Breeding Focus 2018 - Reducing Heat Stress

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Published by

Animal Genetics and Breeding Unit

University of New England

Armidale, NSW, Australia

Animal Genetics and Breeding Unit

University of New England

Armidale NSW 2351

Australia

http://agbu.une.edu.au

ISBN: 978-1-921597-78-7

Cover design by Susan Joyal

Book design by Kathy Dobos

First published, 2018

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Preface

“Breeding Focus 2018 – Reducing Heat Stress” is the third workshop in the series. The Breeding Focus series was developed to provide an opportunity for exchange between industry and research across a number of agricultural industry sectors. With this goal in mind, workshops have included presentations across the livestock and aquaculture industries to take participants outside their area of expertise and encouraged them to think outside the box. This year we increased the scope even further by also inviting presentations from the cropping and horticulture industries. Since the topic of heat stress has recently gained increased attention, we will discuss a wide range of aspects associated with heat stress, such as the physiology of heat stress and phenotypic indicators, genetic approaches and industry impacts.

Heat stress in animals describes a situation where an animal is exposed to high temperatures and unable to dissipate body heat, which causes an increase in body temperature. In the short term, an animal will react to heat stress with behavioural strategies (e.g. seeking shade, panting) to reduce the heat load. With prolonged excessive heat load, feed intake is reduced and production losses occur. Under extreme circumstances, excessive heat load can lead to death. In plants, heat stress can be defined as irreversible damage to plant function and development as a consequence of hot temperatures. Environmental causes of heat stress in plants and animals include high temperatures and high humidity over a long period of time, which is exacerbated by low cloud cover and high solar radiation.

With raising average temperatures, agricultural industries are faced with the challenge to manage potential impacts of heat stress on their crops, their pasture base and welfare and production of their livestock or aquaculture species. Management strategies such as shade and irrigation are effective but costly and, depending on the severity of climatic conditions, may have limited success. Susceptibility of organisms to heat stress can vary due to factors such as age and general health, but also genetic factors, such as breed or variety. Further, as we will hear during the workshop, genetic variation exists within breeds that enables genetic approaches to address heat stress in plants and animals. Selective breeding provides a long term approach that facilitates improvement of the physiology of plants and animals to cope with excessive heat load. The challenge here is to obtain cost-effective phenotypes to describe heat stress.

The chapters of this book discuss where the current climate is trending, and outlines opportunities for the crop, orchard, livestock and aquaculture industries to describe and measure heat stress, all with the focus on genetic improvement.

We would like to thank everyone who has contributed to this event for their time and effort: the authors for their contributions to the book and presentations, the reviewers who all readily agreed to critique the manuscripts. We would like to express a special thanks to Kathy Dobos for her contributions into the organisation of this workshop and the publication. Thank you!

Susanne Hermesch and Sonja Dominik
Armidale, September 2018

Addressing heat stress in pome fruit

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Abstract

Cultivars recently commercialised from Australian apple and pear breeding programs have focused on quality features and disease resistance. In particular, fruit with high blush have been developed in response to market premiums. Breeding of these cultivars, which utilise traditional breeding techniques, have not included formal assessments of extreme heat susceptibility or implications of extreme heat management strategies on quality attributes. Extreme heat can directly impact fruit through sun damage and reduction of red colour. Current and following crops can similarly be impacted by extreme heat through reduction of carbon assimilation. Several management strategies are used in commercial Australian orchards to minimise the consequences of extreme heat (spray-on protectants, evaporative cooling and over-tree netting). These strategies interact with tree processes, and by managing for extreme heat damage, reduction in quality may occur. For instance, it has been shown that over-tree netting reduced sun damage but also reduced blush coverage and intensity for a new blush pear cultivar. Extreme heat events will increase as climate change continues. In response, future breeding programs, including assessments of the implications of extreme heat on quality traits, will likely benefit growers making investment decisions. Further research into the molecular causes and interactions of sun damage and colouration would provide a pathway to breed for heat tolerant blush cultivars for sustainable production under future climates.

Introduction

Pome fruit (apple and pear) production is a significant component of the Australian horticulture sector valued at $631 million in 2015/16 (ABS 2017). Extreme temperatures can negatively affect production, reducing quality and sellable fruit, driving down profits. Pome fruit is damaged by extreme temperatures in a variety of ways. Fruit can be directly damaged by sunburn, fruit colour can bleach, internal flesh structures can break down, leaves can be irreversibly damaged and carbon assimilation reduced. Cumulatively these impacts can substantially influence productivity and profitability. For example, growers reported yield reductions in excess of 50% due to extreme temperature conditions in the Goulburn Valley in February 2009 with some cultivars not harvested at all (Lolicato 2011). With incidence of extreme temperatures in Australia's temperate fruit growing regions expected to increase with anthropogenic climate change (Alexander and Arblaster 2009), strategies to minimise negative impacts from extreme temperatures are necessary to maintain profitable pome fruit orchards into the future.

