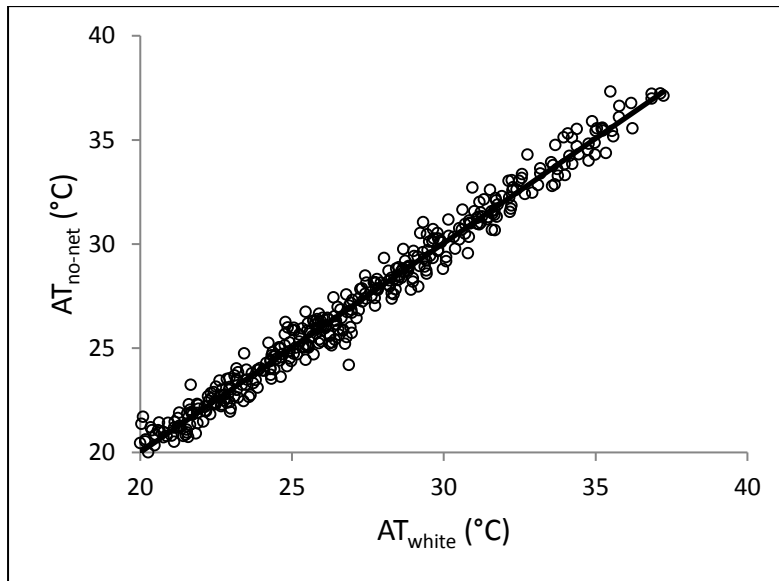


Figure 6. The relationship of maximum daily air temperature under no-net (AT_{no-net}) and white net (AT_{white}) for Summer and Autumn 2014 to 2016. The fitted linear regression (solid line) was described by $AT_{no-net} = 1.004 (\pm 0.006) AT_{white} - 0.081 (\pm 0.155)$; $R^2 = 0.99$, $n = 438$.

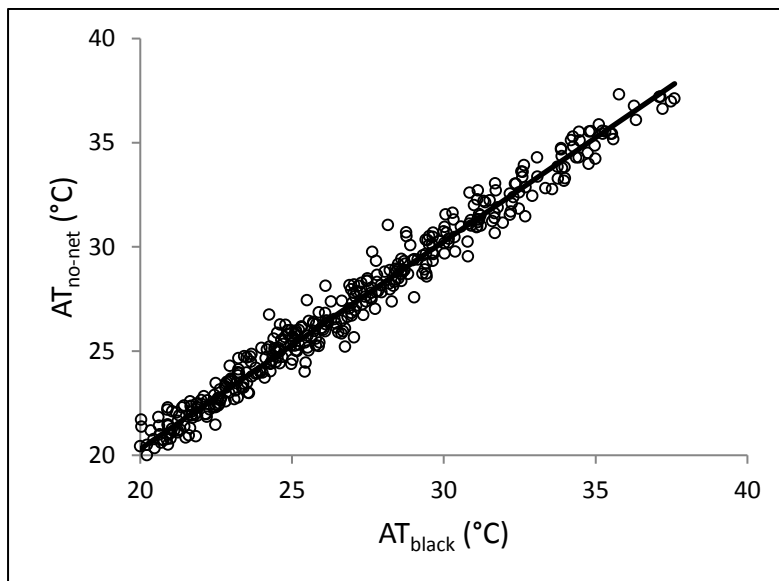


Figure 7. The relationship of maximum daily air temperature under no-net (AT_{no-net}) and black net (AT_{black}) for summer and autumn 2014 to 2016. The fitted linear regression (solid line) was described by $AT_{no-net} = 0.996 (\pm 0.006) AT_{black} + 0.379 (\pm 0.163)$; $R^2 = 0.98$, $n = 438$.

The humidity under the white net during summer was highest and lowest in no net block (table 3). The effect of high humidity was seen in the pest and disease management under the nets. In the first year after the nets were constructed woolly aphids were extremely bad under the nets there was also a high percentage of apples with bitter pit. European mites attacked under the nets in late December 2015, almost defoliating the trees. With pest and disease outbreaks can be more common under netting it is a matter of monitoring more frequently as the conditions under the nets are favourable to outbreaks.

Table 3. Maximum daily relative humidity during summer autumn 2016

| | Black | White | No Net |
|----------------|--------------|--------------|---------------|
| Average | 92.85 | 93.46 | 91.92 |
| Max | 98.44 | 98.52 | 97.74 |
| Min | 66.83 | 67.92 | 62.84 |
| SE | 0.47 | 0.40 | 0.46 |

Average wind speeds are highest under the black net which is on the eastern side followed by the no net which is on the western side (table 4). The white net is the central block between the black and no net treatments. The average wind speeds measured appear to demonstrate a landscape effect where the eastern side open to the easterly winds off the dam and the white net is protected from the prevailing winds. The no net treatment is protected from the rest of the block of Fuji and Cripps Pink apple trees. Although the maximum wind speeds come from the prevailing westerly winds.

Table 4. Average 15 minute wind speed (m/s) May 2015 – April 2016

| | Black | White | No Net |
|----------------|--------------|--------------|---------------|
| Average | 1.12 | 0.64 | 0.89 |
| Max | 4.97 | 6.02 | 7.46 |
| Min | 0 | 0 | 0 |
| SE | 0.005 | 0.004 | 0.005 |

The no net area received the highest global radiation (figure 7). While not exactly the same as the specifications, the white net showed a 15 percent reduction and the black net 26 percent reduction during January and February 2014 and 2015. Specifications are only given as a guide to how the nets will perform and in this case the black net was close to specification and the white net slightly less. A similar trend is followed each summer for global radiation.

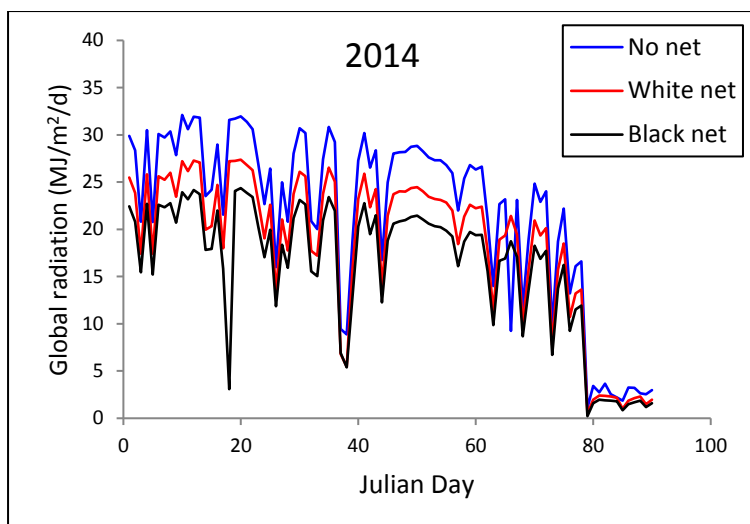


Figure 7. Global radiation measured under the black net, white net and no net rows for summer 2014.

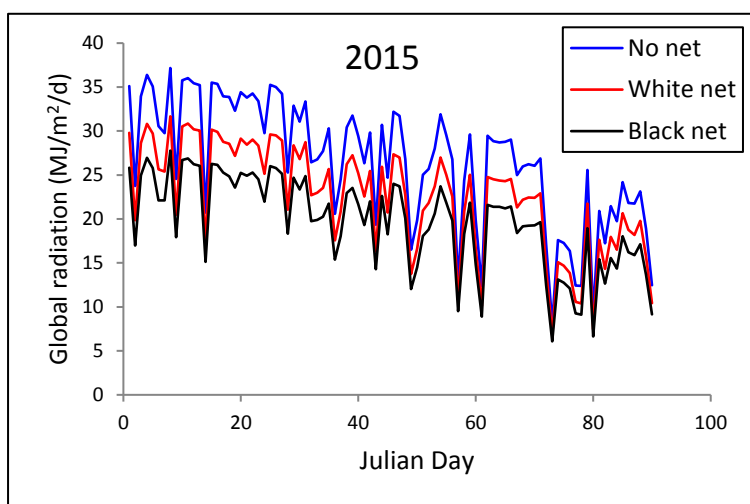


Figure 8. Global radiation measured under the black net, white net and no net rows for summer 2015.

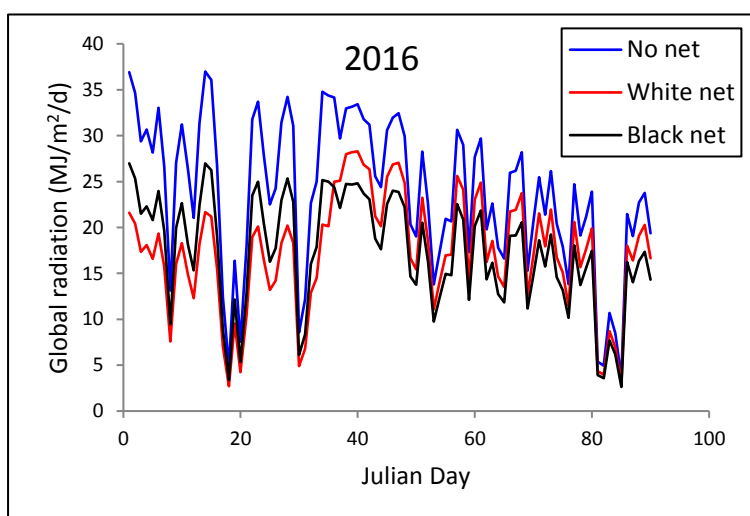


Figure 9. Global radiation measured under the black net, white net and no net rows for summer 2016.

The effect of the black, white and no nets on the interception of light was measured annually as a percentage of total above canopy Photosynthetically Active Radiation (PAR) using a ceptometer. Figure 10 shows the black net had a greater reduction in shade compared with the white net and no net.

