# Cherry cultivar selection: chill hours and climate change

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Biometry

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# Cherry cultivar selection: Chilling and climate change

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Biometry

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Final Report

HAL Project CY11010

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## Purpose of the report

Recent temperature increases in many traditional cherry growing areas may be reducing the ability to fulfil chilling requirements for some varieties leading to production loss currently and in future years. With further temperature increases anticipated, cultivars suitable for specific regions need to be identified so that appropriate orchard planning decisions can be made to ensure the cherry industry prepares and adapts to climate change.

The purpose of this report was to determine which varieties are best planted in the selected regions, through identifying chill thresholds from the literature, identifying regional impacts of climate change and providing information on some climate change adaptation strategies.

This project has been funded by HAL using the Cherry Industry levy and matched funds from the Australian Government.

March 2012

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# Media Summary

Recent climate conditions across much of Australia have altered in response to human caused climate change with all-Australian warming trends of 0.06°C/decade for maximum temperature and 0.12°C/decade for minimum temperature observed from 1910-2004. Warming that has already occurred may have impacted chill accumulation in Australia, although key thresholds still appear to be mostly met. Further warming may begin to impact chill accumulation and therefore production. Anticipation of future chilling conditions across important Australian cherry production areas will assist growers and industry plan for suitable varieties and incorporate potential chill restrictions as part of management strategies.

Insufficient chill can lead to adverse effects for production including sporadic and light bud-break, poor fruit development, small fruit size and uneven ripening times. Given these adverse impacts, there is surprisingly little information on the chilling requirements of sweet cherry cultivars in the scientific literature.

To set initial varietal chill threshold groupings, chill data from the literature combined with information from researchers, growers and nurseries was used to assign each cultivar to a chill category (low, low-moderate, moderate- high, high and very high). These groupings can be refined over time when more information becomes available.

As studies have shown that the Dynamic model consistently performs similarly or better than the other tested chill models, it was used to model future chill requirements of cherry cultivars.

To model regional impacts of climate change on chill accumulation, appropriate Atmosphere-Ocean General Circulation Models (AOGCMs) were chosen for major cherry growing regions (Tatura, Orange, the Yarra Valley, Lenswood, Huonville and Manjimup). Localised temperature increases were calculated per 1, 2, and 3 degree Celsius increase in average global temperature. The projected data were then converted into hourly temperatures as this is the temporal scale required by the Dynamic chill model.

Global warming of 2°C is expected to be reached by approximately 2040. Results showed that this level of warming will negatively affect reliable chill exposure in every growing region investigated.

This report includes a 'chill portion calculator', an interactive spreadsheet that can be linked to weather station outputs to determine the actual chill accumulation at specific sites.

Included in the calculator is another interactive spreadsheet which calculates the likelihood of achieving a certain chill threshold (under the warming scenarios described) allowing the inclusion of more precise information as it becomes available, ensuring results remain viable with further research.

The spreadsheets will offer growers a consistent methodology to measure chill and ultimately, may help to more clearly define chill thresholds for different cultivars and their suitability at different locations.

Establishing baseline chill threshold data and research on climate change adaptation strategies such as low chill rootstocks, providing artificial chill though evaporative cooling and the use of dormancy breakers is needed.

# Technical Summary

Recent climate conditions across much of Australia have altered in response to anthropogenically induced climate change (Karoly and Braganza, 2005) with all-Australian warming trends of 0.06°C/decade for maximum temperature and 0.12°C/decade for minimum temperature observed from 1910-2004 (Nicholls and Collins, 2006). Warming that has already occurred may have impacted chill accumulation in Australia, although key thresholds still appear to be mostly met (Darbyshire et al., 2011). Further warming may begin to impact chill accumulation and therefore production. Anticipation of future chilling conditions across important Australian cherry production areas will assist growers and industry plan for suitable varieties and incorporate potential chill restrictions as part of management strategies.

Insufficient chill can lead to adverse effects for production including sporadic and light bud-break, poor fruit development, small fruit size and uneven ripening times (Saure, 1985; Voller, 1986; Oukabli et al., 2003; Petri and Leite, 2004). Given these adverse impacts there is surprisingly little information on the chilling requirements for sweet cherry cultivars in the scientific literature.

To set initial chill threshold groupings, chill data from the literature combined with information from researchers, growers and nurseries was used to assign each cultivar to a chill category (low, low-moderate, moderate- high, high and very high). These initial groupings can be refined at a future time when more information becomes available.

As studies have shown that the Dynamic model consistently performs similarly or better than the other tested chill models (Alburquerque et al. 2008; Erez et al. 1990; Perez et al. 2008; Ruiz et al. 2007; Viti et al. 2010), it was used to model future chill requirements of cherry cultivars.

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Predictions under 1, 2 and 3 degree warming scenarios are best illustrated by an example. Bing cherry was classified as a high chill variety, meaning it is estimated to require between 61 and 80 chill portions. Under current conditions, Manjimup does not reliability accumulate enough chill for this variety with only 79% of years meeting the lower end of the range (61 chill portions) and only 1% of years meeting the 80 chill portion cut-off. Similarly, Tatura only reaches adequate chill conditions 45% of the time for the upper end of the range but does currently accumulate enough chill for the 61 chill portion threshold. All other sites are suitable for this species under current conditions. With 1°C increase to average global temperatures only Huonville accumulates enough chill across the range of the high chill category. However, all locations except Manjimup still amass adequate chill at the lower end of the category. With 2°C warming, Huonville no longer reliably accumulates enough chill for the 80 cut-off according to the warmer AOGCM. Tatura looses more consistency as well. For 3°C warming, no location accumulates enough chill for the upper edge of the category and only four sites accumulate enough chill at the lower cut-off if the coolest AOGCM is used.

This report includes a ‘chill portion calculator’, that is, an interactive spreadsheet that can be linked to weather station outputs to determine the actual chill accumulation at specific sites.

Included in the calculator is another interactive spreadsheet which calculates the likelihood of achieving a certain chill threshold (under the global warming scenarios described) allowing the inclusion more precise information as it becomes available, ensuring results remain viable if further research occurs.

The spreadsheets will offer growers a consistent methodology to measure chill and ultimately, may help to more clearly define chill thresholds for different cultivars and their suitability at different locations.

Establishing base line chill threshold data and research on climate change adaptation strategies such as low chill rootstocks, providing artificial chill though evaporative cooling and the use of dormancy breakers is needed.

# Introduction

Annual exposure to sufficient winter chilling temperatures is necessary for deciduous fruit trees, including cherry, to successfully break the dormant phase and enter normal growth. Insufficient chill can lead to adverse effects for production including sporadic and light bud-break, poor fruit development, small fruit size and uneven ripening times (Saure, 1985; Voller, 1986; Oukabli et al. 2003; Petri and Leite, 2004). Recent climate conditions across much of Australia have altered in response to anthropogenically induced climate change (Karoly and Braganza, 2005) with all-Australian warming trends of 0.06°C/decade for maximum temperature and 0.12°C/decade for minimum temperature observed from 1910-2004 (Nicholls and Collins, 2006). Warming that has already occurred may have impacted chill accumulation in Australia, although key thresholds still appear to be mostly met (Darbyshire et al., 2011). Further warming may begin to impact chill accumulation and therefore production. Anticipation of future chilling conditions across important Australian cherry production areas will assist growers and industry plan for suitable varieties and incorporate potential chill restrictions as part of management strategies.

This study will provide background on chill model structures and differences, with specific application to cherry. Four commonly used chill models were explored (0-7.2°C, Modified Utah, Positive Utah and Dynamic). Six areas (Tatura, Orange, the Yarra Valley, Lenswood, Huonville and Manjimup) were investigated in a climate change context for 25 cherry varieties. Chill thresholds defined by previous studies and grower consultation were used to inform chill tipping points associated with increased warming as a result of anthropogenically induced climate change.

## Chill background

Temperature conditions are critical in determining sufficient winter chill exposure. However, the process is physiological and likely to be driven by other, yet undetermined, processes (Dennis, 1994). Hormonal controls have been suggested as the mechanism, with early research proposing the process is controlled by a balance of growth promoters and inhibitors (Amen, 1968). More recent research suggests that temperature cues specific hormones, such as indoleacetic acid, gibberellins, abscisic acid, and ethylene, which then control dormancy breaking (Seeley, 1990; Horvath, 2009). To date, the causal biological drivers of dormancy remain elusive to researchers (Dennis, 1994). Resultantly, the physiological response is commonly estimated by temperature based models (e.g. Weinberger, 1950; Richardson et al., 1974; Shaltout and Unrath, 1983; Fishman et al., 1987; Linvill, 1990; Cesaraccio et al., 2004).

In application, chill models commonly accumulate chill over time and when a threshold amount of chill has been amassed, chill is defined as satisfied. Different species require different threshold amounts of chill to break dormancy. Frequently, these chill requirements are defined according to different chill models resulting in chill thresholds reported in different units (e.g. Table 2). For instance, Ghariani and Stebbins (1994) reported chill thresholds for 43 apple and 38 pear varieties using the Utah model (measured in chill units); Zhang and Taylor (2011) determined chill requirement for Sirora pistachio using the Dynamic model (measured in chill portions) and; Baldocchi and Wong (2008) used thresholds defined in chill hours for 18 fruit and nut varieties to investigate future chill conditions in California. Cherry specific thresholds are contained in Table 2.

Unfortunatley it has been established that conversion factors between chill models are not achievable. Luedeling and Brown's (2010) study into the comparability of chill models globally confirms these differences on a large scale, across multiple climates with significant temporal resolution. They used the 0-7.2°C, Utah and Dynamic models in their analysis. It was found that the chill models are not proportional and conversion factors could not be established. Darbyshire et al. (2011) support this global assessment in an Australian setting. They considered historical trends in chill accumulation using four different chill models. Trends differed in magnitude and/or direction between the chill models, with interpretation of recent trends contradictory between chill models in some locations.