Typically, management systems have been introduced to mitigate extreme temperature impacts so that traditional pome fruit cultivars can continue to be grown. Several options are available to growers (e.g. sun protection sprays, evaporative cooling) with over-tree netting increasingly being installed to protect crops from extreme heat, hail and birds. Although over-tree netting provides protection from extreme heat, it can reduce the development of blush colour (Goodwin *et al.* 2018), a key quality attribute linked to premium prices.

Pome fruit breeders and growers face particular challenges in the development of new cultivars and in the integration of new cultivars into orchards. Pome fruit trees are perennial with productive lifespans of 15 – 20 years. Furthermore, pome fruit trees do not fruit in their first year and some cultivars of pear may take up to four years to bear fruit. This means that, depending on the re-development period of the orchard, incorporation of any new cultivar or production system will take decades to be implemented. Breeders also face time challenges in developing new cultivars. Assessment of fruit cannot occur until the fruiting period has initiated, potentially years after the initial cross.

Despite challenges in breeding pome fruit, Australia has developed new apple and pear cultivars. Historically, breeding programs for pome fruit in Australia have focussed on quality traits (e.g. colour, eating quality) and pest and disease resistance (e.g. apple scab) rather than climate suitability. This stems from orchards being highly managed crops with many weather conditions controllable. Western Australia (WA) has largely driven pome fruit breeding in Australia. As an example, the popular apple 'Cripps Pink' (marketed as Pink Lady®) was bred in WA by John Cripps in the 1970's. Then and now the breeding approach undertaken utilises conventional breeding methods, that is hand cross-pollination to create hybrids. From these crosses, thousands of seedlings are produced with a small number then selected for further assessment. Recently, a new apple cultivar 'ANABP-01' (marketed as Bravo™) has been released from the WA program which has a strong burgundy colour. Selection for this apple concentrated heavily on quality standards and ease of orchard management (regular cropping, minimal susceptibility to surface cracking, bitter pit, superficial scald or internal disorders) with climate suitability not formally assessed. Successful cropping in south-west WA has been used as an indicator that the cultivar is suitable for locations with warm to hot long summers like those in south-west WA (FruitWest 2018).

In 1993, the National Pear Breeding program was started to reinvigorate the Australian pear industry due to loss of share in export markets of 'Packham's Triumph' pear. Pears were initially cross bred in WA using classical cross breeding methods. Seeds were then sent to Melbourne, Victoria for testing for pear scab resistance in young seedlings under laboratory conditions. The seedlings were then planted at Tatura, Victoria for fruit evaluation. Up to 60,000 seedlings were evaluated over the 20 years that the program was running.

Originally the aim of the national pear program was to develop an improved ‘Packham’s Triumph’ pear with pear scab resistance and fruit with a symmetrical, smooth shape in response to increased international competition. Early in the program, the aims were expanded to include European pears with improved appearance and eating quality to address consumer requirements and attract a new generation of pear consumers (Turpin *et al.* 2016). In particular, pears with blush were selected due to their superior appearance.

Two cultivars ‘ANP-0131’ (marketed as Deliza®) and ‘ANP-0118’ (marketed as Lanya®) have since been commercialised from this program by Apple and Pear Australia Ltd with a third ‘ANP-0534’ likely to be commercialised. These three cultivars have been used in the Profitable Pear research program (Agriculture Victoria 2018b) which has been investigating effects of orchard management systems (e.g. rootstocks, tree training, planting density) on yield and fruit quality. Results from this program of work were used to evaluate the potential profitability of converting orchard blocks to ‘ANP-0131’ instead of ‘Packham’s Triumph’ and found that new plantings of ‘ANP-0131’ could provide returns of $14,265/ha per annum whilst ‘Packham’s Triumph’ could only provide $967/ ha per annum with a 45% chance negative returns could occur in any one year (Stott *et al.* 2018). These findings highlight that transitioning pear blocks to new cultivars with new planting systems will likely be a more profitable decision than replanting existing cultivars to traditional systems.

Given the financial incentive to modernise pear orchards using newly bred cultivars, consideration of the performance of ‘ANP-0131’ under extreme heat conditions has been investigated (McClymont *et al.* 2016; Goodwin *et al.* 2018). Although extreme heat responses were not included in the primary traits in the breeding program, experiments have been carried out to evaluate fruit surface temperatures for which sun damage is sustained and the ability of over-tree netting to reduce damage and any coincident reduction in colour.

