

# Climate, Winter Chill, and Decision-making in Sweet Cherry Production

Penelope F. Measham<sup>1</sup>

Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, TAS, Australia

Audrey G. Quentin

CSIRO Ecosystems Science, Private Bag 12, TAS, Australia

Nicholas MacNair

Tasmanian Institute of Agriculture, University of Tasmania, Private Bag 98, TAS, Australia

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**Abstract.** Growers naturally adapt and manage production for unpredictable and variable seasonal climates; however, the projected changes in climate introduce a new concern with increased variability in the frequency and severity of extreme climatic events and sustained changes in temperature. This study addresses the complexity of providing clear winter chill information in a form that facilitates grower assimilation and application of that information, ultimately to assist decision-making around variety selection and management. This study established the chill requirement for two commonly grown sweet cherry (*Prunus avium* L.) varieties: ‘Kordia’ and ‘Sweetheart’, and explored the uniformity of bud burst in each. It was found that varieties required different chill hours and that ‘Sweetheart’ reached mean time to, and maximum total bud burst, faster than ‘Kordia’, but no subsequent impact on uniformity of maturity at harvest. There was no significant difference in uniformity of burst between the two varieties. The results obtained by matching chill accumulation to tree phenology showed that cherry-producing regions in Australia will experience sufficient chill to support the production of the variety ‘Sweetheart’ with an increase in mean winter temperature of 1 °C. Regions in Western Australia and Queensland will become marginal, or not suitable, for ‘Kordia’.

Deciduous fruit trees are naturally exposed to annual climatic variations over a growing season that drives phenological progression (Campoy et al., 2011; Charrier et al., 2011; Chung et al., 2011; Darbyshire et al., 2011). Climate subsequently impacts on production management decisions (Charrier et al., 2011; Gaal et al., 2011; Luedeling et al., 2011; Mounzer et al., 2008; Zavalloni et al., 2006) and ultimately on yield (Allderman et al., 2011; Andreini et al., 2012; Chung et al., 2011). As such, many studies have highlighted the need to accurately predict climates into the future, but climate prediction must also be linked to quantifiable plant growth and development patterns: tree phenology.

Predicted changes in climate include increased variability in the frequency and severity

of extreme climatic events and sustained changes in temperature (Darbyshire et al., 2011; Holz et al., 2010; Thomas et al., 2012). Extreme high-temperature events are expected to rise greatly in frequency and predictive models of global climate suggest that the global mean surface air temperature will rise by 2.0 to 4.5 °C by the middle of the 21st century. This level of temperature increase would change the level of winter chill achieved and potentially alter regional suitability for fruit production. Studies (Darbyshire et al., 2011; Luedeling et al., 2011) have shown that sweet cherry, a high-value crop, may be at risk into the future. Insufficient chill can result in poor bud development, sporadic and uneven budbreak, prolonged flowering and fruit development, and non-uniform ripening (Allderman et al., 2011; Brunt, 2012; Chang and Sung, 2000; Charrier et al., 2011; Darbyshire et al., 2011; Kapp, 2008; Kappel et al., 1996, 1997; Mohamed, 2008; Thomas et al., 2012). In quantifying chill, however, there is a lack of complete information of tree responses to climate (Luedeling, 2012) including the timing of initiation and breaking of endodormancy. Endodormancy first needs to be adequately defined (because breaking of endodormancy is dependent on sufficient chill accumulation) (Mohamed, 2008). Only then climate models can align with tree phenology to more accurately predict future risks.

It is critical that information is aligned for growers to make informed choices regarding variety selection into the future. Moreover, chill information must be available in a form that facilitates grower assimilation and application of knowledge. Affecting change at a grower level, in response to climate issues, requires more than providing information (Fleming and Vanclay, 2010). Extension of knowledge and information must be complete, consider the level and type of prior knowledge (tree development) and capacity to change (Juana et al., 2013), and lead to solutions (Fleming and Vanclay, 2010). Climate information and trends therefore are less likely to be relevant to growers than climate information combined with defined and visible cherry tree development stages.