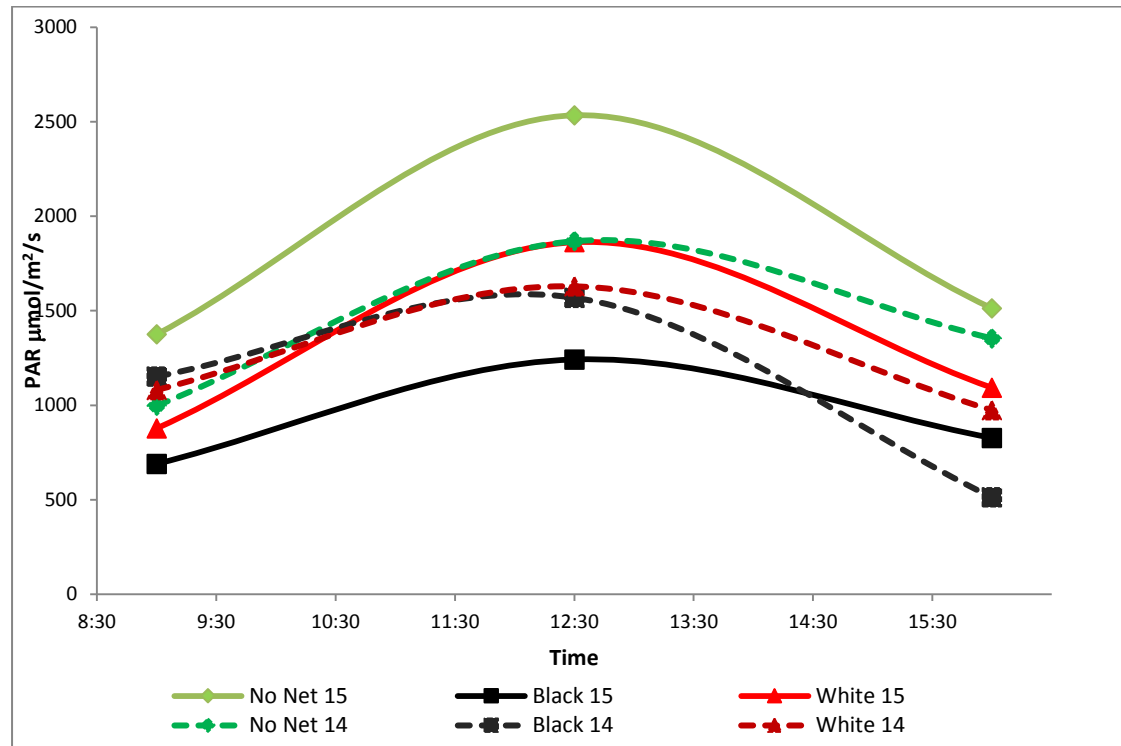


Figure 10. Average photosynthetic radiation interception (PAR) of sky measured at morning, noon and afternoon on March 2014 and February 2015 in the black net, white net and no net rows.

While measurements reflected shade specification of the net, the reduction in PAR was also influenced by tree vigour or vegetative growth.

The fractional PAR is the light intercepted by the tree canopy. Tree vigour was higher under the netted areas than outside the net, as seen in the under canopy readings (figure 11).

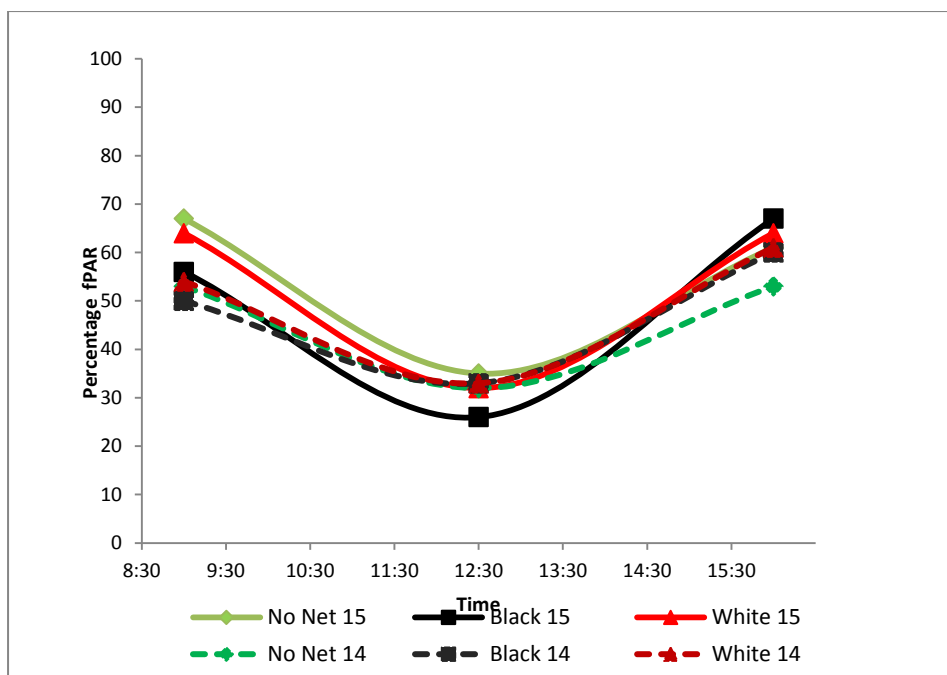


Figure 11. Average percentage of fractional photosynthetic radiation interception (fPAR) measured at morning, noon and afternoon on 12 March 2014 in the black net, white net and no net rows under tree canopy.

Quality

The fruit quality was a measured through the amount of sun damaged fruit, bird damaged, colour development of the background and blush of the apple and maturity of the fruit. Fruit surface temperature was used to measure the amount of sunburn browning that could be expected under netted conditions.

Fruit surface temperature (FST) was higher in the no net area particularly during extreme heat events in late summer and a higher percentage of sunburnt fruit was observed in the no net rows 2.5 percent in 2014. Less than half a percent of the apples were sun damaged that came from the black and white net areas, compared to the no net area.

From the 2014 and 2016 fruit surface temperature (FST) recorded it is reasonable to think that amount of solar radiation reaching the fruit surface should influence the FST. The FST was measured over the summer 2013-14 season (figure 12) and 2015-16 season (figure 13). Average FST was lower under the white net than the black, even though greater solar radiation was recorded under white net.

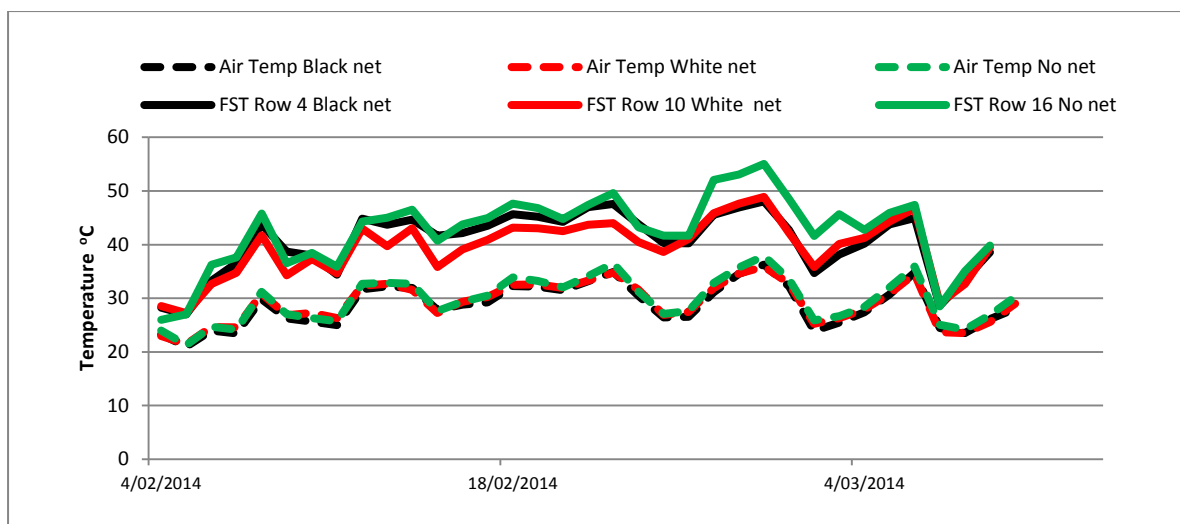


Figure 12. Fruit surface temperature (FST) and air temperature measured in the black net, white net and no net rows at Matijari for February till mid-March 2014.

The FST recordings from 2015 had some computer programming errors at the weather station and have not been presented in this report.

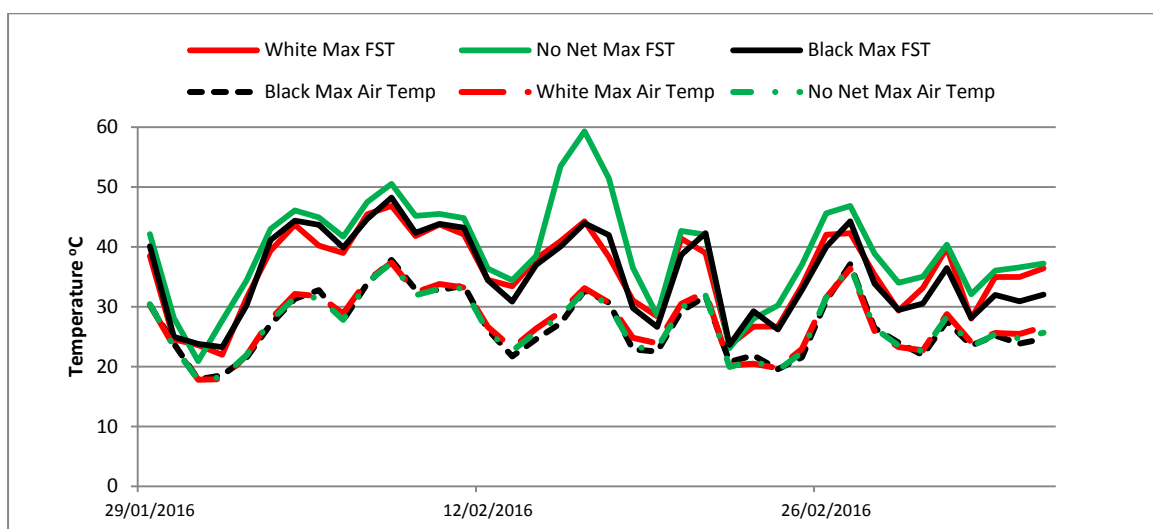


Figure 13. Fruit surface temperature (FST) and air temperature measured in the black net, white net and no net rows at Matijari for February till mid-March 2016.

In 2016 the highest FST was 59.61 °C in the no net block. This was just one sensor in the outside lower canopy on the western side, sun damage was observed in this apple. All other sensors in the no net treatment were only a few degrees warmer than the black and white net.

The daily maximum fruit surface temperature for February 2014 and 2016 the relationship between the white and no net (figure 14) and black and no net (figure 15) show minimal effect on fruit surface temperature. The range of FST start at 20 °C for minimum daily FST and extend through to a maximum of 48 °C with average maximum FST of 48.3 °C for black net, 48.9 °C for white net and 59.6 °C for the no net over the 2 seasons of recording FST.