This overview of heat stress in pome fruit will address two aspects: firstly, the effect of extreme temperatures on pome fruit and secondly, current management practices to mitigate extreme heat. Over-tree netting in particular will be reviewed with regard to reduction of sun damage and on-going effectiveness under climate change conditions. Experiments using ‘ANP-0131’ pear, a newly bred cultivar, which was not assessed for sun damage susceptibility during the selection process, will be used to highlight the value of including such assessments within breeding programs.

Too hot to handle: effects of extreme temperature

Sun damage to pome fruit trees is primarily due to direct solar radiation heating fruit or leaf surfaces. Fruit surface temperature (FST) of exposed fruit on clear days with little wind can be substantially greater than air temperatures. For example, Darbyshire *et al.* (2015) found that ‘Royal Gala’ apple FST could reach 47.8 °C at air temperatures of 34.1 °C. Thresholds of FST are typically used to define sun damage likelihood.

Air temperature is the best weather variable to predict FST and therefore incidence of sun damage, notwithstanding that other weather and tree attributes do influence FST (McCaskill *et al.* 2016). For example, windy conditions can reduce sun damage through facilitating the transfer of heat from the fruit surface to the air. Fruit size can also influence the level of damage sustained. Larger fruit have a greater fruit volume to surface area ratio and are less able to transfer heat than small fruit which have a lower ratio. This attribute means that later maturing cultivars (i.e. autumn) may sustain lower levels of sun damage due to smaller fruit size during the summer months compared with early season cultivars.

Three key effects of extreme temperatures on pome fruit production will be explored; sunburn, colouration and carbon dynamics. Sunburn and colouration directly relate to sellable yield and quality of fruit in the current season. Impacts on carbon dynamics can affect yields of the current crop and potentially the following season. In considering these effects a larger emphasis was focussed on apple as limited research has been conducted in pear (Thomson *et al.* 2017).

Sunburn

Sunburn in apple has been well documented with three types described (Racsko and Schrader 2012).

(1) *Sunburn browning* is identified by a yellow through to dark tan spot on the sun exposed side of the fruit resulting from high FST and ultraviolet-B radiation (Schrader *et al.* 2003a). Fruit with sunburn browning is of lower quality (Figure 1) and is either culled or sold at lower prices. FST's from 46 to 49°C for one hour have been found sufficient to induce sunburn browning in many apple cultivars (Schrader *et al.* 2001). Internal fruit quality traits in progressively sun burned apple have been considered (Schrader *et al.* 2009). It was found that as sunburn severity increased, flesh firmness and soluble solids concentration increased while relative water content and titratable acidity decreased.

(2) *Sunburn necrosis* is characterised by a dark penetrative burn and is the result of a thermal response. FST's of 52°C for 10 minutes were found to be sufficient to cause sunburn necrosis (Schrader *et al.* 2001). Fruit with sunburn necrosis are not sellable (Figure 1) with secondary negative effects, such as increased disease and pest pressure due to a breach of the skin's surface, further reducing fruit saleability.

(3) *Photo-oxidative sunburn* is identified by bleaching on the fruit skin which occurs when shaded fruit is suddenly exposed to sunlight (e.g. after summer pruning) (Figure 1). Small areas of photo-oxidative sunburn are unlikely to be noticed by consumers.

Figure 1. Examples of browning (left), necrosis (centre) and photo-oxidative (right), sunburn in apple (Agriculture Victoria 2018a).

Pear has not been as well researched as apple regarding sunburn damage. Wand *et al.* (2005) found mixed results with sunburn reported for 'Packham's Triumph' pear in a season when air temperatures exceeded 33.2°C but no sunburn was found for a season when maximum temperatures reached 40°C. In Australia, McClymont *et al.* (2016) found FST and duration of heat were important for severity of sunburn in blush pears. They found that a FST of 47°C for 103 minutes led to sunburn browning (Figure 2).

Figure 2. Example of sunburn in 'ANP-0131' pear (McClymont et al. 2016).

Colour

Fruit colour, for blush pome fruit, is an important quality attribute with higher coloured fruit attracting premium prices (Thomson and Goodwin 2018). Anthocyanin compounds are responsible for red colouration in pome fruit. Many factors have been researched to consider anthocyanin production and destruction in relation to colouration in apple including cultivar, temperature, nitrogen (soil or in foliar sprays), other soil nutrients, light exposure and soil pH (Saure 1990). In general, lower temperatures, particularly overnight temperatures, tend to promote anthocyanin production (Blankenship 1987). Conversely, high temperatures negatively influence the accumulation of anthocyanin by reducing the rate of production and lowering stability (Mori *et al.* 2005; Lin-Wang *et al.* 2011; Thomson *et al.* 2017). Lin-Wang *et al.* (2011) compared anthocyanin production in 'Gala' apple between Hawkes Bay in New Zealand, a mild growing site, and Lleida in Spain, a warmer production area. At harvest they found that fruit grown in New Zealand accumulated five times as much anthocyanin as the Spanish fruit (100 nmol cm^{-2} vs 20 nmol cm^{-2}).