Studies and data for sweet cherry are limited compared with other fruit such as apples (Koutinas et al., 2010). Many papers (Andreini et al., 2012; Brown, 2011; Gaal et al., 2011; Kapp, 2008) all expose the need to define the start of dormancy; dormancy was described as commencing at a critical temperature threshold, at harvest, at 50% or 100% leaf fall. Commencement of dormancy by season has also been described: spring (Tanino, 2004), summer (Kapp, 2008), fall (Midgley and Lotze, 2011), and winter (Mohamed, 2008). Dormancy induction is additionally described as a progression through a continuum of stages (Arora et al., 2003; Luedeling, 2012). The bud stage “green tip” or “side green” has been generally agreed to be a visible indication of breaking of endodormancy and the onset of growth (Andreini et al., 2009; Cortes and Gratacos, 2008; Zavalloni et al., 2006). This has been further classified as 50% of buds at green tip (Brunt, 2012; Cortes and Gratacos, 2008; Luedeling, 2012). These studies highlight the complex nature of aligning chill accumulation with dormancy, but there is agreement that release from endodormancy is temperature-dependent (Allderman et al., 2011; Luedeling, 2012).

Climate models traditionally use the period of May through August (southern hemisphere) to quantify chill accumulation. The number of models available, and therefore the various units in which chill can be quantified, also increases the complexity of providing information to decision-makers. Climate modeling, with regard to winter chill in Australia, has been comprehensively developed (Darbyshire et al., 2011). A decrease in the winter chill was achieved in recent years, and there is evidence that this trend will continue (Darbyshire et al., 2011).

This study seeks to showcase the complex nature of chill quantification. Chill requirement (matched to visible phenological cues for endodormancy) was obtained for two commonly grown varieties: ‘Sweetheart’ and ‘Kordia’. ‘Kordia’ is generally considered to have a high chill requirement, ≈1300 chill hours (Brown, 2011; Thomas et al., 2012). One study (Guak and Neilsen, 2013) was sourced regarding chill requirements for ‘Sweetheart’, which showed that a minimum 1000 chill hours were required for the shortest

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duration for bud burst under controlled conditions. Additionally, this study aims to highlight the difficulty in providing clear information depending on method of quantification (controlled and field conditions). Moreover, this study aims to confirm varietal difference in chill requirement and explore the uniformity of bud burst and subsequent impacts on fruit maturation.

### Material and Methods

**Site and plant material.** Trials were conducted in a commercial cherry orchard in Plenty, Southern Tasmania, Australia (lat. 42°71' S, long. 146°90' E) from leaf fall in June 2012 to harvest in Feb. 2013. The mean daily minimum and maximum temperature over the winter period (June to August) was 2.45 and 12.7 °C, respectively. This region experiences a mean annual rainfall of 574 mm. Climate data were obtained from an Australian Bureau of Meteorology station (less than 5 km from the trial site) and site-specific data (temperature, radiation, humidity, leaf wetness) were collected at 10-min intervals over the trial period from a Bio-Instruments PM11 phyto-monitor (Bio-Instruments S.R.L.).

Two varieties on Mazzard rootstock were selected, 'Kordia' and 'Sweetheart', as a result of anecdotal reports of differences in chill hour requirement (James, 2011). Plant samples for determining winter chill in the laboratory consisted of 2-year-old wood from each variety. Trial trees were mature trees (15 years) trained in a bush system and irrigated using microsprinklers. Trees were grown in a north-south row orientation with a row × tree spacing of 4.8 m × 2.5 m on wind-blown sands and dermasols. The crops on both varieties were well managed according to industry standards, but cropload was light (less than 10 fruit per trunk cross-sectional area) assessed as per Measham et al. (2012).

**Temperature treatments.** Both varieties were assessed for response to temperature in the laboratory by calculating bud burst (BB) from wood exposed to pre-determined temperature and time combinations. To achieve this, a collection of 150 samples of 2-year-old wood occurred at the onset of field dormancy. Wood samples were randomly selected from the trees within an orchard block. Wood was healthy, ≈30 cm long, and held a minimum of nine spurs. Hand pruners were used to collect samples and were cleaned with ethanol between each sample to maintain health and hygiene. Ten replicate samples were then placed in one of three temperature treatments (2, 4, and 10 °C) for one of five time periods (500, 750, 1000, 1250, and 1500 h) in a factorial design (two varieties × three temperatures × five time periods). During the laboratory-imposed temperature and time regimes, wood was stored in a steam-sterilized potting mix and kept moist. Once chill duration had been met, wood was placed in a 12-h daylength and high temperature (20 °C) to force BB. Incubators (Lindner + May LMRIL320-I-SD) were used to control temperature.