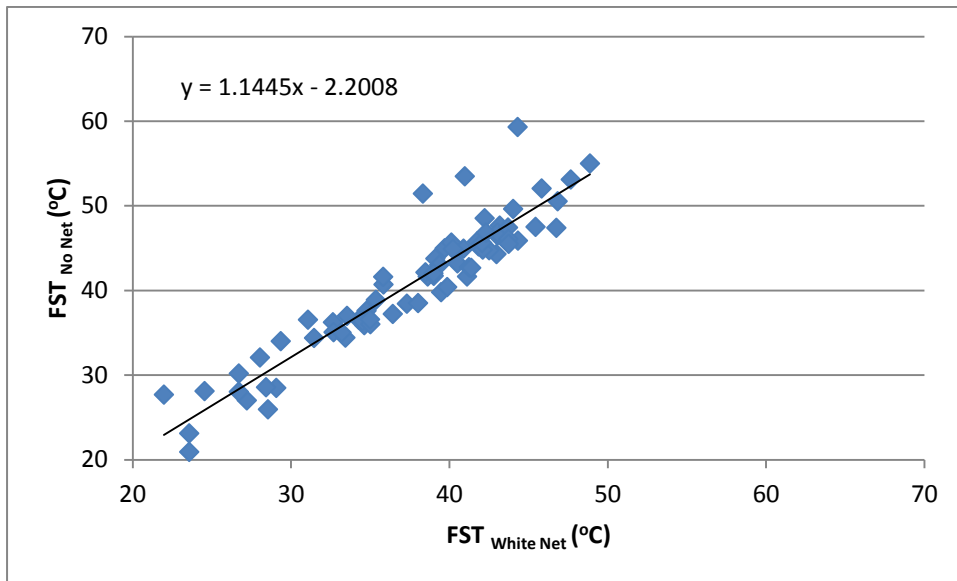


Figure 14. The relationship of maximum daily fruit surface temperature under no-net (FST_{no-net}) and white net (FST_{white}) for February 2014 and 2016.

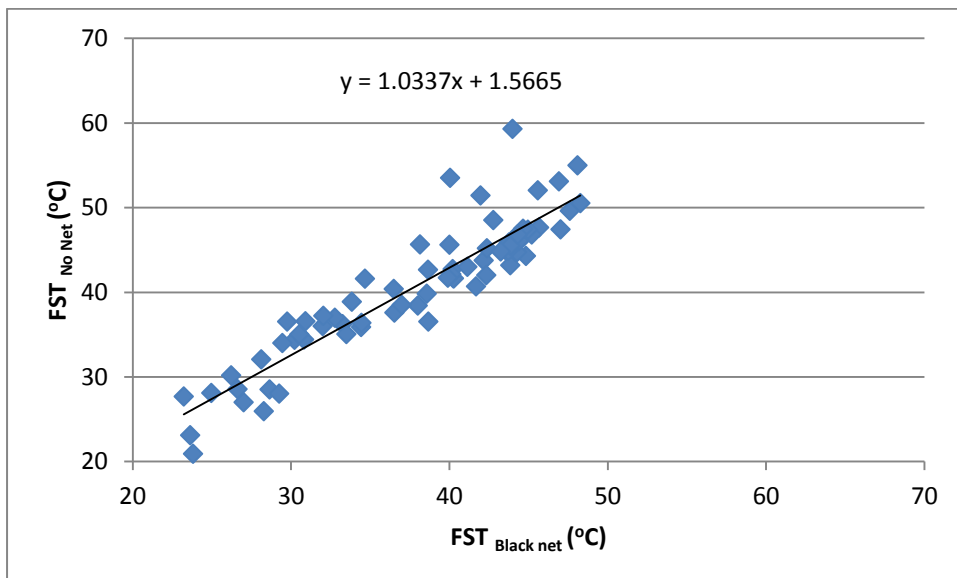


Figure 15. The relationship of maximum daily fruit surface temperature under no-net (FST_{no-net}) and black net (FST_{black}) for February 2014 and 2016.

Background colour, blush and maturity all contribute to the marketability and grade assigned to Pink Lady™ apples. While the results are presented separately it is important to consider them together.

In 2015 at the time of strip picking the majority of apples had reached the ideal background colour (figure 16). Seventy eight percent of fruit in the no net and black net blocks were between F3 to F4, suitable for optimum for long term storage. Sixty eight percent of white net apples were between F3 to F4 (table 5).

Background colour greater than F4 is undesirable for long term storage, as the green background begins to move toward yellow the fruit ripens. Twenty two percent of the no net fruit were beyond the ideal background storage colour in 2015 and 67 percent in 2014 of no net and 53 percent of the white net.



Figure 16. Background and blush colour of Cripps Pink apples at time of strip picking 28/4/2015, black net, white net and no net random sample for maturity testing.

Table 5. Background colour, percentage of apples with F score for background colour, from Ctifl standards for Pink Lady™. Optimum for long term storage F 3-4.

| | F Score <3 Immature | F Score 3 -4 Optimum for long term storage | F Score >4 Optimum for fresh market to over ripe |
|-------------|----------------------------------|---|--|
| 2014 | | | |
| Black | 6 | 93 | 1 |
| White | 5 | 42 | 53 |
| No Net | 2 | 31 | 67 |
| 2015 | | | |
| Black | 0 | 78 | 22 |
| White | 0 | 68 | 32 |
| No Net | 0 | 78 | 22 |

While optimum blush is between R4 and R5 for long term storage, blush greater than R4 is preferred in all fruit. The no net treatment had better blush colour development with majority of apples at greater than R4 (table 6).

Table 6. Blush intensity, percentage of apples with R score for background colour from Ctifl standards for Pink Lady™. Optimum for long term storage F 4-5.

| | R score <4 Immature | R Score 4-5 Optimum for long term storage | R Score >5 Optimum for fresh market |
|---------------|----------------------------------|--|--|
| 2014 | | | |
| Black | 43 | 29 | 28 |
| White | 25 | 38 | 37 |
| No Net | 26 | 34 | 40 |
| 2015 | | | |
| Black | 68 | 25 | 7 |
| White | 56 | 35 | 9 |
| No Net | 47 | 42 | 11 |

Colour management was required under the nets to ensure the colour and maturity meet at the same point. A reflective surface can ensure colour develops with the blush colour meeting market standards.

Maturity tests were undertaken from a sample of 10 apples from each treatment after the strip pick (table 7). The starch conversion guide for the maturity of Pink Lady™ Apples, the 1-6 scoring system was used to assess the apples. At picking, starch conversion scores were at 4, optimum for only short to medium controlled atmosphere storage (figure 17). The Total Soluble Sugar (TSS) was generally lower than the acceptable minimum standard of 13 percent in all areas testing at 11 percent after the first strip pick. The grower did 4 picks of the fruit to harvest the apples at the optimal time of maturity and colour meeting enabling sugar percentage to rise to the required 13 percent. The flesh firmness was measured on opposite sides of the apple averaging 8.2kg in 2015 and 8kg in 2014 with ideal firmness pressure greater than 6.1kg required.

Table 7. Average maturity testing, from the strip pick of a sample of 10 apples from each of the 10 monitoring trees.

| Treatment | Firmness kg | TSS (%) | Starch Index | Acid ml |
|-------------|----------------|------------|-----------------|------------|
| 2014 | | | | |
| Black | 7.3 | 11.8 | 4.0 | 9.0 |
| White | 7.8 | 12.0 | 3.9 | 10.5 |
| No Net | 8.9 | 11.4 | 3.5 | 11.7 |
| 2015 | | | | |
| Black | 8.2 | 10.7 | 4.1 | 10.2 |
| White | 8.2 | 11.4 | 4.3 | 8.7 |
| No Net | 8.2 | 11.0 | 4.1 | 8.9 |



Figure 17. Starch test on 28/4/2015 at the time of strip picking. Showing average starch index >4 suitable for medium to short term storage.

Yield

Both the strip picked data from the 10 monitoring trees in each treatment (table 8) and the commercial pick data from the remaining trees in the block (table 9) have been included to demonstrate the difference in the assessment and importance of working on a commercial property. Forty apples were assessed for size and quality from the strip picked trees.

Encouragingly, average fruit diameters from the strip pick were all very similar between treatments. There was a slight difference in average fruit weight, which when multiplied with the difference in average number of fruit per tree, contributed to the difference in extrapolated yield per hectare.

Table 8. Average fruit diameter, weight, fruit per tree and yield of non-damaged fruit based on strip harvest.

| Treatment | Harvest Date | Average fruit diameter (mm) | Standard Deviation of diameter | Average single fruit weight (g) | Average fruit number per tree | Extrapolated yield (t/ha) |
|-------------|--------------|-----------------------------|--------------------------------|---------------------------------|-------------------------------|---------------------------|
| 2014 | | | | | | |
| Black 2014 | 7/5/2014 | 71.6 | 0.35 | 165.6 | 121.2 | 71.0 |
| White 2014 | 6/5/2014 | 71.8 | 0.35 | 172.6 | 135.6 | 74.9 |
| No Net 2014 | 30/4/2014 | 71.6 | 0.62 | 172.4 | 74.2 | 42.4 |
| 2015 | | | | | | |
| Black 2015 | 29/4/2015 | 71.7 | 0.58 | 170.2 | 155.7 | 65.3 |
| White 2015 | 29/4/2015 | 72.0 | 0.61 | 162.6 | 143.3 | 57.4 |
| No Net 2015 | 1/5/2015 | 71.2 | 0.38 | 161.0 | 218.9 | 90.0 |

The data from the grower harvest (table 6) based on bins picked from the remaining 390 trees per treatment shows a slightly different story. The commercial yields are lower for black net and no net treatment, and higher under the white net. This is largely due to the increased number of trees per treatment, averaging out differences in fruit numbers and the staggered picking over several weeks, allowing for colour to guide the timing of harvest. This meant fruit with less blush than desired may have increased in size and weight before being picked by the growers, with some fruit left on the trees that were already over mature or not considered marketable.

Table 9. Grower yield per treatment total tonnes from each treatment. 2013 yield before netting installed.

| Treatment | 2013 | Harvest Date | 2014 | Harvest Date | 2015 | 2016 |
|---------------|------|--------------|------|--------------|------|------|
| Black | 9.7 | 21/5/2014 | 6.3 | 2/5/2015 | 8.0 | |
| White | 11.3 | 21/5/2014 | 7.7 | 2/5/2015 | 10.3 | |
| No net | 10.3 | 21/5/2014 | 7.0 | 2/5/2015 | 9.7 | |

The amount of sun damaged apples strip picked was less than 1 percent of the fruit picked from the 10 monitoring trees. The black net apples in 2014 had the lowest amount (69 percent) of the fruit marketable and had the highest (79 percent) marketable fruit in 2015. The no net was very stable

across the two harvests with the white net showing decreases in marketability in 2015 due to shape defects and under sized fruit (table 10).

Table 10. Percentage of fruit that was marketable, nonmarketable or had sun damage

| Treatment | % Marketable | % Non-marketable | % Sunburn[#] |
|------------------|---------------------|-------------------------|------------------------------|
| 2014 | | | |
| Black | 69.15 | 30.85 | 0.101 |
| White | 78 | 22 | 0.25 |
| No net | 74 | 26 | 2.5 |
| 2015 | | | |
| Black | 78.7 | 21.3 | 0.5 |
| White | 70.5 | 29.5 | 0.4 |
| No Net | 73.0 | 27.0 | 1.0 |

sunburn is a subset of non-marketable fruit.