Colouration in pear is less well understood, largely due to limited research on the balance between synthesis and degradation of anthocyanin (Thomson *et al.* 2017). Different species and cultivars of blush pear do not behave as a homogeneous group with variability in the presence and extent of blush. European pears (*Pyrus communis* L.) typically show peak accumulation of anthocyanin midseason with varying amounts of reduction in red coloration towards harvest (Steyn *et al.* 2004) whilst Asian pears (*Pyrus pyrifolia* Nakai) show peak anthocyanin accumulation closer to harvest (Huang *et al.* 2009). A review by Thomson *et al.* (2017) highlighted the range of conditions for which colour develops in European pear. They found cultivar variability in the time during the season that anthocyanin is synthesised (early-mid through to mid-late), the degree of colouration, response to light and responses to low and high temperatures.

Carbon processes

Carbon assimilation by leaves is important for pome fruit trees to grow fruit to commercial size at commercially viable crop loads, to grow new plant structures (shoots, leaves) and to store carbon in the woody tissue for use in the following season. Reduction in carbon assimilation in one season can impact fruit yield and quality in the current season as well as impacting yields in the following year.

Through photosynthesis, pome fruit trees produce carbon assimilates. Respiration uses carbon assimilates to grow and maintain plant structures. Rates of both photosynthesis and respiration are reliant on temperature. For apple, normal rates of photosynthesis tend to occur over a wide range of temperatures (15 – 35°C) with an optimal at approximately 30°C (Lakso 1994). As evaporative demand increases with increasing temperatures, hydraulic conductivity of the soil-plant-atmosphere continuum may limit the flux of water resulting in a decline in stomatal conductance. The reduction in stomatal conductance will reduce carbon dioxide uptake, which in turn reduces production of carbon. Compounding this reduction in the production of carbon, stores of carbon are depleted as respiration rates increase non-linearly at higher temperatures, with the respiration rate doubling for every 10°C increase in temperature (Lakso 1994). High temperatures can additionally disrupt photochemical and biochemical reactions and change sub-cellular structures also reducing photosynthesis (Crippen and Morrison 1986; Wahid 2007).

The inhibition of photosynthesis from extreme heat may be a result of enzyme denaturation and destruction of photosystem complexes. Photo-inhibition occurs when leaves are exposed to direct radiation. Plants must continuously repair the damage. The photosystem II (PSII) repair cycle, occurring in chloroplasts, consists of degradation and synthesis of the D1 protein of the PSII reaction centre, followed by activation of the reaction centre (Aro *et al.* 1993). Due to the rapid repair, most PSII reaction centres are not photo-inhibited even if a plant is grown in strong light. Through this repairing process carbon is being used that could otherwise be used to grow fruit. Additionally, environmental stresses, for example, extreme temperatures, limit the supply of carbon dioxide for use in carbon fixation, which decreases the rate of repair of PSII.

Get out of the heat: strategies to mitigate extreme temperatures

Growers utilise various management strategies to minimise or remove the risk of sun damage. The primary strategies used include application of spray-on sun protectants, use of evaporative cooling and installation of over-tree netting. All three options are used commercially in Australia. Gindaba and Wand (2007) compared these three strategies to reduce sunburn in ‘Royal Gala’ in relation to leaf photosynthesis and stomatal conductance. They found all strategies reduced photo respiration linked to lower leaf temperatures and/or lower radiation loads. Furthermore, Gindaba and Wand (2005) found that each option lowered fruit temperature with netting leading to the greatest decrease in fruit temperature and sunburn incidence.

Installation of over-tree netting has increased at many of Australia’s major growing regions. This reflects the multiple benefits netting can provide in addition to sun damage protection (e.g. improved water use efficiency and protection from birds and hail). The potential benefit of netting has been identified by industry with a cost benefit calculator produced to assist growers build a business case for installation of netting (Natural Logic and Econsearch 2015). Given industry’s particular interest in over-tree netting, greater exploration of this strategy will be undertaken including an overview of protection provided under climate change.

Spray-on sun protectants

Spray-on sun protectants are directly sprayed onto fruit and leaves and are typically mineral based (e.g. kaolinite clay, calcium carbonate) or wax based (e.g. Raynox^{TM}). These products provide protection by reflecting a portion of direct sunlight from the fruit or leaves. Use of clay based products in Argentina on ‘Packham’s Triumph’ pear were found to reduce sun damage by up to 15% (Colavita *et al.* 2011). Gindaba and Wand (2007) found use of these products had a negative effect on stomata conductance, surmising that the particles may block the stomata opening, which could lead to greater risk of leaf damage from high temperatures.