Darbyshire et al. (2011) also analysed how four chill models ranked Australian perennial fruit locations from 'low chill' through to 'high chill' sites. They found that the models rank the locations differently in terms of mean chill (1911-2009), with the 0-7.2°C model showing the greatest deviation (Figure 1). This study clearly indicates that chill model choice is important, affects conclusions and that the models are notably different (Table 2).

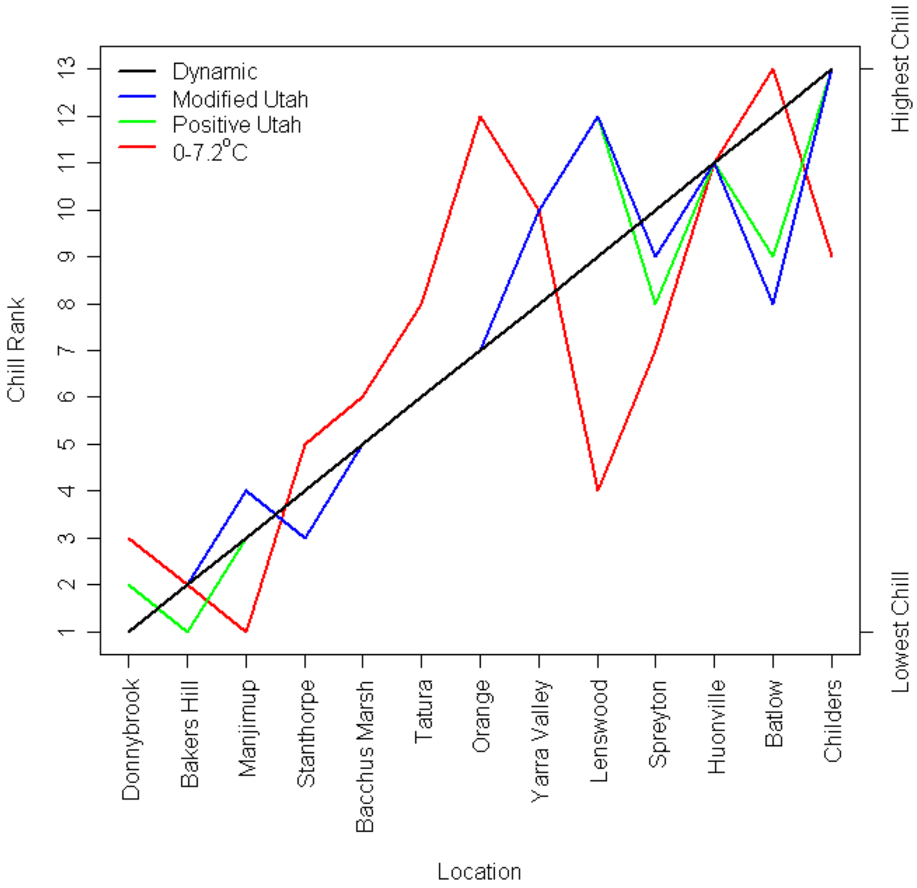


**Figure 1** Chill model ranking of the 13 Australian locations from lowest to highest chill, relative to the Dynamic model ordering (Darbyshire et al., 2011)

Studies reporting chill threshold information for cherries were often found to be inadequately described or inconsistent, both within and between the chill models. In order to supplement this data, breeders, growers and research organisations were contacted to provide additional information. Unfortunately, no further information on chill requirements of cherries was held by these sources.

The sparse amount of information available highlights how poorly the chilling process is understood, how chill accumulation at different sites around the world may not be equivalent and how difficult it is to find appropriate information.

To compare chill in different regions around Australia, a grower survey was constructed and disseminated to growers in Victoria, Tasmania, New South Wales, South Australia and Western Australia. Only five surveys covering six sites were returned, despite follow up contact. The information from the surveys together with values from the literature were used to assign each cultivar to a chill category (low, low-moderate, moderate- high, high and very high) (Table 1) in an attempt to set initial groupings which can be refined with further research. Specific information gathered to determine these groupings by cultivar appear in Table 2.

Commonly, chill is described as being fulfilled when at least 50% of buds break (Gratacos and Cortes, 2008; Seif and Gruppe, 1985). Table 2 contains the percentage bud break for the studies that specified these details. For the studies that did not report how they determined chill satisfaction, it was assumed that bud-break is at least 50%.

**Table 1** Chill unit categorisation for chill portions, chill units and chill hours

| | Chill Portions | Chill Units | Chill Hours |
|---|---|---|---|
| Low | 20-40 | 600-800 | 300-500 |
| low-Moderate | 40-50 | 800-1000 | 500-750 |
| Moderate-high | 50-60 | 1000-1200 | 750-1000 |
| High | 60-80 | 1200-1400 | 1000-1500 |
| Very high | >80 | >1400 | >1500 |

**Table 2** Chilling required to reach at least 50% bud break or less, if no further information was available.

| Cultivar | Chill Portions | Positive Chill Units | Chill Units | Chill Hours | Chill Rating | Source |
|---|---|---|---|---|---|---|
| Bing | | 683 (30% budbreak) | 320-380, 880 | 800-900, 950-1100, 700, 700, 900, 518 (30% budbreak) | High | James (2011), Kuden et al. (1997), Anderson and Richardson (1987), Lehnert (2007), Grahams Factree, Willis Orchards, Gratacos and Cortes (2008) |
| Black Star | | | | | Moderate-High | |
| Brooks | 36.7 | | 539 (68% budbreak) 683 (74% budbreak) | 441 (68% budbreak) 518 (74% budbreak) | Low-Moderate | Jarvis-Shean (2011), Gratacos and Cortes (2008) |
| Celeste | | | 683 (52% budbreak), | 518 (52% budbreak) | Low-Moderate | Gratacos and Cortes (2008) |
| Chelan | | | | | High/Very high | Grower rating |
| Christobalina | 30.4 | | | | Low-Moderate | Jarvis-Shean (2011) |
| Early Burlat | 48 | 1326 (50% budbreak) | 683 (89% budbreak) | 518 (89% budbreak), 1119 (50% budbreak) | Low-Moderate /Moderate-High | Gratacos and Cortes (2008), Seif and Gruppe (1985), Jarvis-Shean (2011) |
| Garnet | | | 683 (39% budbreak) | 518 (39% budbreak) | Very High | Gratacos and Cortes (2008) |
| Grace Star | | | | | Moderate-High | Grower rating |
| Index | | | | | High | Grower rating |
| Kordia (Attika) | | | | <1320 | High | Brown (2011), James (2011), Grahams Factree |
| Lapins | 35 | 539 (61% budbreak), 683 (79% budbreak) | | 700, 441 (61% budbreak), 518 (79% budbreak) | Low/Low-Moderate | Jarvis-Shean (2011), Mariani (1997), Gratacos and Cortes (2008) |
| Marvin | 57.6 | | | | Moderate-High | Jarvis-Shean (2011) |

| Cultivar | Chill Portions | Positive Chill Units | Chill Units | Chill Hours | Chill Rating | Source |
|---|---|---|---|---|---|---|
| Merchant | | | | | Moderate-High/High | Grower rating |
| Minnie Royal | | | | 200-300, 400 | Low | Dave Wilson Nurseries, Grahams Factree |
| Newstar | 53.5 | | 539 (51% budbreak), 683 (70% budbreak) | 441 (51% budbreak), 518 (70% budbreak) | Low-Moderate / Moderate-High | Jarvis-Shean, 2011, Gratacos and Cortes (2008) |
| Nordwunder | | | | | High | Grower rating |
| Rainier | 45 | | | | Low-Moderate | Jarvis-Shean, 2011 |
| Regina | | | | | High | Grower rating |
| Rons | | | | | Moderate High | Grower rating |
| Royal Dawn | | | | | Low | Grower rating |
| Royal Lee | | | | 200-300, 400 | Low | Dave Wilson Nurseries, Grahams Factree |
| Ruby | 48 | | 683 (54% budbreak) | 518 (54% budbreak) | Low-Moderate | Jarvis-Shean, 2011, Gratacos and Cortes (2008) |
| Sam | 70 | | | 800 | Moderate-High | Dave Wilson Nurseries |
| Samba (Sumste) | | | | | Moderate-High | Grower rating |
| Simone | | | | | Moderate-High | Grower rating |
| Skeena | | | | | Moderate-High | Grower rating |
| Somerset | 48 | | 683 (61% budbreak) | 518 (61% budbreak) | Low-Moderate | Jarvis-Shean, 2011, Gratacos and Cortes (2008) |
| Sonata | | | | | Moderate-High | Grower rating |
| Stella | | | 218-310, 200-250 | 600-650, 700-750, 400, 700-800, 1100 | Moderate-High | Kuden et al. ISHS, Mariani (1997), Dave Wilson Nurseries, Willis Orchards, Kuden et al. (1997), Brown (2011) |
| Summit | | | | | High | James (2011) |
| Sunburst | | | | 800 | Moderate-High | Dave Wilson Nurseries |
| Sweet Georgia | | | | | Moderate-High | Grower rating |
| Sweetheart | | | | | Moderate-High | Grower rating |
| Sylvia | | | | 1800 | Very High | Brown (2011) |
| Tulare | | | | 400 | Low | Willis Orchards |
| Ulster | | | | | High | Grower rating |

| Cultivar | Chill Portions | Positive Chill Units | Chill Units | Chill Hours | Chill Rating | Source |
|---|---|---|---|---|---|---|
| Van | | 370-390, 330-380, 1357 (50% budbreak) | 435 (54% budbreak) | 700, 1000-1200, 398 (54% budbreak), 1165 (50% budbreak) | Moderate-High | Kuden et al. (1997), Dave Wilson Nurseries, Gratacos and Cortes (2008), Seif and Gruppe (1985) |

Although only four models have been used to characterise cherry chill (Table 2), it does not necessarily imply that other available more are not plausible. For instance, Cesaraccio et al. (2004) created a sequential chill and growth model. Their model accumulates chill days based on a series of equations relating daily minimum, maximum and mean temperatures, as well as a critical temperature, to chill accumulation. Anti-chill (or growth) units are then similarly accumulated according to a different set of equations. Through using this model, Cesaraccio et al. (2004) found good correlation between observed and modelled budburst day for several fruits in Italy, including seven cherry varieties. These results were shown to be better than using several of the traditional chill models. However, application of the model requires the determination of a critical threshold temperature, which is accomplished through trial and error with phenology data. This is problematic as historical phenological datasets are sparse, especially in Australia, and data that is available is often not a suitable length to test derived parameters. Further, to gain confidence in a model, validation of parameters in other climatic regions is required, which is restricted given the limited application of this and other credible models.