In both seasons the damage from birds was minimal with no large losses from birds recorded before harvest in the rows under the black, white or no net. The apples strip picked from the monitoring trees had less than 1 percent of the fruit damaged by birds. There were no hail events during the monitoring period and so no damage from hail could be assessed. Other previous studies from Queensland have shown netting to be effective in preventing hail damage (Middleton and McWaters 2002).

Conclusions

Winter chill accumulation was monitored during the three years of the project. It was found that netting black or white had minimal impact on chill accumulation. This was also reflected in the mean monthly temperature which only varied by about half to one degree. There is a linear relationship between the air temperature of the black and white net and again when the nets are compared to the no net treatment block. The impact on chill conditions under the net was also seen in the flowering progression which was monitored under the nets in 2014 and 2015. In both years the black, white and no net trees monitored entered into the bud break and reached full bloom on the same day or within days of each other.

The environmental conditions under the nets were very similar although some slight differences can be seen in the weather data recorded. The humidity under the white net during summer was highest and lowest in no net block. The effect of high humidity was seen in the pest and disease management under the nets. In the first year after the nets were constructed woolly aphids were extremely bad under the nets and a high percentage of apples had bitter pit. European mites attacked under the nets in late December 2015, almost defoliating the trees. With pest and disease outbreaks more common under netting it is a matter of monitoring more frequently as the conditions under the nets are favourable to outbreaks. Although, pests and diseases are treatable they just require prompt management.

Solar radiation was the highest in no net followed by white and black net. The fruit surface temperatures recorded in the apples over the late summer period, were higher in the no net apples where the solar radiation was highest. The average difference between no net and the netted was around 3 degrees with the black and white nets only varying by one degree.

Measuring the amount of shade under the tree canopy it was found that tree vigour influenced the Photosynthetically Active Radiation. Outside the canopy the PAR followed the netting specifications rating of the netting black lowest then white and no net.

The fruit size was very similar in the three treatments, with slight differences in fruit weight and number of apples per tree after the strip pick. The grower yields were highest under the white net where the fruit had been allowed to stay longer on the trees. This was to ensure the apples gained more colour. Initial response in the first year yield was reduced due to bitter pit, woolly aphid and colour management.

Colour management is required under the nets to ensure the colour and maturity meet at the same point. A reflective surface can ensure colour develops with the blush colour meeting market standards.

The netting has proven to be successful at the Western Australia netting demonstration site in;

- reducing the impact of birds on the fruit
- reducing the fruit surface temperature
- with minimal impact on winter chill and flowering progression.

Table 11. Cripps Pink responses to Black, White and No Net at Western Australian Netting Demonstration Site.

| | Black Net | White Net | No Net |
|----------------------------------|------------------|------------------|---------------|
| Dormancy | | | |
| Chill Accumulation | No Effect | No Effect | No Effect |
| Flowering Progression | No Effect | No Effect | No Effect |
| Environmental data | | | |
| Air Temperature | No Effect | No Effect | No Effect |
| Fruit Surface Temperature | | | Highest |
| Humidity | | Highest Max | Lowest Min |
| Solar Radiation | Lowest | | Highest |
| Wind average speed | Highest | Lowest | |
| Yield and Quality | | | |
| Grower Yield | Lowest | Highest | |
| Colour | Best Background | Best Blush | Best Overall |
| Maturity | | Highest Sugar | Lowest Starch |

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Appendix

Presentations

Susie Murphy White 2015 Netting the Benefits of climate change. APAL Speed Updating 2015 <http://apal.org.au/research-development-extension/projects/research-reviews/> (accessed 8/3/2016)

Materials produced

Posters

- Murphy White S, Prince R and Starkie L 2015. Is there a difference between Black or White netting? (Manjimup Rotary 2015, Warren Districts Show 2016)
- Prince R, Murphy White S and Starkie L 2015. Benefits of good irrigation in netted apple orchards.

Fact Sheets

- Darbyshire R, 2014. Winter Chill and Fruit Trees. PICCC Research Fact Sheet www.piccc.org.au

Australian Fruit Grower magazine articles

- Murphy White S. June 2014. Netting the Benefits of a changing climate. (Volume 8 Issue 5)
- Prince R and Murphy White S. October 2015. Netting Trial results in Western Australia. (Volume 9 Issue 9)
- Murphy White S, Prince R and Starkie L. December 2015. Black or White netting, which is best? (Vol 9 Issue 11)

Web pages

<https://agric.wa.gov.au/n/4863>

<http://www.piccc.org.au/research/project/440>

<http://www.hin.com.au/projects/winter-chill-and-fruit-trees>

<http://apal.org.au/research-development-extension/projects/apple-pear-production-changing-climate/>

Apple yield response to climate change and netting

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Summary

The effect of increased temperature on potential yield of early-season apples in northern Victoria was investigated using the physiological model MaluSim (Lakso and Johnson 1990). Impacts of netting on yield were also investigated using observed data and MaluSim. With a climate change scenario of a 2 °C increase in maximum and minimum air temperatures, MaluSim predicted increased fruit weights and yields when crop loads were low. However, at higher crop loads, yield potential decreased due to greater source limitations resulting from decreased daily photosynthesis in response to high temperatures later in the season. Overall, the effects of a 2 °C increase in air temperatures on potential yields of Royal Gala apples in northern Victoria were small (+1.3 to -1.6 t/ha, depending on crop load and presence or absence of netting). Yield potential was higher for non-netted trees than netted trees but observed yields were lower for non-netted trees. This highlighted the benefits of netting in reducing crop damage and the influence of orchard management on actual yield.

Evaluation of the performance of MaluSim in predicting yield of Royal Gala apples in north Victoria supported use of this model for preliminary investigation of climate change impacts on yield. However, limitations of use of the model for this purpose were identified and are briefly discussed in this report. Additionally, long-term investigation of the impact of elevated CO₂ on apple yield is required to more accurately predict climate change impacts. A greater understanding of the impact of temperature shifts on fruit maturation, colour development and phenology would further improve predictions of yield under different climate scenarios.

1. Introduction

Mean temperatures for coastal and inland Australian apple growing regions are predicted to rise by 0.7-0.9°C and 1-1.2°C, respectively, by 2030 (Putland *et al.* 2011). Previous research has identified a range of potential impacts of predicted climate change on the productivity and profitability of the Australian apple and pear industries (Putland *et al.* 2011; Darbyshire *et al.* 2013). Climate change has the potential to affect potential productivity of pome fruit trees through effects of changing environmental conditions on the orchards net carbon exchange (difference between photosynthates produced and expended for respiration; Putland *et al.* 2011 and references within). Netting provides a climate adaptive option, particularly for severe weather events such as extreme heat or hail, and is increasingly being installed by growers. Industry has made significant investment in netting infrastructure despite remaining practical questions on the use of hail netting, particularly in warm growing regions. The reduction of solar radiation under netting may influence physiological responses to climate change.

An apple physiological model (MaluSim, Lakso and Johnson 1990) has been used to understand the effects of predicted climate change on net carbon exchange of apples and the upper limit of apple production (yield potential). The aims of this study were to:

- evaluate the model MaluSim with regard to prediction of apple yield under Australian conditions; and
- predict apple yield in netted and non-netted orchards under warmer climate conditions using MaluSim.

Use of the model 'MaluSim' (Lakso and Johnson 1990) to predict apple yield was evaluated in 2012/13 for Royal Gala apples grown at a site in northern Victoria. This site was selected as two adjacent blocks were netted and non-netted. This provided an opportunity to evaluate MaluSim with and without the adaptation option of over-tree netting. Data was collected from 10 trees for both netted and non-netted trees and measurements for each of the 10 trees were treated as repeat observations. Broader evaluation of the model was conducted by the PICCC project, 'Crossing the threshold: adaptation tipping points for Australian fruit trees' and reported by Darbyshire and McClymont (2016).

A future climate scenario of a +2 °C increase in maximum and minimum daily temperatures was investigated for netted and non-netted orchards and compared to a current season (2012/13). To create the future scenario, temperature data from 2012/13 was increased by + 2 °C, 2012/13 solar radiation values were unchanged and other tree parameters were standardised based on observations or default parameters within the model. Fruit weight predictions were compared to predictions based on 2012/13 weather data. Calculations of cumulative tree photosynthesis, respiration and dry weight accumulation, and daily photosynthesis and fruit carbon demand and supply were examined to better understand fruit weight and yield responses suggested by the model.

2. Methods and materials

2.1 Evaluation of ‘MaluSim’

The MaluSim model is a simplified dry matter production model that relies primarily on temperature and radiation inputs to predict carbohydrate accumulation (Lakso and Johnson 1990, Lakso 1992, Lakso et al. 2001, Lakso et al. 2006). The model is written in STELLA and, consequently, can be easily modified by users (Zibordi 2010). It has been shown to behave realistically in a number of apple growing regions and in response to factors such as short-term low light (Lakso et al. 2001). The model operates on a daily time step at the tree scale and balances carbohydrate supply against demand for a ‘standard’ tree. Parameters associated with a ‘standard’ tree (e.g. dates of key phenological events, number of fruit per tree, tree spacing, length of growing season, shoot and spur numbers) can be modified in the model. Required data are summarised in Table 1.

Table 1. Required datasets for MaluSim calibration.

| Dataset | |
|----------------------|---|
| Model inputs | |
| Site parameters | Tree and row spacing, Latitude |
| Weather | Maximum and minimum daily air temperature, Total daily solar radiation |
| Phenology | Date of budburst and harvest |
| Vegetative growth | Shoot and spur number or canopy radiation interception |
| Reproductive sinks | Fruit number per tree (at harvest) |
| Model outputs | Average fruit fresh weight |

2.1.1 Study site and collection of required datasets for model evaluation

Royal Gala apple was selected for evaluation of MaluSim as paired netted and non-netted sites were available, allowing investigation of any impact of netting on potential yield.

The study orchard was a Royal Gala block located at Geoff Thompson’s North Shepparton orchard. The selected block was predominantly covered by permanent netting but five rows on the eastern side of the block were uncovered. Tree age, variety, rootstock and most management activities did not differ between netted and non-netted trees. Data for evaluation of MaluSim were collected during the 2012/13 season.