From a management perspective these products require multiple applications to build and maintain protection throughout a season (e.g. as fruit grows or following rain). Furthermore, these products leave residues of white powder on the fruit, which must be removed prior to packing, with the ease of removal cultivar dependant. Clear spray-on products are also available but tend to only protect from UV radiation and a combination with other options may be required to provide adequate protection.

Evaporative cooling

Sprinkler or spray irrigation systems in or above the canopy reduces FST by evaporative cooling (Evans *et al.* 1995). Gindaba and Wand (2007) found that evaporative cooling did not negatively impact stomata conductance, the only sun damage protection option tested with this result. Drawbacks to this strategy include increased disease pressure and waterlogging (Evans *et al.* 1995; Agriculture Victoria 2017). Use of pulsing of evaporative sprinklers may provide a method to reduce excessive water use when using evaporative cooling systems (Figure 3).

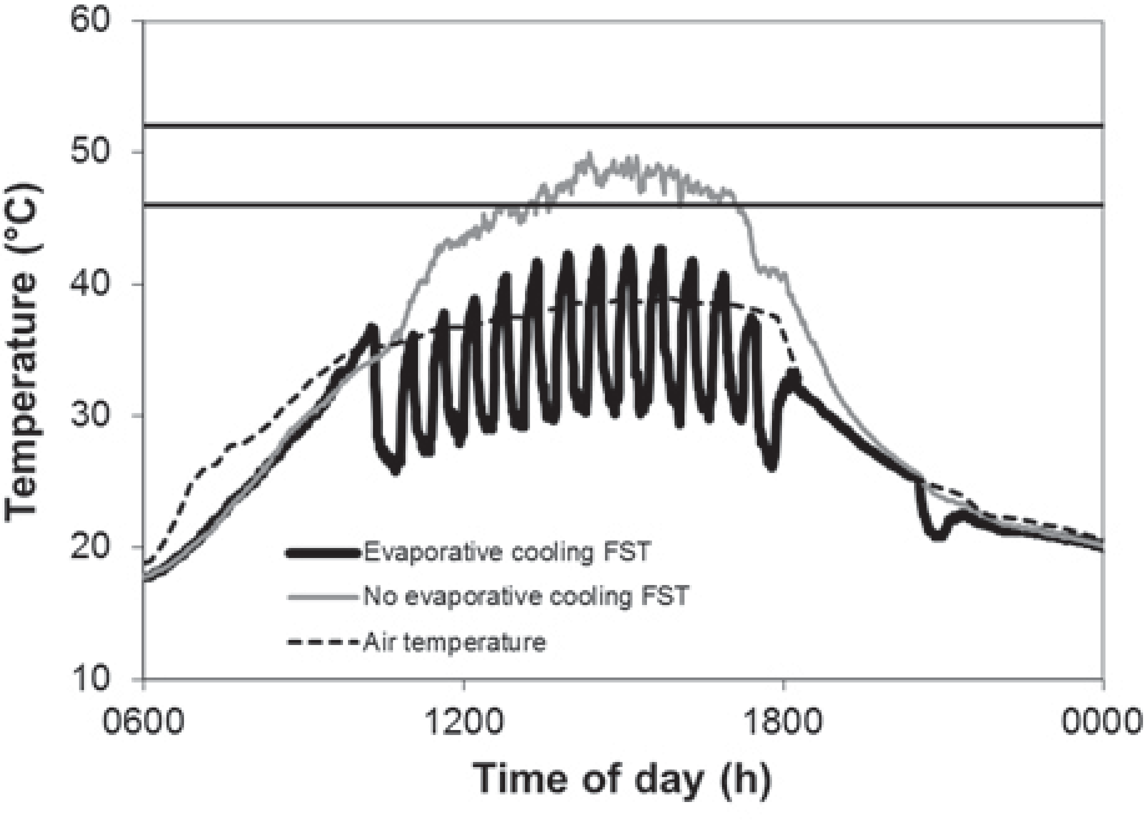

Figure 3. The influence of pulsed evaporative cooling on fruit surface temperature (FST) of 'Royal Gala' apple exposed to direct sunlight in an orchard in northern Victoria. Over-tree microjets were used for evaporative cooling with pulsing set to 'on' for 20 minutes of cooling and 'off' for 15 minutes. The horizontal lines represent FST thresholds for sunburn browning (46°C) and necrosis (52°C) (unpublished data).