## Chill models

The following four chilling models will be further described for background information:

(1) 0-7.2°C model (Weinberger, 1950)

(2) Modified Utah model (Linvill, 1990)

(3) Positive Utah model (Linsley-Noakes et al., 1994)

(4) The Dynamic model (Fishman et al., 1987; Erez et al., 1990)

The four chill models have structural similarities. They all accumulate chill at hourly intervals, require summation of chill to estimate total chill exposure and operate within a defined chilling period. The Modified Utah model has an inbuilt definition of the chilling period, the time while positive chill units are accumulated. Hennessy and Clayton-Greene (1995) used this definition in their assessment of future chilling conditions in Australia. However, this approach can inflate accumulated chill values, especially in cooler regions. The model may accumulate chill prior to biological dormancy and continue to accumulate well into spring when the plant has begun to grow. Further, the positive section of the chilling curve becomes difficult to define in warmer locations which do not experience sharp turning points into and out of positive chill accumulation. Finally, in order to compare chill models identical chill periods are necessary. If the Modified Utah models definition was used, bias may occur towards this model.

## 0-7.2°C model

The 0-7.2°C model is a simple model first developed over 50 years ago and measures chill hours (CH) according to hourly temperature ($T_t$). Temperatures within the 0-7.2°C interval are allocated one chill hour, while temperatures outside this interval record zero chill hours (Equ 1 and Figure 2). To determine total chill ($CH_{tot}$) for a given chill period, chill hours are summed from predetermined start (st) and end (en) times.

$$CH_{tot} = \sum_{t=st}^{en} CH \begin{cases} T_t < 0°\text{C} & ; CH_t = 0 \\ 0°\text{C} \leq T_t \leq 7.2°\text{C} & ; CH_t = 1 \\ T_t > 7.2°\text{C} & ; CH_t = 0 \end{cases}$$

Equ 1

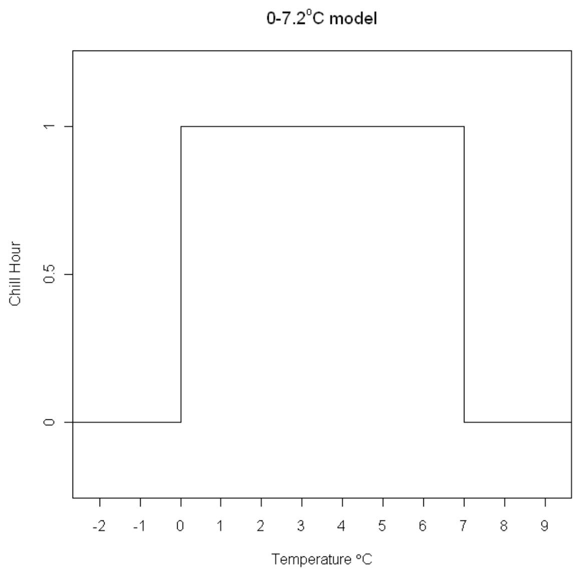


**Figure 2** Chill hour allocation for hourly temperatures (°C) according to the 0-7.2°C model

## Modified Utah model

Richardson et al. (1974) conducted experiments using peaches to improve accuracy in determining dormancy release. Building on the 0-7.2°C model, they added complexity through assigning optimum chilling temperatures (2.5-9.1°C), with temperature either side of the optimum range declining in ability to accumulate chill. Another important addition was the incorporation of the negation effect that high temperatures (≥16°C) can have on previously accumulated chill. Linvill (1990) proposed the Modified Utah model, which uses a sine curve to smooth the original Utah model. The Modified Utah model is more appealing than the original Utah model due to the more gentle response, that is, no solid step boundaries, which is more likely representative of biological processes. The two models are still quite similar (Figure 3) and therefore, for this study the Modified Utah model will be used in preference of the original Utah model.

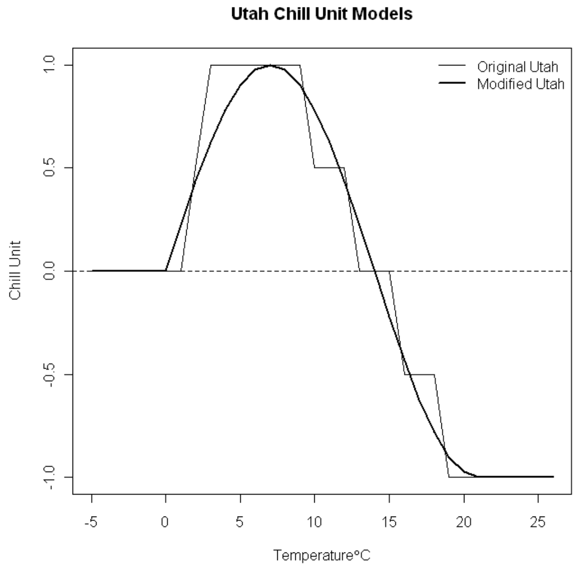


**Figure 3** The Modified and original Utah model chill unit allocations for hourly temperature (°C)

Similarly to the 0-7.2°C model, the Modified Utah model allocates chill units (CU) for hourly temperatures ($T_t$) which are also summed over a predetermined chilling period to estimate total chill exposure ($CU_{tot}$) (Equ 2).

$$CU_{tot} = \sum_{t=st}^{en} CU \begin{cases} T_t \leq 0℃ & ; CU_t = 0 \\ 0℃ < T_t \leq 21℃ & ; CU_t = \sin\left(\frac{2\pi T}{28}\right) \\ T_t > 21℃ & ; CU_t = -1 \end{cases}$$

Equ 2

## Positive Utah model

The Positive Utah model is an iteration of the original Utah model however the negation influence of high temperatures is excluded. The model defines optimal chill accumulation between 2.4 and 9.1°C and steps down to nil positive chill units for temperatures less than 1.4°C and greater than 12.4°C (Figure 4 and Equ 3).

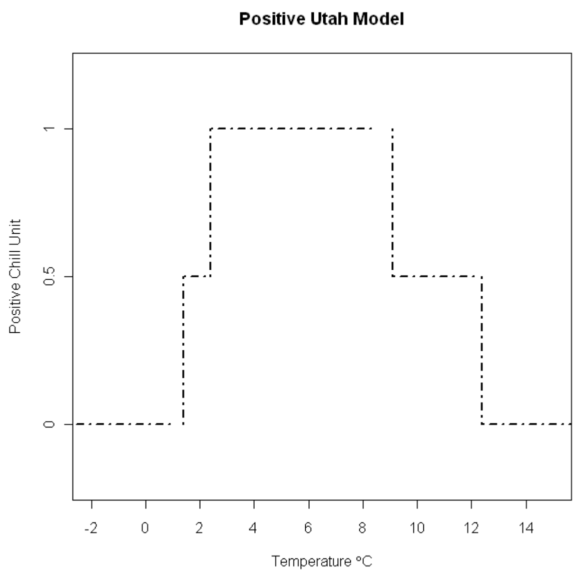


**Figure 4** The Positive Utah Model chill allocations for hourly temperature (°C)

This model also allocates positive chill units (PCU) for hourly temperatures ($T_t$) with total chill exposure ($PCU_{tot}$) determined by summing PCU over a predetermined chilling period (Equ 3).

$$PCU_{tot} = \sum_{t=st}^{en} PCU \begin{cases} T_t \leq 1.4°C & ; PCU_t = 0 \\ 1.4°C < T_t \leq 2.4°C & ; PCU_t = 0.5 \\ 2.4°C < T_t \leq 9.1°C & ; PCU_t = 1 \\ 9.1°C < T_t \leq 12.4°C & ; PCU_t = 0.5 \\ T_t > 12.4°C & ; PCU_t = 0 \end{cases}$$

Equ 3

## Dynamic model

The Dynamic model determines chill exposure differently to the other two models. It accumulates chill more interactively and calculates chill portions in a time dynamic two-step process. The creation of an intermediate product, promoted by cold temperatures, is initially determined. This intermediate product can then be destroyed by subsequent warm temperatures. Moderate temperatures are defined to have a positive influence on chill accumulation. Once a threshold amount of the intermediate product is created it is irreversibly banked as a chill portion that cannot be destroyed regardless of subsequent temperatures. Figure 5 provides a basic representation of the Dynamic model. Darbyshire et al. (2011) outline the specific algorithms for this model. Again, chill portions are calculated using hourly temperature (°K) input and chill portions are summed over a specified chill period to obtain total chill exposure.