Table 2 Description of the study site

| Site | Season | Latitude | Longitude | Tree and Row spacing | Training System | Row Orientation |
|------------|---------|----------|-----------|----------------------|-----------------|-----------------|
| Shepparton | 2012/13 | -36.33 | 145.40 | 1.5 x 4.8 m | Central-leader | NNW-SSE |

Weather stations were located within the netted and non-netted orchard areas to measure daily maximum and minimum air temperature ($^{\circ}\text{C}$; HMP155, Vaisala Oyj, Vantaa, Finland) and daily total solar radiation ($\text{MJm}^{-2}\text{day}^{-1}$; SPN1, Delta T Devices Ltd, Cambridge, UK). Data were logged (dataTaker DT80M, Thermo Fisher Scientific Inc, Yokohama, Japan) from 15 December 2012 at 1 minute intervals during January, and at 10 minute intervals at other times of the year. Meteorological data between budburst and 15 December 2012 were interpolated from relationships established for radiation and temperature over the remainder of the season between a nearby weather station and the onsite stations.

Budburst day-of-year (DOY = 248) was estimated based on date of flowering at the site and date of budburst of Gala at a nearby orchard. Fruit number at harvest and canopy radiation interception data were collected from 10 trees for both netted and non-netted sites. Measurements for each of the 10 trees were treated as repeat observations. Fruit were colour picked over a two week period in late-January and early-February. Fruit number and fruit weight were recorded at each pick and the mid-date of harvest (31 January 2013) was used as the harvest day-of-year in MaluSim. Light interception measurements at full canopy, prior to harvest, for each tree were taken in January 2013. A ceptometer was used to measure light interception in the morning, at midday and in the afternoon. Daily light interception was calculated by averaging the morning, midday and afternoon measurements.

2.1.2 Comparison of observed and predicted fruit weight, 2012/13 season

Two parameterisations of MaluSim were run for analyses. Firstly, the default MaluSim values were used (Netted-Default and NonNetted-Default) and secondly, alternate values for shoot and spur numbers were used to adjust the modelled light interception values to be similar to measured values (Netted-Light Interception and NonNetted-Light Interception). To set the adjusted shoot and spur numbers, MaluSim was rerun for each tree with progressive adjustments to shoot and spur numbers (maintaining the ratio of shoots to spurs to match that of the default values) until the predicted light interception was within $\pm 2\%$ of the observed light interception. For both parameterisations, the netted and non-netted data were evaluated independently as well as combined. Use of the default maximum fruit growth rate was considered to be a reasonable assumption for an initial investigation of model performance as Empire and Royal Gala are both early season apple varieties.

2.2 Predictions of apple yield under a warmer climate

A future scenario of a $+2^{\circ}\text{C}$ increase in maximum and minimum daily temperatures was investigated for netted and non-netted orchards by inputting solar radiation data and adjusted air temperature data ($+2^{\circ}\text{C}$) from 2012/13 to MaluSim with other (site, phenology and tree) parameters standardised. Site and phenology inputs were unchanged from those used in the initial model evaluation (section 2.1). Default shoot and spur numbers (194 and 343, respectively) were used. Crop load (fruit number per tree) was varied from 25 to 450 to ensure any lack of response to changed climate conditions was not due to sink-limited yield restrictions.

Fruit weight predictions for 2012/13 were compared with predictions using the $+2^{\circ}\text{C}$ scenario. Cumulative tree photosynthesis, respiration and dry weight accumulation, and daily photosynthesis and fruit carbon demand and supply were examined to better understand fruit weight (yield) responses suggested by the model.

3. Results

3.1 Evaluation of 'MaluSim'

The results using default parameters of MaluSim tended to overestimate fruit weight compared with observed fruit weight (Figure 1A). Combining both the netted and non-netted results, RMSE was 39 g which equates to a 28 % error in estimating mean fruit weight (Table 3). Using the default parameters, the predicted fruit weights for the Netted site were more accurate than those for the Non-Netted site, RMSE 14 and 36 g (9 and 29 % of mean fruit weight), respectively (Table 3).

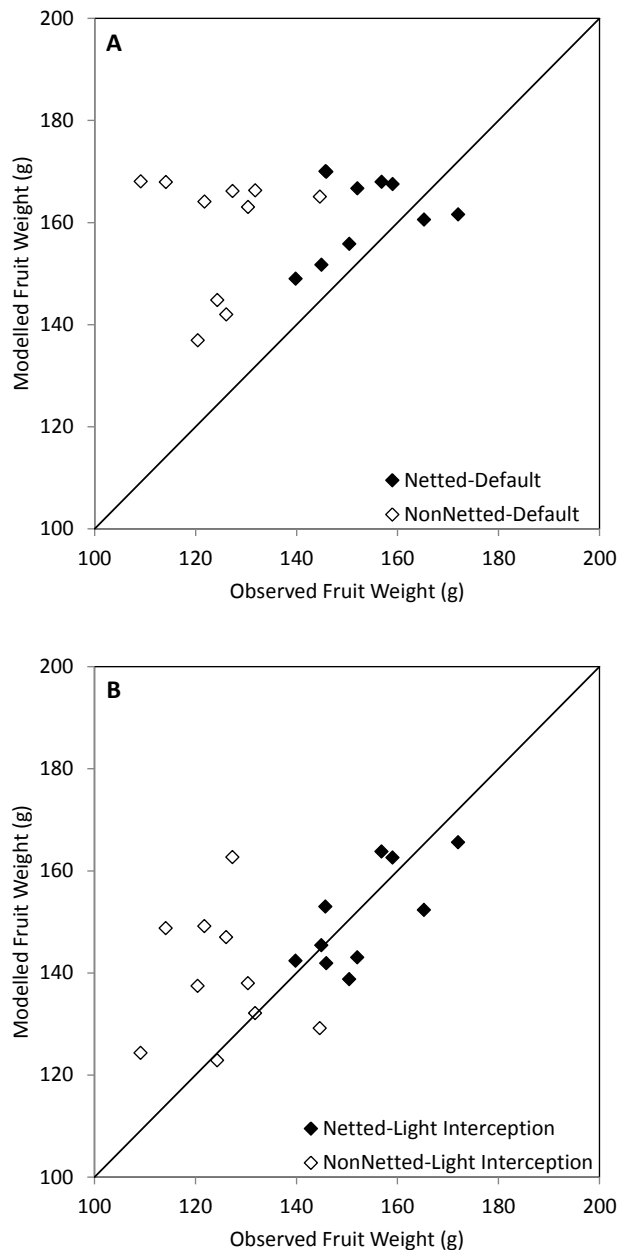


Figure 1 MaluSim predicted and observed mean fruit weight (fresh weight in grams) for netted and non-netted trees in 2012/2013. **A)** MaluSim fruit weight predictions using default shoot and spur number inputs. **B)** MaluSim fruit weight predictions using adjusted shoot and spur numbers.

Table 3 Statistics of MaluSim predicted and observed fruit weight at Royal Gala Netted and NonNetted sites using default shoot and spur numbers (Default) and adjusted shoot and spur numbers to align light interception values in the model with measured values.

| Site | Coefficient | p-value | R ² | RMSE (g) |
|-------------------------------|-------------|-------------|----------------|-----------|
| Netted-Default | 0.20 | 0.47 | * | 14 |
| NonNetted-Default | 0.05 | 0.92 | * | 36 |
| All-Default | 0.13 | 0.35 | | 39 |
| Netted-Light Interception* | 0.98 | <.001 | 0.46 | 8 |
| NonNetted-Light Interception | -0.08 | 0.86 | * | 21 |
| All-Light Interception | 0.39 | 0.02 | NA | 22 |

*linear model intercept was not significant, statistics are for analysis omitting the intercept

The model predictions using parameterised adjustments of shoot and spur numbers were improved for both the netted and non-netted trees (Figure 1 and Table 3). For the combined data, RMSE was improved to 22 g or 16 % of the mean fruit weight. MaluSim better predicted fruit weight for the netted trees with RMSE of 8 g or 5 % of the mean fruit weight. In comparison, predictions for the non-netted trees yield RMSE of 21 g or 17 % of mean fruit weight.

3.2 Predictions of apple yield under a warmer climate

Potential fruit weight was predicted using MaluSim for two main scenarios:

1. **2012/13:** Measured daily maximum and minimum air temperatures from the 2012/13 season, with a range of crop loads for netted and non-netted Royal Gala orchards in north Victoria.
2. **+ 2 °C:** Adjusted air temperatures (2012/13 temperatures + 2 °C), with a range of crop loads for netted and non-netted Royal Gala orchards in north Victoria.

3.2.1 Weather inputs

Total solar radiation was 20 % lower under netting than in the non-netted site. Daily maximum air temperature varied slightly between netted and non-netted sites with a tendency on hot days for maximum air temperature under netting to be less than the non-netted site. Prior analysis of weather data showed that air temperature was similar at netted and non-netted sites (Milestone Report 2, McClymont and Goodwin 2013, McClymont et al. 2013).

Table 4 Summary of measured weather inputs at netted and non-netted sites during the 2012/13 season. Max AT = maximum air temperature, Min AT = minimum air temperature, Daily Rad = total daily solar radiation.

| | Netted | | | Non-netted | | |
|----------------|--------------|-------------|--|--------------|-------------|--|
| | Max AT (°C) | Min AT (°C) | Daily Rad (MJm ⁻² day ⁻¹) | Max AT (°C) | Min AT (°C) | Daily Rad (MJm ⁻² day ⁻¹) |
| Ave (± st dev) | 26.5 (± 6.7) | 9.5 (± 4.5) | 19.7 (± 6.7) | 27.2 (± 6.7) | 9.5 (± 4.5) | 24.4 (± 8.2) |
| Max | 41.8 | 21.3 | 28.2 | 42.8 | 21.4 | 34.9 |
| Min | 13.0 | -0.3 | 2.7 | 13.5 | -0.3 | 3.4 |

3.2.2 MaluSim calculation of photosynthesis, respiration and dry matter accumulation

MaluSim calculates daily photosynthesis based on canopy interception of daily solar radiation with adjustments to photosynthetic rate dependent on air temperature (Darbyshire and McClymont 2016). Over the period from budburst to harvest, similar leaf area and canopy light interception were generated by MaluSim for each scenario, with only slight differences between netted and non-netted sites and no differences for differing crop loads (Table 5). Leaf area development was more rapid under the + 2 °C scenario than the **2012/13** scenario (data not shown).

Table 5 Leaf area and canopy light interception predicted at harvest by MaluSim under **2012/13** (2012/13 season air temperature data) and + 2 °C (2012/13 season temperatures + 2 °C) scenarios at netted (Net) and non-netted (NN) sites.

| Scenario | Leaf area (m ²) | | Light interception (%) | |
|----------|-----------------------------|------|------------------------|------|
| | Net | NN | Net | NN |
| 2012/13 | 10.9 | 11.0 | 41.9 | 42.0 |
| + 2 °C | 11.0 | 11.0 | 42.1 | 42.0 |

Over the budburst to harvest period, cumulative photosynthesis was effectively unchanged by increased air temperatures (+ 2 °C scenario) and was approximately 10 % lower at the netted site than the non-netted site (Table 6). However, daily photosynthesis during the first 70 – 75 days of the season was greater under the + 2 °C scenario than the **2012/13** scenario (Figure 2). After this time, daily photosynthesis tended to be greater under the **2012/13** scenario than the + 2 °C scenario (Figure 2).