Over-tree netting

Over-tree netting provides direct protection from radiation by the placement of shade material above the tree canopy or draped directly over the tree. The reduction in radiation is determined by the net weave and colour with most netting providing approximately a 20% reduction in direct solar radiation. Installation of over-tree netting provides additional benefits such as hail protection, bird protection, increased water use efficiency (due to lower rates of evapotranspiration), reduced wind and improved spraying conditions (Lolicato 2011). Whitaker and Middleton (1999) evaluated netting for return on investment in relation to hail damage for orchards in the Granite Belt in Queensland. They found equivalent annual return of investing in netting across all apple cultivars of $1,030/pa. Installing netting can potentially lead to some disadvantages such as increased vegetative vigour, reduced red colour development and increased disease pressure (Gindaba and Wand 2005; Lolicato 2011; Goodwin *et al.* 2018), noting that many of these can be managed by growers. Lower light environment under netting may influence tree carbon dynamics. For instance, Gindaba and Wand (2007) found that netting down regulated photosynthetic activity due to lower radiation interception and may have led to smaller fruit sizes in 'Royal Gala'.

To evaluate the potential sun damage protection over-tree netting provides, Darbyshire *et al.* (2015) evaluated sunburn in 'Royal Gala' apple for netted and non-netted blocks. They calculated minimum air temperature thresholds which led to FST suitable for sunburn. For sunburn browning, minimum air temperatures threshold of 34.1°C and 37.9°C were found for non-netted and netted fruit, respectively. Considering these results over historical air temperature records and across 10 growing locations, installation of netting was found to reduce risk of sunburn browning in 'Royal Gala' by 50 to 85%.

Webb *et al.* (2017) extended these results to consider potential sunburn incidence in 'Royal Gala' apple across Australia under anthropogenic climate change. They found that use of over-tree netting continued to reduce sunburn risk by at least 50% as climate change advances (Figure 4). However, sunburn risk, including under netting, does increase with climate change. Figure 4 shows that with netting, the number of days in January that will likely be suitable for sunburn damage increases from, on average, two days historically up to 5 days by 2090 at Tatura. This highlights that over-tree netting does provide a notable reduction in sunburn risk but this advantage will decrease with increased extreme weather as a result of climate change.

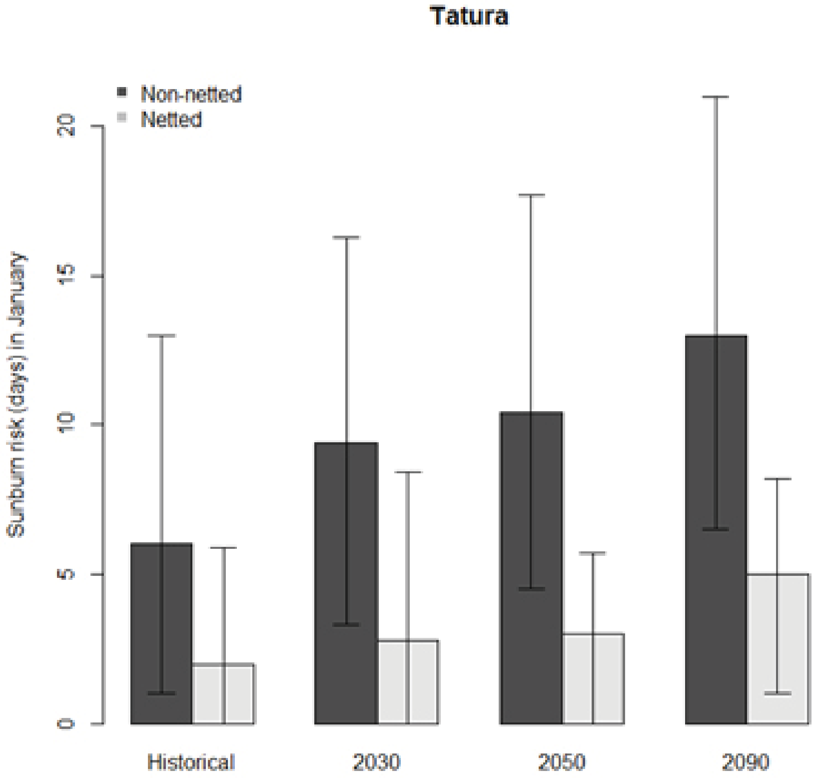

Figure 4. Number of potential sunburn browning days in January for 'Royal Gala' apple at Tatura, Victoria. The solid column is the median with the 10th and 90th percentiles of the data indicated by the bars. Adapted from Webb et al. (2017). Note the bars on the plot refer to the range of sunburn risk across climate modelling.

Bred for heat? Assessments of 'ANP-0131' pear

As previously outlined, the national pear breeding program has commercialised two new blush pears for production. 'ANP-0131' pear grown under modern orchard system has been found to be more profitable than traditionally grown 'Packham's Triumph' (Stott *et al.* 2018). Assessments which led to the selection of 'ANP-0131' did not include an evaluation of susceptibility to extreme heat damage. However, subsequent to the selection of 'ANP-0131', research has been conducted to examine extreme heat thresholds for sunburn in 'ANP-0131'. Here, an extension of these studies was conducted to evaluate likely sunburn damage under climate change following methods in Webb *et al.* (2017).