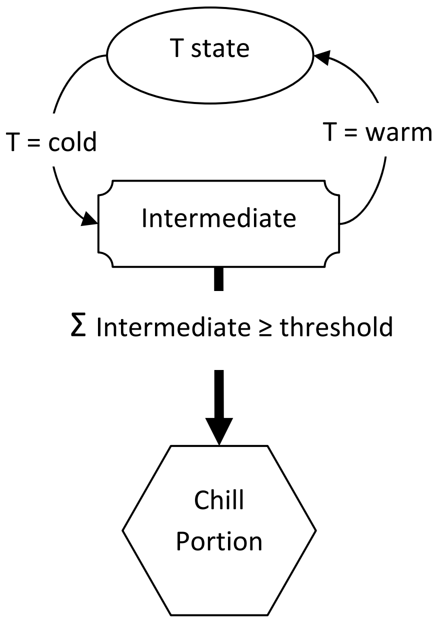


**Figure 5** Representation of key aspects of the Dynamic model, for hourly temperatures, T (°K). Depending on the initial temperature (T state) the creation of an intermediate product is prompted. Subsequent warm temperatures can destroy the intermediate product. When a threshold amount of the intermediate is amassed a chill portion is irreversibly produced. (Darbyshire et al., 2011)

As demonstrated in Table 2, multiple chill models are used by researchers with no consensus reached for a ‘best’ chill model. However, several studies have been conducted investigating chill model skill. For instance, Alburquerque et al. (2008) used the 0-7.2°C, Utah and Dynamic models to test chill model ability to predict flowering dates in seven sweet cherry varieties. The study was conducted in Spain across several locations over two seasons. The Dynamic and Utah models were found to perform equally well but results from the 0-7.2°C model were poor in comparison. They concluded the use of the 0-7.2°C model for sweet cherry in their locations was no longer appropriate.

Viti et al. (2010) compared the skill of the Utah and Dynamic models in determining the chill requirement for apricot species in Spain and Tuscany. They found that the Dynamic model was less sensitive to temperature changes and was slightly more accurate that the Utah model. However, the author’s highlight that improvement in accuracy in both models was needed. Perez et al. (2008) investigated the application of four chill models in two climatically different regions in Chile. The analysis over two seasons concluded that the 0-7.2°C model was ineffective at differentiating subtropical and temperate climates. Further, this model was not able to account for inadequate chill observations in Thompson Seedless grapes at the subtropical site. The Utah model was found to better distinguish the sites, with the Dynamic model best able to explain the regional differences.

Ruiz et al. (2007) tested the suitability of the 0-7.2°C, Utah and Dynamic models in predicting flowering in 10 apricot varieties over three years. The 0-7.2°C model was inconsistent, with the difference in recorded chill requirement between seasons as great as 30%. They found both the Utah and Dynamic models reported homogeneous chill requirements and found strong correlations between the two models. Ruiz et al. (2007) summarise that either the Utah or Dynamic model could be reliably used.

Zhang and Taylor (2011) conducted a 5 year study to estimate chill requirements of Sirora pistachio in Australia. They used the 0-7.2°C, Utah and Dynamic models to estimate chill requirements by forcing cuttings in growth chambers. Through their experiments, they found it difficult to determine a chill threshold using either the 0-7.2°C or the Utah model due to large variability in calculated chill thresholds between the seasons. The Dynamic model proved to be more consistent and a threshold chilling requirement of 59 portions was established for this species.

These studies outline that the Dynamic model consistently performs similarly or better than the other tested chill models. The positive findings in favour of the Dynamic model are most likely due to the structure of the model. The model incorporates many observations of temperature effects on chill including, optimum chilling temperatures, negation effects of high temperatures and the positive influence of moderate temperatures on chill accumulation. Further, the model is non-static in nature which would be expected to better reflect biological processes. The Modified Utah model similarly contains optimum chilling temperatures and negative influence of high temperatures. However, when using this model, chill that is accumulated early in the season can be negated some time later by late season high temperatures. The Positive Utah model is a derivative of the Utah model which does not include the negation aspects of high temperatures. It has been found to perform better than the Utah model in mild locations in South Africa (Linsley-Noakes et al., 1994) and described walnut phenology well in California (Luedeling et al., 2009).

The Dynamic model only considers the impact of high temperatures in influencing the production of an intermediate product, which is linked to time. Once a sufficient amount of the intermediate product is formed a chill portion is irreversibly created, and cannot be reversed by high temperatures later in the season. The 0-7.2°C model is very simplistic and does not incorporate many of the observed effects of temperature on chill accumulation, such as the negative effect of high temperatures. The step-change structure of the model forces solid boundaries to chill accumulation, for example, 7.3°C will accumulate nil chill hours while 7.2°C will be allocated a full chill hour. Given the restricted knowledge on the chilling process this level of accuracy is unlikely to be defendable.

The 0-7.2°C model is dated and many studies have found it to perform poorly in predicting observed changes (Ruiz et al., 2007; Alburquerque et al., 2008; Perez et al., 2008; Zhang and Taylor, 2011). Nonetheless, this model has been extensively used in research and continues to be with a recent study in California using only this model to investigate future chilling conditions (Baldocchi and Wong, 2008). The Dynamic model appears to be a leader for chill model choice, however it has received limited application.

## Climate Change & Chilling

Limited research has focused on the potential effect of climate change on chill accumulation, although many studies discuss potential negative impacts (Legave et al., 2008; Wand et al., 2008; Harrington et al., 2010; Darbyshire et al., 2011). The impact of future warming on chill accumulation is not necessarily obvious. Warming may increase the frequency of temperatures warmer than the chilling optimum, decreasing overall accumulation. Further, higher incidence of high temperatures may occur over winter, negating previously accumulated chill, lowing chill accumulation. Alternatively, in cooler locations, warming may shift temperatures into the optimum chill accumulation zone, increasing chill received. The chill models add complexity to these relationships, especially the Dynamic model. This model is time dynamic and therefore, the progression of temperature over time also influences chill accumulation. Thus, the chill models need to be run with climate projection data to ascertain potential impacts.

Hennessy and Clayton-Greene (1995) conducted an investigation into the potential impact of warming on chill accumulation in southern Australia. They found that locations with higher present mean temperatures and wider diurnal ranges were at greater risk of experiencing lower chill accumulation. However, their study is now over 15 years old, used a single chill model (Modified Utah model) and climate projection data produced in 1992. Luedeling et al. (2011) conducted a global analysis of projected changes to chill accumulation according to the Dynamic model. However, the spatial scale of Luedeling et al. (2011) study is too coarse for practical application in Australia. The approach undertaken in this assessment of chill conditions for sweet cherry in Australia will draw on aspects of both Hennessy and Clayton-Greene's (1995) and Luedeling et al. (2011) studies. Similarly to Luedeling et al. (2011), the Dynamic model will be used for assessments. Following Hennessy and Clayton-Greene (1995) a sensitivity approach to climate projection data will be used. Specifically, how individual site chill conditions change in response to localised temperature increases as dictated by global temperature changes.

# Materials and Methods: Cherry Chill Projections

## Data

Historical daily minimum and maximum data from 1911-2009 for the six locations were sourced from 0.05° x 0.05° grids (Jones et al., 2009). This dataset was required as quality historical *in situ* meteorological data are not available. This data has been previously used to investigate historical chilling conditions in Australia (Darbyshire et al., 2011). These data are used to represent natural variability of chill accumulation at the sites in the projection results.

Climate projection output from 21 Atmosphere-Ocean General Circulation Models (AOGCMs) were provided by the Queensland Climate Change Centre of Excellence (QCCCE) using pattern scaling data provided by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and techniques described for OzClim in Page and Jones (2001) and Ricketts and Page (2007). Where climate variables for some AOGCMs were not available from CSIRO, they were in-filled by QCCCE using regression methods. The projection data was provided as localised monthly minimum and maximum temperature perturbations per 1°C global temperature increase from the 1975-2004 baseline period.

## Atmosphere-Ocean General Circulation Model (AOGCM) selection

Selection of AOGCMs for use in projection analyses is critical to ensure an appropriate range of future conditions are included in the results. Output from AOGCMs can vary greatly, which is due to different characterisation of the climate system in the models. These differences reflect incomplete knowledge of the whole climate-ocean-land system, with no single model determined as most accurate.

Use of all AOGCMs is computationally intensive and the complex results may cloud interpretation. For this project, the full model range (coolest to warmest) is needed and including the intermediate models will not add further insights. Thus, for each study location two AOGCMs, the coolest and warmest were selected for projection analysis.

Prior to model selection, three AOGCMs were excluded as they have been found to perform poorly over the Australian region by previous studies (van Oldenborgh et al., 2005; Suppiah et al., 2007; Smith and Chandler, 2010). The Australian continent was then divided into grids of approximately 550 x 550 km grids and AOGCM output was calculated for each of these grid cells. The six research sites fall within four of the grid cells, with selection of AOGCMs condensed to these four areas. For each of these four regions, the warmest and coolest models were selected (Table 3), ensuring the full range of likely future climates were included. This approach has been developed by the CSIRO and will be part of new methodologies associated with climate change projection analysis.

**Table 3** AOGCMs, representative area (sites) for which the model was selected and reason for inclusion

| AOGCM | Representative area (sites) | Inclusion comment |
|---|---|---|
| CSIRO Mk 3.5 | VIC (Tatura, Yarra Valley)<br>TAS (Huonville)<br>WA (Manjimup)<br>SA (Lenswood)<br>NSW (Orange) | Overall warmest model |
| BCCR-BCM2.0 | WA (Manjimup | Overall coolest model |
| MIROC3.2_medres | SA (Lenswood)<br>VIC (Tatura, Yarra Valley) | Overall coolest model |
| FGOALS-g1.0 | TAS (Huonville) | Overall coolest model |
| ECHO-G | NSW (Orange) | Overall coolest model |

To demonstrate differences in the projection data between the sites and the range of model responses, localised mean winter temperature increase according to 1°C increase in average global temperatures is shown in Table 4. For the winter months, Huonville, Lenswood and Manjimup warm less than Orange, Tatura and the Yarra Valley and indeed at a slower rate than the global average.