Table 6 Photosynthesis, respiration and dry matter accumulation between budburst and harvest predicted by MaluSim under **2012/13** (2012/13 season air temperature data) and + 2 °C (2012/13 season temperatures + 2 °C) scenarios at netted (Net) and non-netted (NN) sites with a range of crop loads.

| Crop load (fruit/tree) | 2012/13 | | | | | | + 2 °C | | | | | |
|---------------------------|--|-------|-------------------------------------|------|------------|------|--|-------|-------------------------------------|------|------------|------|
| | Photosynthesis (g CO ₂) | | Respiration (g CO ₂) | | Dry Matter | | Photosynthesis (g CO ₂) | | Respiration (g CO ₂) | | Dry Matter | |
| | Net | NN | Net | NN | Net | NN | Net | NN | Net | NN | Net | NN |
| 25 | | | 2220 | 2291 | 1805 | 1846 | | | 2730 | 2793 | 1804 | 1843 |
| 50 | | | 2256 | 2328 | 2252 | 2302 | | | 2774 | 2840 | 2294 | 2338 |
| 75 | | | 2291 | 2365 | 2693 | 2758 | | | 2816 | 2885 | 2756 | 2821 |
| 100 | | | 2325 | 2402 | 3117 | 3201 | | | 2858 | 2929 | 3208 | 3289 |
| 150 | | | 2392 | 2472 | 3928 | 4047 | | | 2938 | 3014 | 4023 | 4139 |
| 207* | 12637 | 13875 | 2462 | 2549 | 4707 | 4882 | 12758 | 13867 | 3020 | 3104 | 4751 | 4937 |
| 250 | | | 2510 | 2601 | 5162 | 5403 | | | 3073 | 3163 | 5111 | 5371 |
| 300 | | | 2557 | 2655 | 5525 | 5846 | | | 3126 | 3221 | 5396 | 5708 |
| 350 | | | 2597 | 2702 | 5775 | 6157 | | | 3169 | 3272 | 5562 | 5923 |
| 450 | | | 2659 | 2776 | 6039 | 6506 | | | 3237 | 3352 | 5759 | 6182 |

*Average number of fruit per tree observed in 2012/2013.

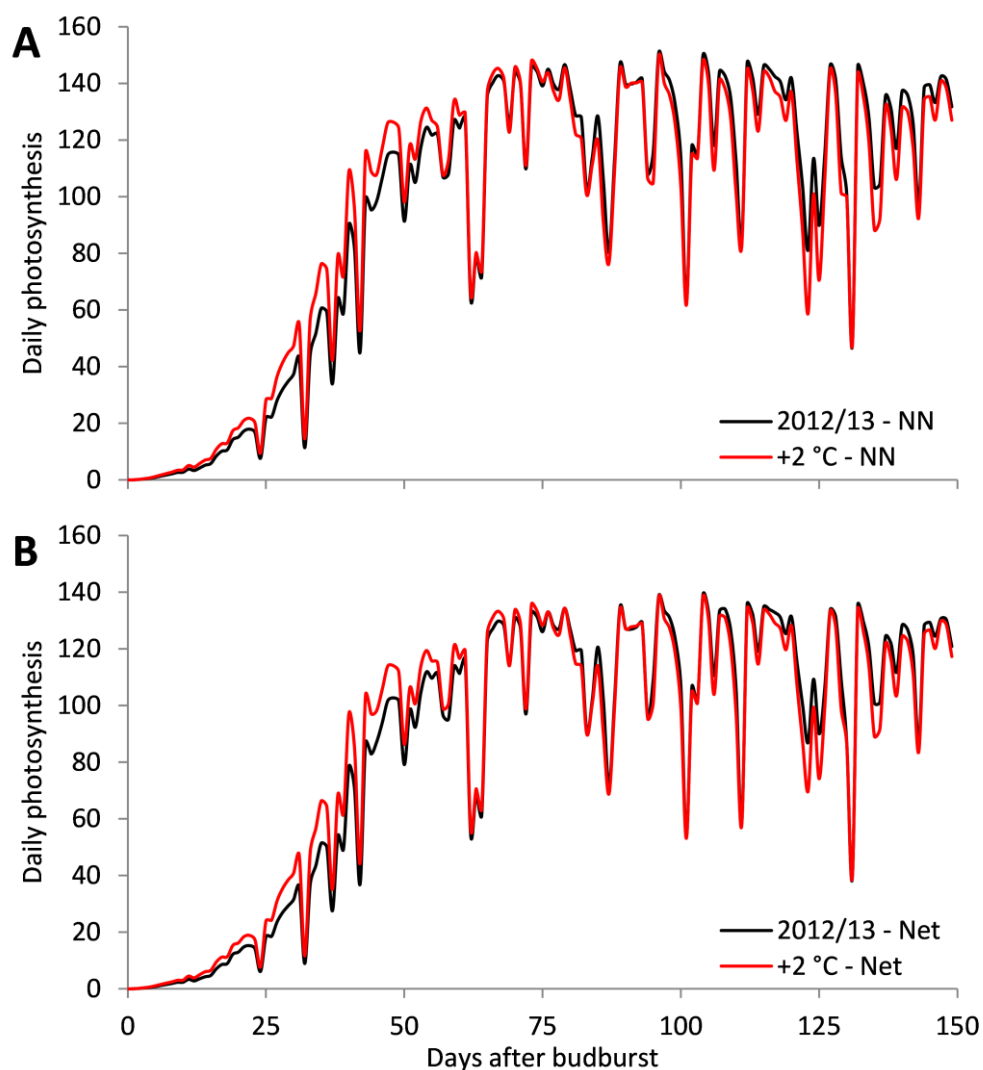


Figure 2. Daily photosynthesis (g CO₂/day) between budburst and harvest under measured 2012/13 temperature conditions (2012/13) and with a 2 °C temperature increase (+2 °C) for **A)** non-netted (NN) and **B)** netted (Net) Royal Gala trees

MaluSim calculates daily respiration by an exponential relationship dependent on air temperature and scaling for the size of plant parts (Darbyshire and McClymont 2016). Over the budburst to harvest period, cumulative respiration was approximately 20 % greater in response to increased air temperature (+ 2 °C scenario, Table 6). Respiration was slightly lower at the netted site than the non-netted site for **2012/13** (3 – 4 % lower, depending on crop load) and + 2 °C (2 – 3 % lower) scenarios. Respiration increased with increasing crop load due to increased total respiration by greater numbers of fruit.

Dry matter accumulation is a function of demand of plant parts for photosynthate and supply (photosynthesis - respiration). Predictably, dry matter accumulation increased with increasing fruit number as more 'sinks' were able to utilise produced photosynthates. Similarly, greater photosynthate production at non-netted sites (compared to netted sites) enabled greater dry matter production, despite slightly higher respiration. Response of dry matter accumulation to increased air temperatures varied, depending on crop load. Dry matter production was similar or higher under the + 2 °C scenario when fruit number was 250 or less, and lower when fruit number was 300 or more.

3.2.3 MaluSim prediction of fruit weight and daily balance of fruit CO₂ supply and demand

MaluSim partitions dry matter between plant parts (shoots, fruits, wood, and roots). The amount of dry matter partitioned to fruits determines fruit weight. Demand by the different plant parts for photosynthates varies through the season. For example, demand by shoots for photosynthates increases rapidly from the start of season, peaking after approximately one month and then decreasing until shoot growth ceases. Whereas fruit demand for photosynthates is low early in the season and increases steadily mid-season until a peak potential growth rate is reached prior to harvest. Under excess carbon supply circumstances, each growing part is allocated its full demand of dry matter. When photosynthate supply is limited, the growing parts compete for resources. The “strength” of each growing part to compete differs with shoots the strongest followed by fruit, wood and roots. Under limited supply conditions, dry matter allocated to fruit is less than the demand to grow at maximum potential.

For the **2012/13** and **+2 °C** scenarios, predictions of fruit weight fell as fruit number per tree increased (Figure 3A) but yield (fruit weight x fruit number) continued to increase (Figure 3B) over the range of modelled crop load (25 to 450 fruit per tree). For crop loads between 25 and 100 fruit per tree, there was little change in predicted fruit weight with increasing crop load, suggesting that yield was predominantly sink-limited (i.e. potential supply of photosynthate to fruit was greater than fruit demand). At higher crop loads (150 fruit per tree and greater), fruit weight began to decline steadily, indicating that, at least on some days, fruit growth was source-limited (i.e. supply of photosynthate was not meeting fruit demand). Yield began to plateau at a crop load of approximately 300 fruit per tree. For both **2012/13** and **+2 °C** scenarios, predicted fruit weights and yields were lower for the netted site than the non-netted (Figure 3). These differences were primarily due to decreased radiation under netting, leading to decreased photosynthate production.

For netted and non-netted sites, MaluSim predicted a slight increase in fruit weight and yield with a +2 °C increase in temperature at low crop loads (< 250 fruit per tree, Figure 3). However, at higher crop loads, increased temperatures (+2 °C scenario) resulted in reductions in predicted fruit weights and yields (for the given crop load, Figure 3) from more respiration. The largest predicted fruit weight was 186 g (+2 °C scenario without netting and a crop load of 25 fruit per tree). The smallest predicted fruit weight was 100 g (+2 °C scenario under netting with a crop load of 450 fruit per tree). The highest yield predicted was 71.3 t/ha (**2012/13** scenario without netting and a crop load of 450 fruit per tree).