McClymont *et al.* (2016) conducted key analyses to evaluate FST that can lead to sunburn damage in 'ANP-0131' pear. They used thermocouples placed under the skin of the fruit to monitor FST at one minute intervals for nearly a two month period. Advantageously, their experiment included a brief period of high temperatures in 2014 which was followed by relatively mild conditions. These conditions minimised confounding factors influencing the results as any sun damage observed at harvest was likely the result of this period of extreme temperatures. They found a FST threshold of 47°C for sunburn browning in 'ANP-0131' and proposed a tentative FST threshold of 50°C for sunburn necrosis. They found that both the FST and duration of exposure to heat were important in the emergence of sunburn supporting earlier work in apple (Schrader *et al.* 2003b).

Using data from the same experiment, Goodwin *et al.* (2018) determined minimum air temperature thresholds for sun damage for 'ANP-0131'. They found that the minimum air temperature threshold for sunburn browning was 30.8°C for a non-netted block. Fruit for which FST were recorded did not reach the threshold for sunburn damage under netting. These authors found that over-tree netting reduced sunburn from 29% at the non-netted site to 10% at the netted site. Using this air temperature threshold for sunburn damage, the potential increase in sunburn incidence under anthropogenic climate change was calculated (Figure 5), following methods in Webb *et al.* (2017). Similarly to 'Royal Gala', the risk of sunburn damage increased as climate change advances; however the number of potential risk days was much higher (compare Figure 4 and Figure 5).

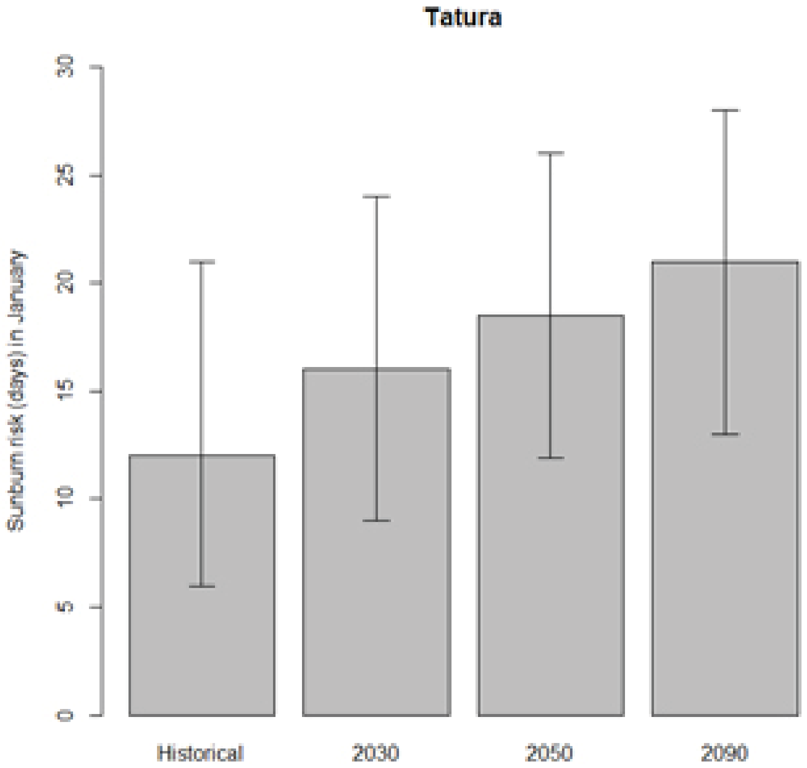

Figure 5. Number of potential sunburn browning days in January for 'ANP-0131' pear grown in the open at Tatura, Victoria. The solid column is the median with the 10th and 90th percentiles of the data indicated by the bars. The number of potential sunburn browning days was based on an air threshold of 30.8°C (Goodwin et al. 2018) using methods from Webb et al. (2017). The potential reduction in risk under netting was not assessed as the FST for the netted fruit did not exceed the threshold for damage (47°C). Note the bars on the plot refer to the range of sunburn risk across climate modelling.

Goodwin *et al.* (2018) additionally investigated the impact of over-tree netting on blush coverage and intensity. This is important as in order to market ‘ANP-0131’ as Deliza® there is a marketing minimum requirement of 20% red coverage. They found that under over-tree netting, 39% of fruit did not meet this requirement while 15% of the non-netted fruit failed to meet this requirement. Although not a market requirement, they also found that the blush intensity of fruit from the non-netted block was greater than fruit under netting. The balance between reduction of sun damage and coincident reduction in blush coverage and intensity needs to be managed well to ensure high quality, profitable fruit is produced.