**Table 4** Localised mean winter temperature (°C) increase per 1°C increase in average global temperatures. The range represents the coolest – warmest AOGCM result.

| Study location | Mean winter temperature (°C) |
|---|---:|
| Huonville | 0.60 – 0.85 |
| Lenswood | 0.69 – 0.93 |
| Manjimup | 0.57 – 0.91 |
| Orange | 0.73 – 1.21 |
| Tatura | 0.68 – 1.09 |
| Yarra Valley | 0.63 – 1.03 |

### Projected hourly temperatures

Projection data was created for localised temperature change according to 1, 2 and 3°C increases in global average temperature for each site. Monthly minimum and maximum temperature perturbations per 1°C global temperature increase for each AOGCM were added to the respective historical daily temperature time-series at each location. For example, the localised August minimum temperature perturbation at Huonville was added to the historical August minimum daily temperature time series at Huonville. The temperature perturbations per degree warming were scaled up to represent 2 and 3°C global perturbations. This involved a simple multiplication of the localised change per degree warming at each site by the respective global temperature increase (2 or 3). Similarly to 1°C perturbations these 2 and 3°C changes were added to the historical daily dataset to produce projected temperature series.

The projected daily temperature time-series were then converted into hourly temperatures, as this is the temporal scale required by the chill model. The algorithm used describes daily temperatures according to a sine curve and uses a logarithmic function for night-time cooling, following methods in Linvill (1990) and Darbyshire et al. (2011). The hourly scale temperature projection data for 1, 2 and 3°C increases were run through the Dynamic model at each location and for both the warmest and coolest AOGCM. Chill was defined to accumulate from 1 May – 31 August inclusively for all locations.

# Results

The chill categories (low, low-moderate, moderate-high and very high) determined through published results in literature and grower surveys were used to estimate the percentage likelihood of chill received at each location. The percentages reported represent natural variability in the system while the range of results indicate AOGCM variability. Values less than 90% were classified as receiving inconsistent chill, based on the 'safe winter chill' variable developed by Luedeling et al. (2009).

Initially, conditions according to the historical dataset were calculated (

Table 5) as a baseline reference for the projected data. All locations consistently currently receive low and low-moderate chill. Manjimup does not receive consistent high or very high chill. Only Huonville and the Yarra Valley reliably receive very high chill portions. Projected changes to chill received according to localised change per 1, 2 and 3°C average global temperature increase were tabulated (Table 6, Table 7 and Table 8).

**Table 5** Current chill condition according to the chill categorisations. Values are percentage (%) of years (99) that received the cut-off amount of chill portions indicated. Values highlighted are those where less than 90% of years received adequate chill.

| | Low | | Low-Moderate | | Moderate-High | | High | | Very High |
|---|---|---|---|---|---|---|---|---|---|
| *Cut-off (chill portion)* | 20 | 40 | 41 | 50 | 51 | 60 | 61 | 80 | >80 |
| Huonville | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| Yarra Valley | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 98 | 94 |
| Orange | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 92 | 87 |
| Lenswood | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 91 | 88 |
| Tatura | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 45 | 33 |
| Manjimup | 100 | 100 | 100 | 100 | 100 | 85 | 79 | 1 | 1 |

**Table 6** Chill condition according to average global temperature increase 1°C. L and H respectively indicate the coolest and warmest AOGCM. Values are percentage (%) of years (99) that received the cut-off amount of chill portions indicated. Values highlighted are those where less than 90% of years received adequate chill.

| | Low | | | | Low-Moderate | | | | Moderate-High | | | | High | | | | Very High | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cut-off (chill portion)* | 20 | | 40 | | 41 | | 50 | | 51 | | 60 | | 61 | | 80 | | >80 | |
| *Climate model* | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H |
| Huonville | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 96 | 97 | 95 |
| Yarra Valley | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 73 | 41 | 63 | 33 |
| Orange | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 83 | 46 | 77 | 39 |
| Lenswood | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 71 | 54 | 63 | 46 |
| Tatura | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 10 | 1 | 4 | 0 |
| Manjimup | 100 | 100 | 100 | 100 | 100 | 99 | 91 | 77 | 90 | 75 | 51 | 23 | 46 | 17 | 0 | 0 | 0 | 0 |

**Table 7** Chill condition according to average global temperature increase 2°C. L and H respectively indicate the coolest and warmest AOGCM. Values are percentage (%) of years (99) that received the cut-off amount of chill portions indicated. Values highlighted are those where less than 90% of years received adequate chill.

| | Low | | | | Low-Moderate | | | | Moderate-High | | | | High | | | | Very High | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cut-off (chill portion)* | 20 | | 40 | | 41 | | 50 | | 51 | | 60 | | 61 | | 80 | | >80 | |
| *Climate model* | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H |
| Huonville | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 95 | 56 | 89 | 44 |
| Yarra Valley | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 28 | 1 | 20 | 1 |
| Orange | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 54 | 4 | 41 | 1 |
| Lenswood | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 97 | 100 | 95 | 28 | 2 | 17 | 2 |
| Tatura | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 97 | 100 | 97 | 99 | 54 | 99 | 41 | 0 | 0 | 0 | 0 |
| Manjimup | 100 | 100 | 93 | 64 | 93 | 58 | 70 | 12 | 63 | 10 | 16 | 0 | 14 | 0 | 0 | 0 | 0 | 0 |

**Table 8** Chill condition according to average global temperature increase 3°C. L and H respectively indicate the coolest and warmest AOGCM. Values are percentage (%) of years (99) that received the cut-off amount of chill portions indicated. Values highlighted are those where less than 90% of years received adequate chill.

| | Low | | | | Low-Moderate | | | | Moderate-High | | | | High | | | | Very High | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cut-off (chill portion)* | 20 | | 40 | | 41 | | 50 | | 51 | | 60 | | 61 | | 80 | | >80 | |
| *Climate model* | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H | L | H |
| Huonville | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 66 | 6 | 51 | 2 |
| Yarra Valley | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 97 | 100 | 97 | 100 | 48 | 100 | 38 | 3 | 0 | 1 | 0 |
| Orange | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99 | 100 | 64 | 100 | 47 | 18 | 0 | 9 | 0 |
| Lenswood | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 92 | 100 | 91 | 94 | 49 | 91 | 37 | 2 | 0 | 1 | 0 |
| Tatura | 100 | 100 | 100 | 93 | 100 | 89 | 99 | 30 | 98 | 24 | 75 | 0 | 74 | 0 | 0 | 0 | 0 | 0 |
| Manjimup | 100 | 93 | 76 | 9 | 74 | 5 | 22 | 0 | 20 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# Discussion

To demonstrate interpretation of these results, Bing cherry is used as an example. Bing was classified as a high chill variety, meaning it is estimated to require between 61 and 80 chill portions. Under current conditions Manjimup does not reliability accumulate enough chill for this variety with only 79% of years meeting the lower end of the range and 1% meeting the 80 chill portion cut-off. Similarly, Tatura only reaches adequate chill conditions 45% of the time for the upper end of the range but does currently accumulate enough chill for the 61 chill portion threshold. All other sites are suitable for this species. With 1°C increase to average global temperatures only Huonville accumulates enough chill across the range of the high chill category. However, all locations except Manjimup still amass adequate chill at the lower end of the category. With 2°C warming, Huonville no longer reliably accumulates enough chill for the 80 cut-off according to the warmer AOGCM. Tatura looses more consistency as well. For 3°C warming, no location accumulates enough chill for the upper edge of the category and only four sites accumulate enough chill at the lower cut-off if the coolest AOGCM is used.

When interpreting results, it should be appreciated that neither the warmer or cooler AOGCM is more likely and indeed neither is an average result between the two. Also, the range of the categories cannot be further refined at this point. Although some cultivars do have more accurate threshold information (see Table 2).

## Chill portion accumulation and chill threshold calculator

This report includes a 'chill portion calculator', that is, an interactive spreadsheet that can be linked to weather station outputs to determine the actual chill accumulation at specific sites.

Included in the calculator is another interactive spreadsheet which calculates the likelihood of achieving a certain chill threshold (under the global warming scenarios described) allowing the inclusion more precise information as it becomes available, ensuring results remain viable if further research occurs.

The spreadsheets will offer growers a consistent methodology to measure chill and ultimately, may help to more clearly define chill thresholds for different cultivars and their suitability at different locations.

## Stages of dormancy and rest completion

Winter dormancy evolved in cold climates to limit freezing injury in susceptible tissues (Taiz and Zieger, 1991). In a paper proposing a universal terminology for dormancy and system of classification, Lang (1987) defined dormancy as "the temporary suspension of visible growth of any plant structure containing a meristem". Lang's (1987) definition is further refined with the terms para,- eco- and endo-dormancy depending on the regulatory process at play (Lang et al., 1987).

Ecodormancy is regulated by environmental factors (e.g. temperature), paradormancy is regulated by physiological factors outside the affected structure (e.g. signals from leaf or budscales) and endodormancy is regulated by physiological factors inside the affected structure (e.g. in bud meristems) (Lang et al., 1987). Lang (1987) and others (Campoy, 2011) suggest that dormancy is likely to be regulated by multiple processes that are both interactive and dynamic.

Chill requirements are genetically determined but differences in chilling also exist between buds, with flower buds having a lower chilling requirement than vegetative buds (Sheard, 2011). Some authors report that chilling and post dormant heat requirement in stone fruit and pears are correlated (Mahmood et al. 2000; Seif and Gruppe 1985): high chill varieties have high heat requirements in spring which may be advantageous in avoiding frost damage.