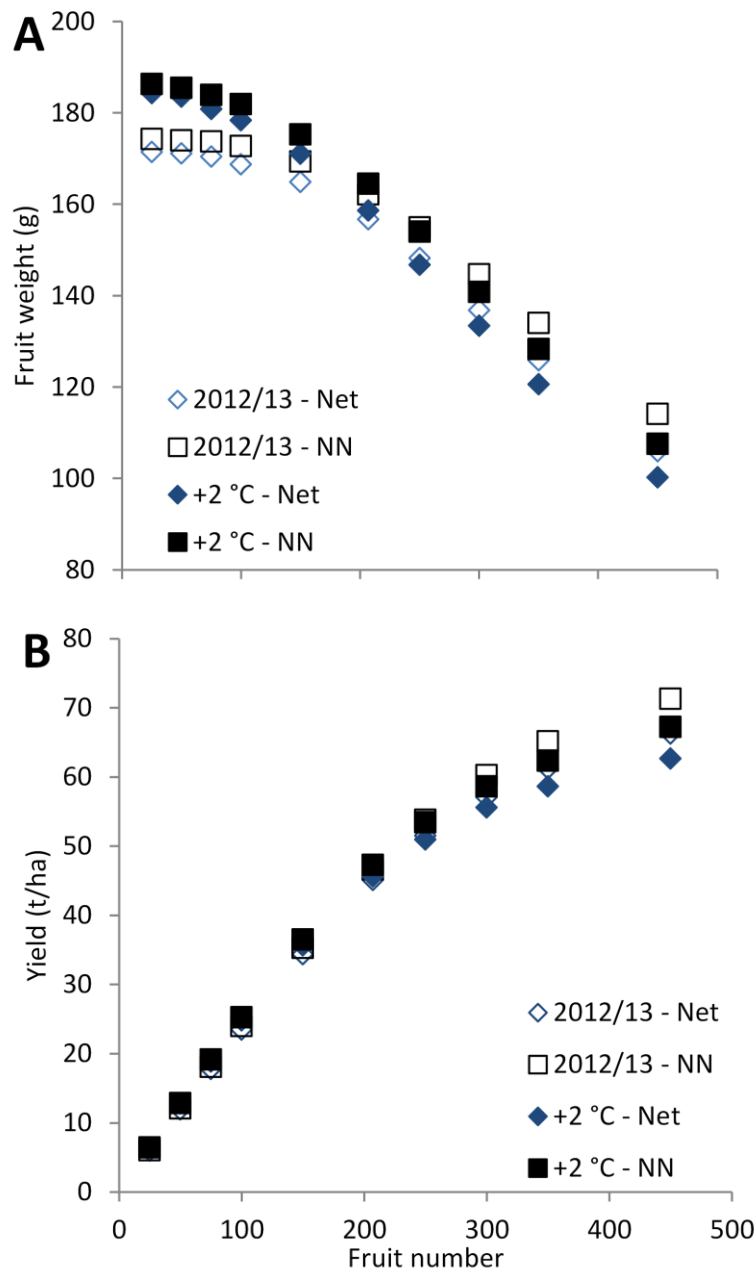


Figure 3 Predicted **A)** fruit weight and **B)** yield under measured 2012/13 temperature conditions (2012/13) and with a 2 °C temperature increase (+2 °C) for netted (Net) and non-netted (NN) Royal Gala trees.

At low crop loads, trees were able to match supply of photosynthates to fruits with demand on most days (Figure 4), resulting in high fruit weights. At higher crop loads, supply of photosynthates to fruits did not match demand on a greater number of days (due to increases in respiration). Figure 4 demonstrates how timing of availability of photosynthates and fruit growth patterns could influence fruit growth and yield responses to warmer climate scenarios. Fruit demand for photosynthates was predicted to be higher under the +2 °C scenario than the 2012/13 scenario. Although total production of photosynthates was similar under the +2 °C and 2012/13 scenarios, timing of availability differed. More photosynthate was available under the +2 °C scenario (than the 2012/13 scenario) early in the season, coincident with low fruit demand (Figures 2 and 4). Later in the season (when fruit demand for photosynthate was greater), the 2012/13 scenario tended to have more photosynthate available (Figures 2 and 4).

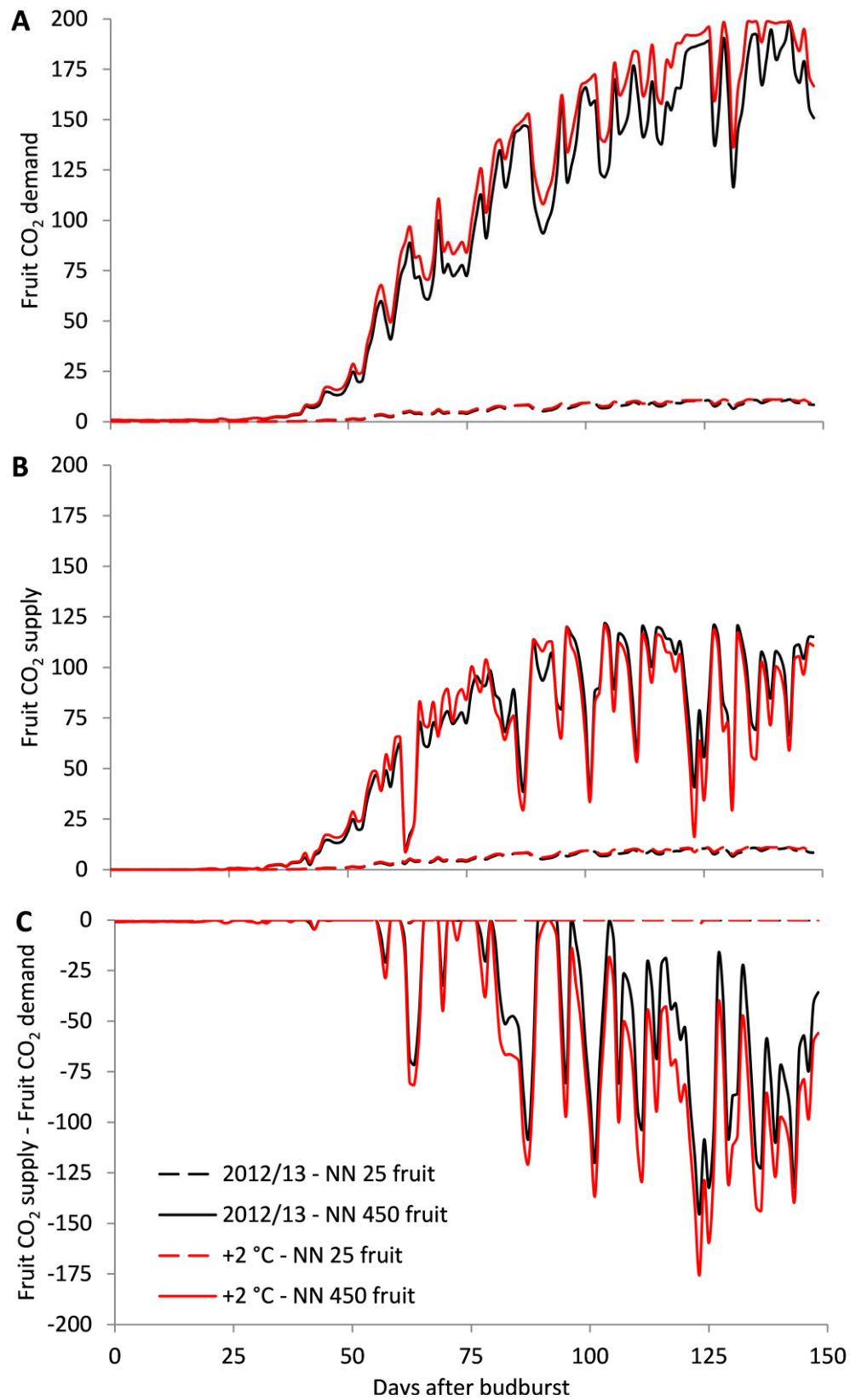


Figure 4. Effects of increased temperatures and crop load on daily **A)** fruit demand for photosynthates, **B)** supply of photosynthates to fruit and **C)** the balance between supply and demand for photosynthates.

4. Discussion and Conclusions

4.1 Evaluation of 'MaluSim'

The predictive ability of MaluSim for Royal Gala was found to be adequate if adjustments to shoot and spur numbers, in line with observed light interception values, are made. MaluSim better predicted fruit weight for netted compared with non-netted trees. MaluSim tended towards overestimating fruit weight for the non-netted trees (points above the line Figure 1). This is more likely the result of management intervention than differential model performance between netted and non-netted systems.

Potential causes of the modelled overestimate for the non-netted trees may be due to tree stress and/or crop load management. Considering tree stress, evaporative demand, and hence tree water requirement, is higher in non-netted orchards than netted orchards. Non-netted trees may have suffered transient water stress if either irrigation volume or frequency of irrigation events did not match tree water requirements. Noting that the orchard manager did supply more water to the non-netted trees, it is not clear whether this was sufficient to avoid tree stress.

Regarding crop load management, the non-netted site was thinned later than the netted site. This means that less carbon was available for the early-season growth of retained fruit on the non-netted trees compared with the netted trees. This could have contributed to slower fruit growth rates early in the season in the non-netted trees than the netted and subsequent lower than predicted fruit weight at harvest.

MaluSim was designed as a model to evaluate potential yield. That is, expected yield assuming ideal conditions. Given the model design for potential yield, not field yield, it is reasonable to expect the model will have a tendency to overestimate fruit weight in many commercial orchard situations. Furthermore, evaluation of the performance of MaluSim needs to consider possible measurement errors (i.e. errors in model inputs and observed parameters), use of the model outside the range of parameters for which it was constructed, and failure of observations to meet particular model assumptions. At a practical level, the programming language used for MaluSim (Stella), limits use of MaluSim for investigation of potential climate impacts. Ideally, such investigations would involve modelling many iterations of simulated weather data to account for natural variability in climate and use of multiple climate change models. At present, MaluSim requires the user to 'run' each scenario individually and manually extract data summaries, making such detailed investigations impractical. These issues are discussed in greater detail by Darbyshire and McClymont (2016), who concluded that positive validation of MaluSim under Australian conditions was not achieved, based on poor prediction of yield by MaluSim for Royal Gala and Cripps Pink at multiple sites in Australia. However, performance of MaluSim in predicting fruit weight of Royal Gala trees at the North Shepparton site, with adjustment for light interception and consideration of environment and management impacts, supported use of the model for preliminary investigation of influences of climate change on potential yield.

4.2 Predictions of apple yield under a warmer climate

The following points consider the main findings of modelling potential yield under a warmer climate and factors that could modulate yield response or improve model performance are discussed.