**Chill accumulation.** Chill for the temperature treatments and the natural conditions in the field, were calculated in chill hours (CH) and chill portions (CP) using the chill hours model (0 to 7 °C) and the dynamic model, respectively. These models were chosen to represent the two extremes of models available. Chill was calculated over the phenological period of dormancy onset (as indicated by 100% leaf fall) to dormancy release (as indicated by 50% BB (buds at side-green)).

**Phenological data.** BB in laboratory and field wood was recorded every second day from the onset of any buds at side-green. In the field, this occurred in late August; BB was determined by visually assessing each bud on each sample.

In the field, BB was assessed using visual assessments on 25 replicate 2-year-old wood samples (replicates were single trees) from each variety. Mean time to complete budburst (MTB) and coefficient of uniformity of bud burst (CUB) were calculated as follows:

$$MTB = \sum(t_x \times n_x) / \sum n$$

$$CUB = \sum n / \left[ (MTB - t_x)^2 \times n_x \right]$$

where  $t_x$  is the time in days, starting from Day 0, the day of first visible side-green,  $n_x$  is the number of buds completing bud burst on days  $x$ , and  $n$  is the total number of buds bursting.

Uniformity at harvest was also assessed by measuring fruit size and weight at commercial harvest from an aggregated bulk sample of 625 fruit from each variety (from a random sampling of 25 fruit per trial tree) and grouped according to commercial size classes. Size (diameter) was measured using vernier calipers, and weight recorded using an AND digital balance (Model GX-4000).

**Regional analysis.** Using the chill portion data established from this trial, the resultant chill requirements for both varieties were used to assess the future viability of five growing regions in Australia.

**Statistical analysis.** The effect of time, temperature, and variety on BB under controlled limits in the laboratory and the effect of variety on MTB and CUB achieved in the field were analyzed using analysis of variance. Levene's test of equality of error variance in fruit size at harvest (as an indication of

uniformity in maturity) was used. All statistical analyses were performed in SPSS (SPSS Inc., Chicago, IL). Differences between means were considered significant at  $P < 0.05$ .

### Results

**Temperature exposure.** There was a significant interaction of variety and time on the percentage of BB recorded in the laboratory, but a main effect of temperature was found (Table 1). A general trend of decreased BB with increasing temperature was observed, particularly evident in 'Sweetheart' (Table 2) with maximum burst ( $81.4\% \pm 11.9\%$ ) achieved after prolonged exposure at the lowest temperature. The pattern of BB differed between the two varieties with higher BB in general in 'Sweetheart' than 'Kordia'; 'Sweetheart' achieved more than 50% BB at 2 °C for all time treatments above 500 h and at 4 °C above 750 h (Table 2), whereas 'Kordia' did not achieve a BB over 50% at any time or temperature combination (Table 2). 'Kordia' also exhibited an erratic response to exposure times with higher burst rates recorded at 750-h and 1250-h exposure times (Table 2). Calculating chill from temperature exposure treatments showed that 'Sweetheart' achieved greater than 50% BB at 750 CH or more, whereas 'Kordia' did not achieve 50% at all with a maximum BB of only 30% at 1250 CH (Fig. 1). Chill portions remained low because temperatures did not fluctuate. 'Sweetheart' achieved over 50% BB at ≈20 CP or more (Fig. 2).

**Phenological impacts.** Greater than 50% BB was achieved in the field. Chill was calculated as 1066 CH and 54 CP for 'Sweetheart'

Table 1. *F*-statistic and *P* values of a three-ways analysis of variance on percentage of bud burst of 2-year-old wood of sweet cherry trees sampled in an orchard in southern Tasmania.

	df	<i>F</i> -statistic	<i>P</i> value
Variety	1	102.16	<0.001
Temperature	2	17.06	<0.001
Time	4	13.65	<0.001
Variety × temperature	2	0.24	0.79
Variety × time	4	3.41	<b>0.01</b>
Temperature × time	8	1.03	0.41
Variety × temperature × time	8	1.78	0.08

df = degrees of freedom.