## Signs of insufficient chill

In cherries, signs of insufficient chill include reduced branching (Mahmood et al., 2000, Oukabli and Mahou, 2007) prolonged dormancy, protracted and sporadic flowering, with trees often showing signs of apical dominance: Vegetative buds at the tips of shoots and branches start to grow first, inhibiting bud break on those located below or delaying their growth (Oukabli and Mahhou, 2007, Mahmood et al., 2000, Sheard, 2008).

Mahmood et al. (2000) showed that for Stella, the number of branches progressively increased with increasing exposure to chill conditions, after which it remained constant, suggesting a saturation response. In the same trials, leaf fresh and dry weights increased with increasing exposure to chill (Mahmood et al., 2000).

As flower buds have a lower chilling requirement than leaf buds they usually emerge first (Sheard, 2008). In low chill years, leaf emergence can be delayed for several weeks resulting in very low leaf to fruit ratios and ultimately also low fruit set (Sheard, 2008). Further, in low chill years, leaf and flower buds may emerge synchronously, both competing as sinks for carbon reserves which may also lead to low fruit set (Sheard 2008, Noppakoonwong et al., 2005, Erez and Yablowitz, 1997).

A grower reported that in Ballingup (WA, 2011), varieties such as "Index, Regina and Supreme did not show any bud burst until well into December. Others varieties such as Bing and Stella commenced bud burst relatively early on lower branches but development was very slow and often had not reached the top of the tree until late December" (R. Robertson, pers. comm., 2012).

Insufficient chill can also lead to pollination and fertilisation problems (Kuden et al., 1997, Brown 2011). Flower abnormalities associated with chilling in cherries include low pollen production (illustrated in Figure 7a) and the malformation or absence of pistils and ovaries (illustrated in Figure 6a) which result in small and deformed blossoms (Brown, 2011, Oukabli and Mahhou 2007, Mahmood et al., 2000).

Oukabli and Mahhou (2007) showed that vascular connections to the bud only become fully functional just before budbreak (see Figure 7 b). With insufficient chilling, vascular connections are not established and the flower abscises (Oukabli and Mahhou, 2007).

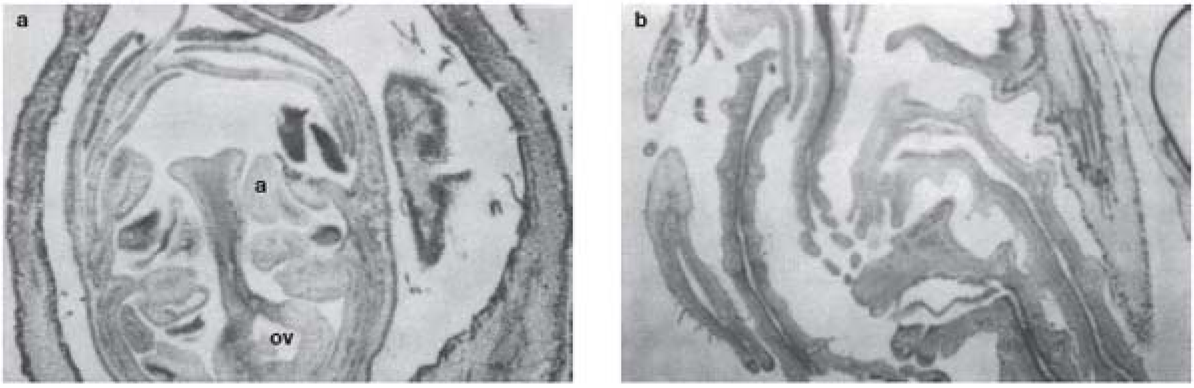


**Figure 6** Section longitudinal view of flower bud of *Prunus avium* L. sampled at anthesis for « Bigarreau Burlat » showing an atrophied ovule (a, × 50) and disorganized and isolated flower primordial (b, × 200) — *Vue d'une coupe longitudinale de bourgeon de* Prunus avium *L. prélevé sur « Bigarreau Burlat » à l'anthèse montrant un ovule atrophié (a, × 50) et un primordia foliaire isolé (b, × 200).*

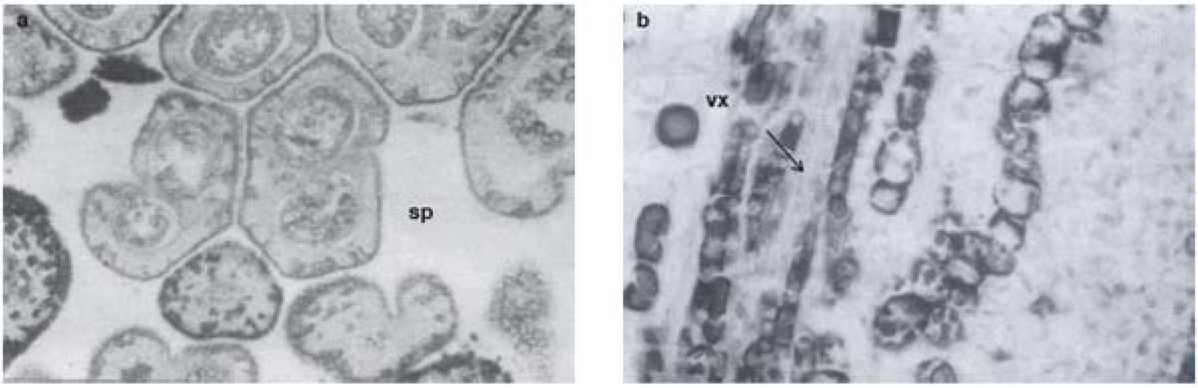


**Figure 7** Bud of « Bigarreau Burlat » taken at anthesis with pollen sacs enclosed a little quantity of pollen (a, × 150), arrow showing xylem element (b, × 400) — *Bourgeon de « Bigarreau Burlat » prélevé à l'anhèse avec des sacs polliniques refermant une petite quantité de pollen (a, × 150). La flèche montre les éléments du xylème (b, × 400).*

Source: Oukabli and Mahhou (2007).

# Climate change adaptation

## Rootstocks

The choice of rootstock may improve bud break of high chill fruit tree varieties growing in warm climates (Putland 2011; Campbell 2007). This has been demonstrated for apples (Wilkie, Middleton and Putland, 2011) and peaches (Seif and Guppe, 1985).

Responses to the grower survey indicated that cultivars on Gisela rootstocks had lower chill requirements than Colt or F12/1 growing in the same location. Cultivars on Gisela rootstocks lose leaves 2 weeks earlier and flower 5-6 days earlier than the same cultivar on other rootstocks (Figure 8), indicating that dwarfing precocious rootstocks may accumulate chill more easily or are more sensitive (S. Chapman, pers. Comm. 2011).

The photos in Figure 8 below show (a) Gisela 6 rootstock (b) Colt rootstock and (c) Sweetheart on Colt in the foreground, Sweetheart on G6 in the background and (d) photo (c) taken a week later.

Photo (c) shows that Sweetheart on Gisela 6 is in full flower, whilst Colt exhibits only vegetative growth and possible signs of insufficient chill.

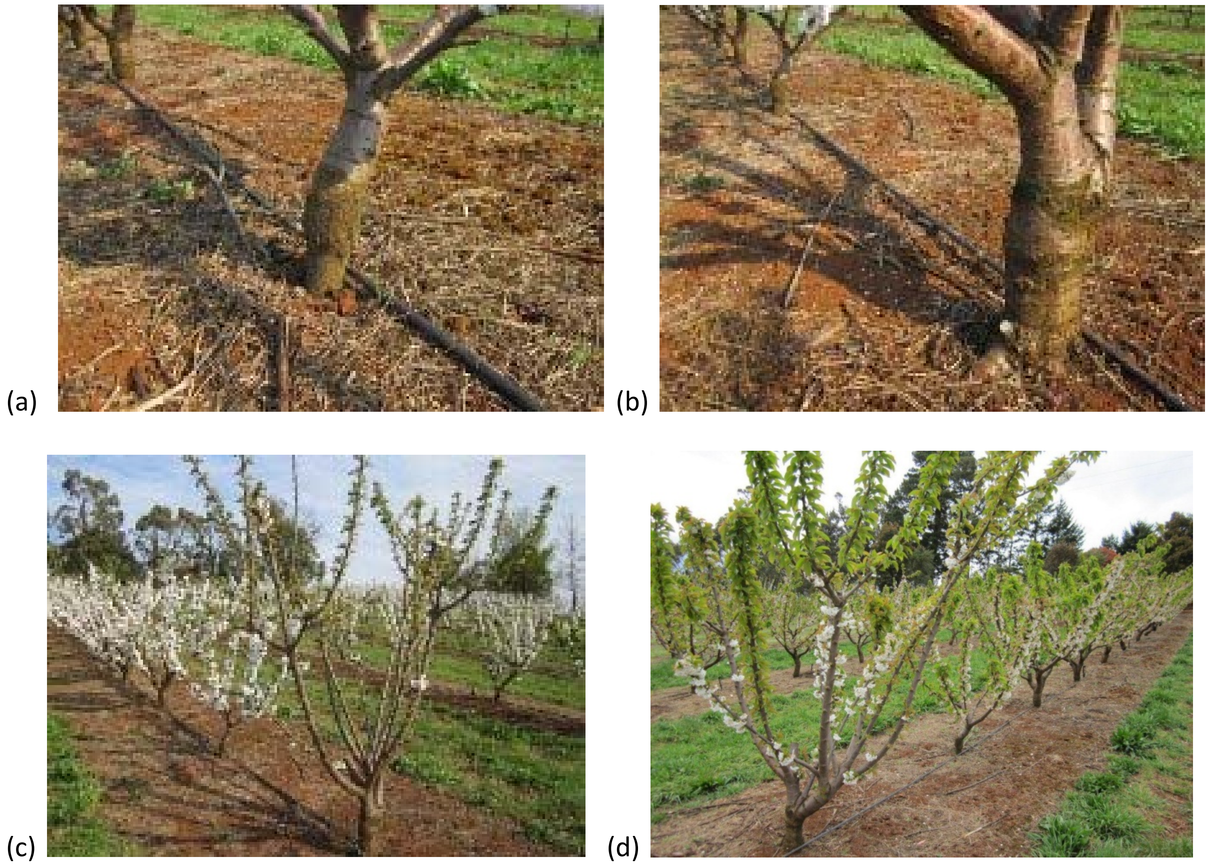


**Figure 8 (a)** Gisela 6 rootstock (**b)** Colt rootstock ( **c)** Sweetheart on Colt in the foreground, Sweetheart on Gisela 6 in the background (d) photo (**c)** a week later. Photos courtesy M. Chapman.