- The predicted impact of increased temperatures (+ 2 °C) on yield was minor under the conditions modelled in this investigation (-1.6 to +1.3 t/ha) dependent on crop load and presence or absence of netting).
- Given that growers are most likely operating in the medium to high crop load range, yield of Royal Gala apples in north Victoria would be expected to remain unchanged or fall slightly under a warmer climate. This outcome is similar to that projected by Stockle et al. (2010) for apples grown in Washington State, USA. Although the response predicted by Stockle et al. appeared to be based on earlier harvest date. Whereas yield loss in our modelling resulted from source limitations during the fruit growth period.
- Yield could be maintained by increasing crop load. However, at high crop loads, additional yield loss may occur due to increased downgrading or cullage of small fruit as average fruit weight falls. Avoidance of such additional losses would require either adjustment of market expectations regarding fruit size or improved crop management to decrease variability in fruit size.
- Predicted yields were lower under netting than without netting. Observed yields did not support this finding and in the medium to long-term, netting would offer greater yield potential because of decreased occurrence of sunburn and hail damage. It is noted that, netting reduced solar radiation by approximately 20 % at the north Shepparton site. Modelling a greater reduction in solar radiation (30 %) lowered the crop load at which fruit weight and yield began to fall in response to increased air temperatures (data not shown).
- The modelling undertaken in this investigation assumed no changes to budburst or harvest date with increased temperatures. Darbyshire et al. (2016) reported that that most pome fruit growing regions in Australia will have similar flowering phenology timing for 2030 whilst progressive delays are expected for 2050 and 2090. Maturity and harvest could occur earlier (Warrington et al. 1999, Stockle et al. 2010) or later (Iglesias et al. 2002) under a warmer climate, with associated decreases or increases in yield potential, and any shift will be influenced by both physiological impacts of higher temperatures and market expectations regarding fruit maturity and colour. Colour development would most likely be impaired by higher temperatures (Faragher 1983, Iglesias et al. 2000, 2002).
- This investigation focussed on the period from budburst to harvest. Later season effects, including timing of leaf fall, should be considered. Accumulation of reserves during the period from harvest to leaf fall will affect tree performance in the following season (Greer et al. 2002).
- Royal Gala is an early season variety and is picked in late January. Late season varieties may experience greater negative impacts of increased temperatures on accumulation of photosynthates during the fruit growth period and, subsequently, yield.
- A uniform increase in air temperature is unlikely across the season. Use of a climate model that predicts within season variation in temperatures could further emphasise disparities between photosynthate supply and demand at particular growth stages.
- The modelling undertaken in this investigation did not consider possible effects of elevated atmospheric carbon dioxide (CO₂) concentrations. To include this aspect, greater

understanding of apple tree functioning under both higher CO₂ levels and higher temperatures need to be understood. Stockle et al. (2010) estimated changes in apple yield under future climate change with and without an enhancing effect of CO₂. Without an enhancing effect of CO₂, apple yields were projected to fall slightly. Increases in yield were expected when increased CO₂ was incorporated in modelling. However, notably they commented that “projections for apples are more uncertain as tree fruit models are less developed and previous studies are not available”.

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Understanding apples and pears in a changing climate: overview of the grower workshops

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September 2016

Grower Workshops 2013

Three technical working group meetings were conducted during August (Queensland), September (South Australia) and October (Victoria), involving 32 growers, industry representatives and service providers. The purpose of the technical working groups was to present relevant local research outcomes as well as identifying gaps in growers' knowledge around climate change that could be addressed at a later date.

The technical working group locations and members were identified using input from DAFWA, DAFF QLD, DEPI VIC, Lenswood Co-op and APAL; South Australia was suggested by APAL. Each technical working group was based on an already existing group, and the meetings scheduled to coincide with other meetings to gain maximum feedback and avoid meeting fatigue and poor attendance.

Format and information provided was tailored to the specific needs of the group based on input from local industry development officers, APAL and the research organisations involved. The Queensland working group session was structured around a presentation of the current project as well as a questionnaire and the South Australian and Victorian sessions started with an interactive presentation about chill, and, in the case of Victoria, fruit temperature, followed by a 60-90 minute facilitated Q&A session.

Outcomes from the workshops varied depending on the location:

- The Queensland workshop discussions focussed on the impact of extreme weather, with most growers agreeing that climate change and climate variability impacted on their orchards; lack of rain, rain at the wrong time, erratic bloom, poor colour development and hail damage all scored highly in the survey.
- In South Australia the discussions centred on inconsistency in the reporting of chill; depending on the model used, chill hours, chill units or chill portions. The lack of conversion factors was mentioned. Only the dynamic model, which uses chill portions, predicted a high chill season based on local data. This was consistent with the short intensive flowering observed. Post-session feedback was positive with suggestions made to repeat the working group next year, albeit to a larger audience as part of the national workshop series.
- In Victoria discussions also focussed on chilling models and temperature thresholds that lead to heat-related fruit damage in the Goulburn Valley. Again, informal feedback was

positive with the suggestion made to communicate more results as they become available through emails or workshops.

Grower workshops 2014

Three workshops for apple and pear producers were conducted in production regions in collaboration with apple and pear growers' organisations during May (Victoria), July (Queensland) and September (Western Australia). Nearly 50 producers, industry representatives and service providers participated. The purpose of the workshops was to present an outline of the project, to present relevant local research outcomes and to review the last season to identify production trends and issues, share lessons learnt and identify future trends and issues.

Nearly 50 producers, industry representatives and service providers participated in this round of workshops. The purpose of these workshops was to present research outcomes from the first three years of the project such as the modelled predictions for the regions and relevant local climate change impacts as well as adaptation strategies, and to seek feedback on the past season, perceived climate change risks and the project itself. Each interactive workshop was tailored to the individual needs of the three targeted groups through either general presentations on climate change research, intensive training in the Climate Change Risk Management Matrix, and/or site specific presentations on modelled chill requirements and heat damage projections.

Additionally, in order to reach a much wider pome fruit audience, project outcomes were highlighted at the 2015 National Horticulture Convention of APAL and AUSVEG, where team members across all participating research organisations were present at the Horticulture Centre of Excellence stand to answer growers' questions and get feedback on the project.

Grower workshops 2015

Three workshops were held in apple and pear production regions to communicate up-to-date research outcomes such as the model predictions from the last three years to industry in a consistent manner as well as gathering information about the past season, perceived climate change risks and feedback on the project to 48 growers.

Each workshop was held in conjunction with, or as part of, an industry forum/meeting/tour to attract as many growers as possible and to avoid meeting fatigue.

The workshops were held in Applethorpe (QLD) in conjunction with the Perth Hills Orchard Improvement Group during their QLD study tour in July; as a stand-alone Climate Change Risk Management Matrix session with QLD growers in Applethorpe in July; and a climate change workshop in Bilpin (NSW) in September.

Seventeen growers from the Perth Hills Orchard Improvement Group visited the Applethorpe Research Station as part of their QLD study tour. As the central part of their half day tour of the research station, a climate change workshop event was held to discuss some of the outcomes from current research and, in particular, some of the issues facing the growers in the Perth Hills district. This region was not part of the WA grower workshop event held in Manjimup in 2014.

During the workshop, presentations were made by Heidi Parkes, Peter Nimmo and Allan McWaters about the climate change research project currently underway including the modelled predictions, management of QFF (one concern under a changed climate) and new apple varieties better suited to different disease and climate pressures.

The Climate Change Risk Management Matrix is a tool developed by DAF QLD to address uncertainty by identifying the impacts, risk and vulnerability associated with climate change and adaptive responses. Identifying and analysing risks and opportunities, using this risk management approach, can help to plan responses to climate variability and climate change and thus enable growers to be proactive and more effective in adapting to future uncertainty. This tool has been adapted to be used not only in grains and meat and wool production but also in horticulture.

As New South Wales has not been included in former National Roadshow tours and based on interest shown from the Sydney Basin area, Kevin Dodds from NSW DPI and an interested grower in Bilpin, Bill Shields were contacted and a workshop organised. The interactive workshop on a grower's property with about 25 participants entailed a tailored winter chill presentation by Rebecca Darbyshire (The University of Melbourne), introduction to climate change impacts on pome fruit, and research outcomes from the project such as the latest dormancy breaker research from QLD by Heidi Parkes as well as modelled predictions for the region plus a field walk. The session was organised, facilitated and evaluated by Kevin Dodds (NSW DPI) and Jenny Treeby (DEDJTR, VIC). In the evaluation, growers pinpointed earlier bud burst, flowering and maturity as well as sunburn as their main climate change related challenges. The workshop gave them a better understanding of the complexity of factors involved in budburst and flowering and the chill portions calculator was seen as an excellent tool/incentive to collect and utilise their own data better.

In order to reach a much wider pome fruit audience, project outcomes were displayed at the Horticulture Centre of Excellence stand at the 2015 National Horticulture Convention. A poster, six state specific chill fliers using the chill portions model, the HIN (www.hin.com.au) project webpage, and the chill calculator were used as a static display. Additionally, time was made to meet the project researchers at the stand during program breaks, an option which was taken up by quite a few growers who felt that this was a great opportunity to have a chat with a scientist.

Lessons learnt

1. Having a core team responsible for communication (Heidi Parkes, DAF QLD), Susie Murphy-White (DAFF WA), Rebecca Darbyshire (UoM) and Jenny Treeby (DEDJTR VIC) ensured timely, relevant and consistent information was being made available to growers at the workshops and the APAL conference. This also emphasised a multi-state approach (including New South Wales) and added importance to the project outputs and resulted in messages such as in New South Wales, where the presenters were thanked for their presentations and the effort made to come to that location.
2. Presenting locally relevant data, using model predictions established within the projects by researchers resulted in the grower audience being engaged and feeling confident to ask questions and provide feedback and lessons learnt in their orchard.
3. Utilising well established grower groups such as in Queensland and New South Wales as well as local, well respected extension officers (Front Line Advisors) such as Clinton McGrath (DAF QLD) and Kevin Dodds (NSW DPI) ensured ease of facilitation.
4. Evaluation of workshops is still suffering from low return rates of around 50% of even short evaluation forms possibly due to a lack of understanding of the importance of this form of feedback. Interactive keypad technology as employed in the last round seems to have had a better return rate (possibly due to novelty factor) and will be contemplated for further projects.
5. Knowledge gaps identified as a result of these workshops include:
 - varietal chill requirements for existing and new varieties
 - lack of understanding of the difference between chill hours, units and portions, and the use of chill portions as the most accurate measure of winter chill available
 - adaptation strategies to heat stress
 - does soil temperature influence endo and /or ecto dormancy?
 - do phenology models based on meteorological data adequately represent buds within a tree?
 - is the current knowledge of pome fruit physiology extensive enough to be able to accurately predict winter chill accumulation processes?
 - there is a strong focus on the potential impact of extreme events on the industry under future climate scenarios, with less understanding about the potential impacts of more subtle increases in temperature
 - need for more accurate in-season and longer term climate forecasting to enable growers to take actions that reduce climate risk

Resources:

<http://www.hin.com.au/projects/apple-and-pear-production-in-a-changing-climate>

<http://www.hin.com.au/projects/winter-chill-and-fruit-trees>
[regional-chill-accumulation-victoria](#)
[regional-chill-accumulation-queensland](#)
[regional-chill-accumulation-for-new-south-wales](#)
[regional-chill-accumulation-for-south-australia](#)
[regional-chill-accumulation-for-tasmania](#)
[regional-chill-accumulation-for-western-australia](#)

Blogs:

<http://www.hin.com.au/projects/apple-and-pear-production-in-a-changing-climate/explore-your-regional-climate.....>