Table 2. Maximum bud burst for 2-year-old wood from 'Sweetheart' and 'Kordia' trees exposed to three temperature regimes for five different time periods three temperature treatments.

Variety	Time (h)	Temperature (°C)		
		2	4	10
Sweetheart	500	33.7 ± 11.0	31.5 ± 1.0	1.0 ± 0.1
	750	64.2 ± 14.6	46.5 ± 15.8	67.5 ± 7.0
	1000	67.2 ± 9.0	59.5 ± 16.5	12.5 ± 10.5
	1250	69.8 ± 12.7	67.8 ± 13.1	45.2 ± 14.7
	1500	81.4 ± 11.9	56.6 ± 14.7	43.4 ± 16.3
Kordia	500	8.2 ± 1.8	1.5 ± 0.7	0.2 ± 0.1
	750	43.5 ± 10.3	10.8 ± 5.7	5.0 ± 1.5
	1000	8.7 ± 7.2	0.8 ± 0.8	0.0 ± 0.0
	1250	41.6 ± 10.6	18.3 ± 11.3	0.0 ± 0.0
	1500	1.4 ± 1.2	1.7 ± 1.2	0.0 ± 0.0

and 1307 CH and 67 CP for 'Kordia'. Varieties differed significantly in MTB in the field ( $P < 0.001$ ). 'Sweetheart' showed a significantly faster response to climate with a lower MTB than 'Kordia' ( $5.3 \pm 0.3$  d compared with  $10.2 \pm 2.9$  d, respectively). There was also a significant difference between varieties in maximum BB ( $P < 0.05$ ). 'Sweetheart' required  $10.4 \pm 0.4$  d to reach 100% BB, whereas 'Kordia' required  $16.0 \pm 1.3$  d (Fig. 3). Although 'Kordia' exhibited a prolonged flowering, there was no significant difference in uniformity of bud burst (CUB) between the two varieties ( $P > 0.05$ ). Some 'Kordia' buds did not develop; these were examined microscopically and no anatomical abnormalities were found (data not presented).

There was a significant difference in fruit size between varieties ( $P < 0.001$ ). Mean fruit size, defined as diameter, was  $29.8 \pm 1.4$  mm and  $26.9 \pm 1.5$  mm for 'Sweetheart' and 'Kordia', respectively. The majority of 'Sweetheart' fruit was grouped into the 28- to 30- and 30- to 32-mm size class (41% and 43%, respectively), whereas the majority (52%) of 'Kordia' was grouped into the 26- to 28-mm size class (Fig. 4). Fruit from both varieties however were normally distributed; and Levene's test of equality showed that for size, there was no significant difference in variance ( $P = 0.63$ ). In both varieties, a significant relationship between diameter and weight existed; for 'Sweetheart',  $\text{weight} = 0.932 * \text{diameter} - 15.415$  ( $R^2 = 0.87$ ) and for 'Kordia',  $\text{weight} = 0.735 * \text{diameter} - 9.178$  ( $R^2 = 0.68$ ).

**Regional analysis.** 'Sweetheart' showed sufficient chill requirement at 20 CP in the laboratory but 54 CP in the field. 'Kordia' did not achieve chill in the laboratory, but in the field, 67 CP was sufficient. These values were compared with estimates of decreased winter chill in five cherry production regions in Australia (Darbyshire et al., 2011). The values calculated in this study followed phenological cues and were not calculated from May through August. As such a direct comparison was not possible. However, with the reduced accumulation times and chill values calculated in this study, it was still observed that some regions (Western Australia and Queensland) had marginal, or insufficient, chill for 'Kordia' under future projections (Table 3). Most regions showed sufficient chill to support the production of 'Sweetheart' with risk to production in Western Australia only under a  $2^\circ\text{C}$  predicted change in winter temperature (Table 3) when using the field-derived chill.