The choice of rootstock may provide a climate adaptation strategy in areas of low chill.

## Dormancy breakers

Dormancy breakers such as mineral oil, Giberellic Acid (GA), potassium nitrate ($KNO_3$), Thiourea, hydrogen cyanamide ($H_2CN_2$) and fatty acids and their esters (Waiken, Armourbreak) are used to advance and/or synchronise flowering, improve fruit set and advance harvest date in stone fruit crops (Gratacos and Cortes 2008a; Sheard 2008; Noppakoonwong, 2005). Chemicals must be applied at sub-lethal concentrations to be effective, but incorrect timing or rate may result in phytotoxic damage to fruit buds and resultant poor fruit set (Noppakoonwong, 2005). The situation is made even more complex as reproductive buds are more sensitive to phytotoxic effects than vegetative buds and some dormancy breakers have a greater effect on floral buds, whereas others have a greater effect on vegetative buds (Sheard, 2008; Noppakoonwong, 2005). In many cases, the mode of action that these compounds effect in releasing plants from dormancy is largely unknown.

Rest breaking agents can only compensate for a limited amount of chill. Their application may best be timed using the Dynamic model (Glozer et al*.,* 2005, Glozer and Neiderholzer, 2006, Granger 2001, Sheard 2008) and physiological observations (Sheard, 2008).

Restrictions on several Rest Breaking Agents (RBAs) have been imposed due to environmental concerns or mammalian toxicity (Sheard, 2008). At present, researchers are looking for safer and less toxic alternatives (Gernandez and Craig, 2011; Sheard 2008).

In trials on Bing sweet cherry in South Africa (Sheard, 2008) found the most promising RBAs to be a combination of Dormex® (hydrogen cyanamide) 1% plus 3% mineral oil and Lift (thidiazuron and mineral oil). Growers have reported beneficial effects with Waiken (fatty acid esters) and Armourbreak (alkoxylated fatty amine) (M. Chapman, pers. Comm. 2012).

**Dormex® (Hydrogen cyanamide)**

Dormex® (hydrogen cyanamide) is a widely used rest breaking agent for many crops. It is relatively toxic and currently under regulatory review by European Union (EU) (Settini, 2005). Current research is focussed on optimising application time to increase its effectiveness in cherries.

In cherries, hydrogen cyanamide can compensate for 20-30% of chill requirements, but this is likely to vary with rootstock and in combination with other treatments. Sheard (2008) showed that Bing was responsive to hydrogen cyanamide when 49-57 chilling portions had accumulated.

Sheard (2008) also found that the timing of HCN application may be more critical than the rate. If applied too early (e.g. during endodormancy), it is ineffective. If it is applied too late, that is, close to natural budburst, it is phytotoxic, resulting in damage to flower buds and negatively impacting fruit set (Sheard, 2008).

**Lift**

Lift is a combination of thidiazuron and mineral oil. In trials with rest breaking agents in South Africa, Sheard (2008) found that cherries were responsive to Lift over a greater length of time than other treatments, indicating that the time of application may not be as critical with Lift as with some other products.

From his experimental work, Sheard (2008) suggests that RBA application be based on a combination of chill accumulation and stage of bud development stage (Sheard, 2008). Specifically:

> "In low chill years (<40 chill portions by end of July) applications could be based on physiological stage of bud development (pink side) while in high chill years (>50 chill portions) applications could be based on both chilling accumulation and the visual appearance of the bud".

Further studies are required to determine the most effective RBAs, optimum timing, rate and combination of products. Different cultivars (low, medium and high chill) may respond differently and the rootstock effect should be considered in further work.

# Evaporative cooling and artificial chill

Even if nights are sufficiently cool, daytime temperatures over 16°C can negate chill accrual (Allan, 2004). In South Africa, evaporative cooling has successfully been used to provide artificial chilling for kiwifruit and grapes in area with mild winters (Allan , 2004). Significant improvements in budburst and production have been achieved and artificial chilling is now used on a large scale (Allan, 2004).

When daytime temperatures are expected to exceed 16°C and night time temperatures remain below 12°C, chill can accrue. Evaporative cooling is provided by running overhead sprinklers intermittently (Allan, 2004). Ideally, the sprinkler cycles should wet the buds effectively and the interval short enough to keep bud temperatures from rising above 16°C during the day (Allan, 2004). Appropriate temperature thresholds will need to be determined for cherries. It may also be possible to reduce night temperatures using evaporative cooling.

The combination of evaporative cooling and dormancy breakers is likely to have a synergistic effect and this has been demonstrated for hydrogen cyanamide (Allan, 2004). Together, they increased bud-break in grapes to over 80%, compared to 50% alone for Dormex® and 0% for control vines (Allan, 2004).

As a climate change adaptation strategy, evaporative cooling to provide artificial chill looks promising, especially when combined with RBAs and low chill rootstocks.

# Technology transfer

This report includes a 'chill portion calculator', that is, an interactive spreadsheet that can be linked to weather station outputs to determine the actual chill accumulation at specific sites.

Included in the calculator is another interactive spreadsheet which calculates the likelihood of achieving a certain chill threshold (under the global warming scenarios described) allowing the inclusion more precise information as it becomes available, ensuring results remain viable if further research occurs.

The spreadsheets will offer growers a consistent methodology to measure chill and ultimately, may help to more clearly define chill thresholds for different cultivars and their suitability at different locations.

This research was presented at the Victorian Cherry Conference on the 1st of March, 2012 in Wangaratta Victoria.

# Recommendations

With global warming of 2°C predicted to negatively affect every growing region investigated in this study, more research on chill is urgently needed. Reliable baseline data for cultivar chill thresholds is sparse, especially under Australian conditions. It would also be timely to focus research on potential climate change adaptation strategies such as low chill rootstocks, evaporative cooling and a more complete understanding of rest breaking agents and application timing for optimal outcomes. Multiple strategies may have a synergistic effect in maximising the amount of chill accumulated at orchards in future years.

# References


Alburquerque, N, García-Montiel, F, Carrillo, A, Burgos, L, (2008). Chilling and heat requirements of sweet cherry cultivars and the relationship between altitude and the probability of satisfying the chill requirements. Environmental and Experimental Botany. 64 (2):162-170

Allan, P. (2004). Winter chilling in areas with mild winters: its measurement and supplementation. Proc. VII IS on TZFTS. ISHS (pp 47-52).

Amen, RD, (1968). A model of seed dormancy. Botanical Review. 34 (1):1-&

Anderson, J.L. and Richardson, E.A. (1987). The Utah chill unit/flower bud phenology models for deciduous fruit: their implication for production in subtropical areas. Acta Hort. (ISHS) 199:45-50. http://www.actahort.org/books/199/199_10.htm

Baldocchi, D, Wong, S, (2008). Accumulated winter chill is decreasing in the fruit growing regions of California. Climatic Change. 87:S153–S166

Brown, G. (2011). Investigating and overcoming negative effects of global warming on cherry dormancy. HAL Project CY09012

Brown, G. (2011). Investigating and overcoming negative effects of global warming on cherry dormancy. HAL Project CY09012.

Campbell, J. (2007). Winter chill: apples and pears for warmer districts. Australian Fruitgrower. May pp. 18-19. www.apal.org.au

Campoy, J.A. and Egea, D.R. (2011). Dormancy in temperature fruit trees in a global warming context: A review. Scientia Horticulturae 130:357-372

Cesaraccio, C, Spano, D, Snyder, RL, Duce, P, (2004). Chilling and forcing model to predict bud-burst of crop and forest species. Agricultural and Forest Meteorology. 126 (1-2):1-13

Darbyshire, R, Webb, L, Goodwin, I, Barlow, S, (2011). Winter chilling trends for deciduous fruit trees in Australia. Agricultural and Forest Meteorology. 151:1074-1085

Dave Wilson Nurseries. www.davewilson.com (accessed 15/5/2011).

Dennis, FG, (1994). Dormancy - What we know (and don't know). HortScience. 29 (11):1249-1255

Erez, A, Fishman, S, Linsley-Noakes, GC, Allan, P, (1990). The dynamic model for rest completion in peach buds. Acta Horticulturae. 279:165-174

Erez, A. and Yablowitz, Z. (1997). Effect of dormancy breaking agents with Armobreak in the peach. . Acta Hort. (ISHS) 441:183-190. http://www.actahort.org/books/441/441_24.htm

Fishman, S, Erez, A, Couvillon, GA, (1987). The temperature-dependence of dormancy breaking in plants - Computer-simulation of processes studied under controlled temperatures. Journal of Theoretical Biology. 126 (3):309-321

Gernandez, G. and Craig, R.L. (2011). Effects of alternatives to hydrogen cyanamide on commercial kiwifruit production. Acta Hort. (ISHS) 9913:357-363

Ghariani, K, Stebbins, RL, (1994). Chilling requirements of apple and pear cultivars. Fruit Varieties Journal. 48 (4):215-222

Glozer, K, Niederholzer, F.J. (2006). The Dynamic Model and rest breaking agents in California. 'French' Prune Production. Hortscience 41:1031.