Discussion

Pome fruit breeding in Australia has led to several new cultivars being commercialised in recent years. These breeding programs face the challenge of long time and investment horizons. For example, the national pear breeding program was established in 1993 with the first cultivar commercialised in 2012. Long time frames for assessment are principally due to the time for hybrids to crop (up to six years for European pear). Given the extended time from breeding to commercialisation and the high degree of tree management by orchardists, formal inclusion of assessments of heat tolerance have not been included in pome fruit breeding. This is understandable as there are several management strategies currently available to growers to mitigate extreme heat conditions (spray-on sun protectants, evaporative cooling and over-tree netting).

The influence of these management strategies to reduce sun damage on other aspects of production need to be understood to holistically evaluate their value. Results from Goodwin *et al.* (2018) illustrate the potential quality impacts on blush of over-tree netting for pear. Additional management procedures to increase blush under netting, such as modification to netting colour to filter for wavelength(s) that stimulate anthocyanin production or the use of reflective surfaces in the inter-row may provide a pathway for low rates of sun damage whilst maintaining colour coverage and intensity. Greater understanding of how to match these strategies with the timing of colour development and consideration to the training system (that is, how exposed fruit are within the canopy) is required to provide future recommendations to growers. More generally, further research is needed to better understand the suite of management strategies which maximise production quality of ‘ANP-0131’ pear.

The evaluation of extreme heat management options, and combination of options, for existing and new cultivars is particularly important given the increased likelihood of extreme heat conditions in Australia as climate change progresses (Alexander and Arblaster 2009). Webb *et al.* (2017) showed that under climate change, the likelihood of sunburn damage increased for ‘Royal Gala’ apple across most Australian growing regions with and without netting. This highlights that reliance on management to control extreme heat impacts will likely decrease in effectiveness in the future.

Management alone may not be sufficient to produce high blush fruit with low levels of sun damage. If breeding for heat tolerance remains a low priority, breeding programs may benefit from inclusion of assessments of sun damage with and without management intervention to provide advice on optimal management strategies. These need to be considered in terms of reduction of sun damage, impact on quality markers (e.g. blush coverage) and impact on key tree growth functions (e.g. stomatal conductance). The second commercialised blush pear ('ANP-0118') provides a pertinent example of the need of such assessments with sunburn susceptibility of this cultivar and effectiveness of heat management strategies currently unknown. Previous studies provide guidance on such experimentations (Schrader *et al.* 2003a; Gindaba and Wand 2008; McClymont *et al.* 2016; Goodwin *et al.* 2018).

An alternate or additional approach to using management to minimise extreme heat impacts is to breed for these traits. Selecting genotypes with high anthocyanin accumulation under netting is one option to reduce the negative effects of netting on blush. Another research direction could be to better understand the molecular interactions which lead to both sun damage and blush colouration. For instance, a greater understanding of the role that the amount and pattern of anthocyanin accumulation and degradation plays in both heat and light tolerance (Steyn *et al.* 2004; Li and Cheng 2009; Steyn *et al.* 2009; Lin-Wang *et al.* 2011).

Another approach may be to breed for particular traits. For instance, future breeding programs could investigate cultivar tolerance of Rubisco activase to high temperature (Feller and Vaseva 2014). Rubisco activase regulates the activity of Rubisco, the enzyme that catalyses carbon dioxide assimilation in photosynthesis. The application of thermal and visible to near-infrared imagery can enable a high-throughput evaluation of genotypes for tolerance to heat stress in the field (Leinonen and Jones 2004; Sankaran *et al.* 2015).

Breeding and management strategies may still be insufficient to overcome the impacts of climate change on the commercial profitability of pome fruit. Profitability may be impacted by extreme heat effects and other weather-related impacts (e.g. lower winter chill). In these circumstances, growers may need to transition from pome fruit to other more suitable crops or alternate farming operations. Research conducted for site suitability for winter chill between crop types provides a means of investigating these strategies (Darbyshire *et al.* 2016).

Breeding of new pome fruit cultivars in Australia has historically relied on traditional cross methods and assessment of fruit quality and disease resistance. These objectives have been well founded given target markets of high quality fruit and the high levels of management implemented in orchards. As climate change continues to unfold, this approach may require some modification. The interaction between extreme heat damage and blush colour provides a particular example where management strategies, such as netting, may negatively influence fruit traits which were specifically selected. Inclusion of assessments that evaluate such trade-offs would be beneficial in future work. Finally, greater research into the molecular mechanisms which control extreme heat damage and colour development would provide a pathway for breeders to select for cultivars with good heat tolerance and good colour to provide sustainable cultivar options to growers into the future.

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