## Discussion

Winter chill exposure to fruit trees is an important prerequisite for initiating successful bud burst (Albuquerque et al., 2008; Campoy et al., 2011; Charrier et al., 2011). Chill was quantified in this study, albeit in 1 year, but the results clearly demonstrated that the success of initial and total BB increased with time at low temperatures (Lang et al., 1987) and under natural field conditions (Luedeling, 2012). This is consistent with other

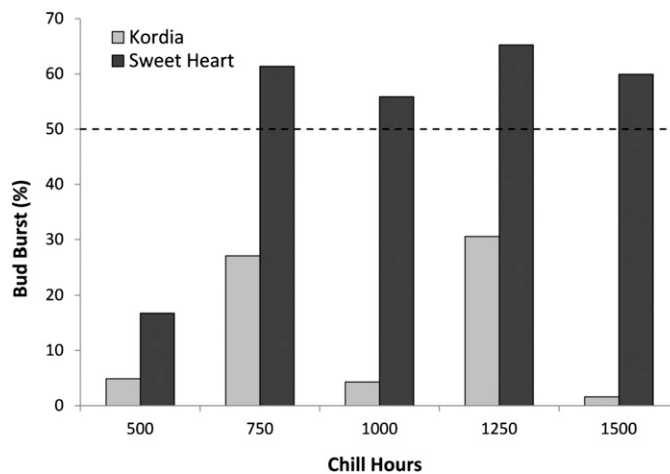


Fig. 1. Percentage of bud burst (BB) in 'Kordia' and 'Sweetheart' exposed to chill calculated as chill hours (CH) using the chill hours model. The dotted line represents 50% BB, indicating those treatments in which chill requirement have been met.

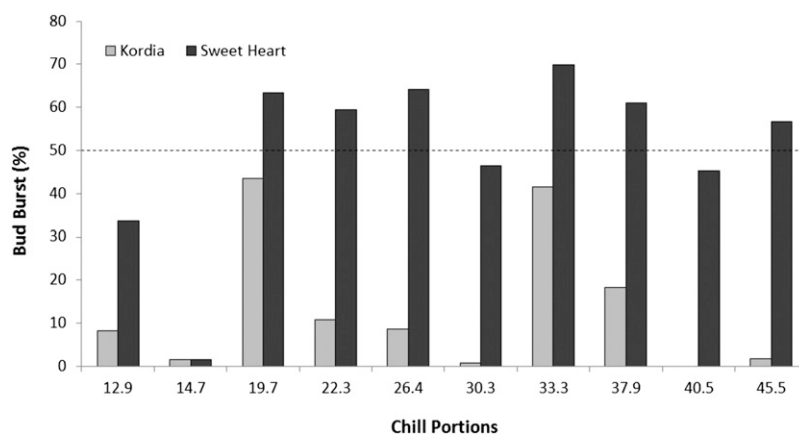


Fig. 2. Percentage of bud burst (BB) in 'Kordia' and 'Sweetheart' exposed to chill calculated as chill portions (CP) using the dynamic model. The dotted line represents 50% BB, indicating those treatments in which chill requirement have been met.

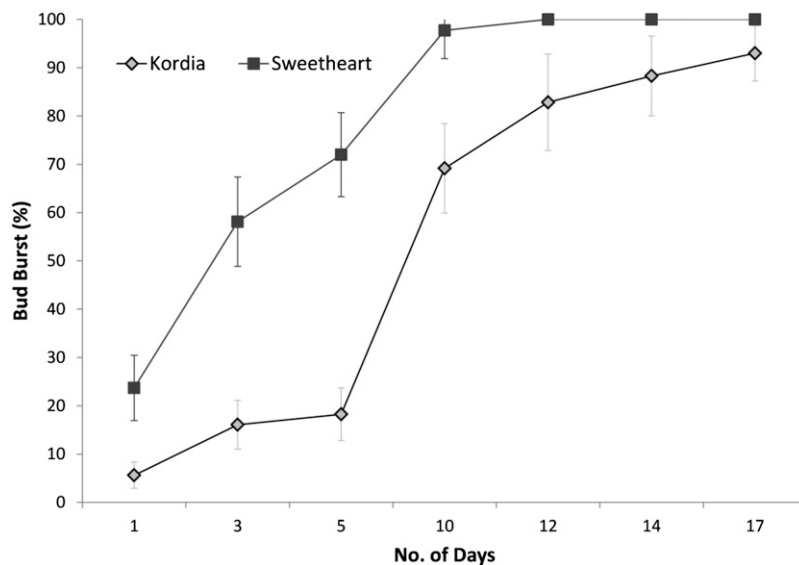


Fig. 3. Percentage of bud burst (%) from initial budbreak recorded in the field over 20 d. Error bars represent the SEM.