Glozer, K., Vrant, J.A. and Coates, W.W. (2005). Evaluation of chill models in 'Bing" sweet cherry rest-breaking trials in California from 1994 to the present: validation of the Dynamic model. HortScience 40:1141

Grahams Factree www.factree.com.au (accessed 13/8/2011)

Granger, A. (2001). Overseas Travel Report. Attendance at the International Cherry Symposium 2001. HAL project CY0005

Gratacos and Cortes (2008). Chilling requirements of ten sweet cherry cultivars in a mild winter location in Chile. ISHS Acta Horticulturae 795: V International Cherry Symposium.

Gratacós, E. and Cortés, A. (2008). Phenology and production of sweet cherry cultivars in a low chilling area of central chile . Acta Hort. (ISHS) 795:239-244. http://www.actahort.org/books/795/795_32.htm

Harrington, CA, Gould, PJ, St.Clair, JB, (2010). Modeling the effects of winter environment on dormancy release of Douglas-fir. Forest Ecology and Management. 259 (4):798-808

Hennessy, K, Clayton-Greene, K, (1995). Greenhouse warming and vernalisation of high-chill fruit in southern Australia. Climatic Change. 30:327-348

Horvath, D, (2009). Common mechanisms regulate flowering and dormancy. Plant Science. 177 (6):523-531

James, P. (2011). Australian Cherry Production Guide (draft). Rural Solutions, SA.

Jarvis-Shean, K. (2011). Chill Requirements in chill portions, calculated using the Dynamic Model. Dept of Plant Sciences, UC Davis.

Jones, D, Wang, W, Fawcett, R, (2009). High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal. 58:233-248

Karoly, D, Braganza, K, (2005). Attribution of recent temperautre changes in the Australian region. Journal of Climate. 18 (3):457-464

Küden, A.B., Küden, A. and Kaska, N. (1997). Cherry growing in the subtropics. Acta Hort. (ISHS) 441:71-74. http://www.actahort.org/books/441/441_7.htm

Lang, Early, J.D. Martin, G.C. and Darnell, R.L. (1987). Endo-, Para- and Ecodormancy: Physiological terminology and classification for dormancy research. HortScience 22(3):371-377.

Legave, J, Farrera, I, Almeras, T, Calleja, M, (2008). Selecting models of apple flowering time and understanding how global warming has had an impact on this trait. Journal of Horticultural Science & Biotechnology. 83 (1):76-84

Lehnert, R. (2007). Breeding cherries for hot climates. Good Fruit Grower, 15th May 2011.

Lehnert, R. (2007). Breeding cherries for hot climates. Good Fruit Grower, www.goodfruit.com (accessed 15/5/2011).

Linsley-Noakes, GC, Allan, P, Matthee, G, (1994). Modification of rest completion prediction models for improved accuracy in South African stone fruit orchards. Journal of the Southern African Society for Horticultural Sciences. 4 (1):13-15

Linvill, DE, (1990). Calculating chilling hours and chill units from daily maximum and minimum temperature observations. HortScience. 25 (1):14-16

Luedeling, E, Brown, P, (2010). A global analysis of the comparability of winter chill models for fruit and nut trees. International Journal of Biometeorology. 55 (3):411-421

Luedeling, E, Girvetz, EH, Semenov, MA, Brown, PH, (2011). Climate change affects winter chill for temperate fruit and nut trees. Plos One. 6 (5)

Luedeling, E, Zhang, M, McGranahan, G, Leslie, C, (2009). Validation of winter chill models using historic records of walnut phenology. Agricultural and Forest Meteorology. 149:1854-1864

Mahmood, K, Carew, J.G., Hadley, P. And Battey, N.H. (2000). Chill unit models for the sweet cherry cvs Stella, Sunburst and Summit. Journal of Horticultural Science and Biotechnology 75(5):602-606.

Mahmood, K. Carew, J.G., Hadley, P and Battey, N.H. (2000). The effect of chilling and post-chilling temperatures on growth and flowering of sweet cherry (Prunus avium L.).

Mariani, A. (1997). Stone fruit varieties for milder climates. www.crfg.org/tidbits/StoneFruit.html (accessed 14/7/2011).

Nicholls, N, Collins, D, (2006). Observed climate change in Australia over the past century. Energy and environment. 17 (1):1-12

Noppakoonwong, U., Scripinta, P., Pasopa, P., Subhadrabandhu, S., George, A.P., and Nissen, R.J. (2005). A trial of rest-breaking chemicals on low-chill peach and nectarine. In Production technologies for low-chill temperate fruits — Reports from the Second International Workshop (Eds. George, A. and Boonprakob, U.). ACIAR Technical Reports No. 61.

Oukabli, A, Bartolin, S, Viti, R, (2003). Anatomical and morphological study of apple (Malus X domestica Borkh.) flower buds growing under inadequate winter chilling. Journal of Horticultural Science & Biotechnology. 78 (4):580-585

Oukabli, A. Mahhou, A. (2007). Dormany in sweet cherry (*Prunus avium* L.) under Mediteranean climatic conditions. Biotechnol. Agron. Soc. Enviorn 11(2):133-139

Page, CM, Jones, D, 2001. OzClim: The development of a climate scenario generator for Australia. In: Zerger, A., Argent, R.M. (Eds.), MODSIM 2001 International Congress on Modelling and Simulation, Modelling and Simulation Society of Australia and New Zealand.

Perez, FJ, Ormeno, JN, Reynaert, B, Rubio, S, (2008). Use of the dynamic model for the assessment of winter chilling in a temperature and a subtropical climatic zone of Chile. Chilean Journal of Agricultural Research. 68:198-206

Petri, JL, Leite, GB, 2004. Consequences of insufficient winter chilling on apple tree bud-break. In: Jindal, K.K., Sharma, R.C., Rehalia, A.S. (Eds.), Proceedings of the Viith International Symposium on Temperate Zone Fruits in the Tropics and Subtropics, pp. 53-60.

Putland, D. (2011) The influence of climate on pome fruit production. The effect on temperature on pome fruit phenology. In “The apple and pear industry’s response to climate change and climate variability; a desktop study”. Growcom pp. 1.

Richardson, EA, Seeley, SD, Walker, DR, (1974). A model for estimating the completion of rest for redhaven and elberta peach trees. HortScience. 9 (4):331-332

Ricketts, JH, Page, CM, 2007. A Web Based Version of OzClim for Exploring Climate Change Impacts and Risks in the Australian Region. *Univ Western Australia*, Nedlands.

Ruiz, D, Campoy, J, Egea, J, (2007). Chilling and heat requirements of apricot cultivars for flowering. Environmental and Experimental Botany. 61:254-263

Saure, MC, (1985). Dormancy release in deciduous fruit trees. Horticultural Reviews. 7:239-300

Seeley, S, (1990). Hormonal transduction of environmental stresses. HortScience. 25 (11):1369-1376

Seif, S. and Gruppe, W. (1985). Chilling requirements of sweet cherries (Prunus avium) and interspecific cherry hybrids (prunus x ssp.). Acta Hort. (ISHS) 169:289-294. http://www.actahort.org/books/169/169_40.htm

Settini, L. (2005). Hydrogen Cyanamide – Related Illnesses – Italy, 2002-2004. MMWR Weekly 54(16): 405-408.

Shaltout, AD, Unrath, CR, (1983). Rest completion prediction model for Starkrimson Delicious apples. Journal of the American Society for Horticultural Science. 108 (6):957-961

Sheard, A.G. (2008). Factors leading to poor fruit set and yield of sweet cherries in South Africa. MSc. Thesis Dept Hort. Sci. University of Stellenbosch.

Smith, I, Chandler, E, (2010). Refining rainfall projections for the Murray Darling Basin of south-east Australia—the effect of sampling model results based on performance. Climatic Change. 102:377-393

Suppiah, R, Hennessy, K, Whetton, PH, McInnes, K, Macadam, I, Bathols, J, Ricketts, J, Page, CM, (2007). Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. Australian Meteorological Magazine. 56 (3):131-152

Taiz, L. And Zeiger, E. (1991). Plant Physiology. Benjamin/Cummings. California, USA.

van Oldenborgh, GJ, Philip, SY, Collins, M, (2005). El Nino in a changing climate: a multi-model study. Ocean Science. 1:81-95

Viti, R, Andreini, L, Ruiz, D, Egea, J, Bartolini, S, Iacona, C, Campoy, JA, (2010). Effect of climatic conditions on the overcoming of dormancy in apricot flower buds in two Mediterranean areas: Murcia (Spain) and Tuscany (Italy). Scientia Horticulturae. 124 (2):217-224

Voller, CFP, (1986). Predicting rest-breaking: Principles and problems. Deciduous Fruit Grower. 36 (8):302-308

Wand, SJE, Steyn, WJ, Theron, KI, 2008. Vulnerability and impact of climate change on pear production in South Africa. pp. 263-271.

Weinberger, JH, (1950). Chilling requirements of peach varieties. Proceedings of the American Society for Horticultural Science. 56 (Dec):122-128

Wilkie, Middleton and Putland (2011). The effect of projected temperature changes on growth and development. In "The apple and pear industry's response to climate change and climate variability; a desktop study". Growcom, p 68.

Willis Orchards http://www.willisorchards.com/product/Stella+Cherry+Tree?category=247 (accessed 15/8/2011).

Zhang, J, Taylor, C, (2011). The Dynamic model provides the best description of the chill process on 'Sirora' pistachio trees in Australia. HortScience. 46 (3):420-425