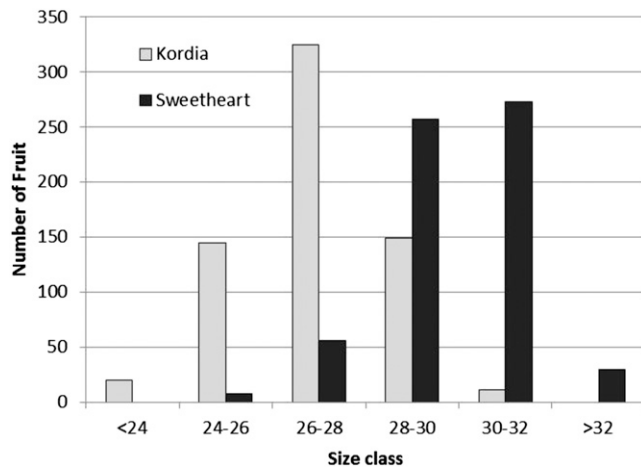


Fig. 4. Number of 'Kordia' and 'Sweetheart' fruit in each size class at harvest maturity.

Table 3. Winter chill values (CP) experienced in cherry-producing regions of Australia (adapted from Darbyshire et al., 2011) and forecast values with a mean increase in winter temperatures of 1 and 2 °C.

State	Region	Current	1 °C	2 °C
Tasmania	Huon Valley	88	87	86
Victoria	Yarra Valley	86	84	83
South Australia	Adelaide Hills	86	81	76
New South Wales	Orange	85	84	83
Queensland	Stanthorpe	72	69 <sup>z</sup>	64 <sup>z</sup>
Western Australia	Manjimup	67 <sup>z</sup>	57 <sup>z</sup>	47 <sup>y</sup>

<sup>y</sup>Marginal or insufficient chill for variety 'Kordia'.

<sup>z</sup>Marginal or insufficient chill for variety 'Sweetheart' from field assessment.

studies in various fruit and nut tree crops including apples (Guak and Neilsen, 2013), blackcurrants (Westmore, 2006), peaches (Richardson et al., 1974), walnuts (Charrier et al., 2011), and sweet cherry (Cortes and Gratacos, 2008). Numerous studies have shown that increased time of exposure to chilling results in increased release of dormancy, BB, and flower induction (Garcia-Luis et al., 1992; Lang et al., 1987; Moss, 1976), but few studies have reported the relationship between decreasing temperature and BB. Guak and Neilsen (2013) determined optimum temperature for chill accumulation to be between -2 and 7 °C and this study also showed that low temperatures are critical to successful BB in cherry. Temperatures as low as 2 °C are considered in some models as negating chill accumulation (Darbyshire et al., 2011; Luedeling et al., 2011) but were highlighted as contributing to meeting chill in this study.

In this study, 'Kordia' did not achieve adequate chilling requirement in the laboratory trials, although the trial ran to the upper limit of requirement set by Brunt (2012). Brown (2011) suggests that chill requirement can be higher than the set upper limit in some varieties, whereas Cortes and Gratacos (2008) discuss the difference between the field and laboratory in terms of fluctuating field temperatures and subsequent impact on quantifying chill. Luedeling (2012) moreover suggests that the constant temperatures used in controlled experiments created chill quantification not applicable to field conditions. This study supports this claim with the large

difference seen between laboratory and field settings. An additional factor may be that the forcing temperature exposure for 'Kordia' was not sufficient in the laboratory trials; however, in the field, 'Kordia' achieved 50% BB 10 d after the first sighting of budbreak and confirms previous quantifications for this variety (Brown, 2011). The growers' estimate that a moderate to high chilling requirement of  $\approx 750$  h is needed (James, 2011) for 'Sweetheart' was shown to be an accurate estimation in this study using laboratory-generated chill. Field accumulation was higher at just over 1000 chill hours; this value is in agreement with Guak and Neilsen (2013). This was found using the reduced accumulation period set by tree phenology and could have been conceivably higher still using traditional chill accumulation periods.

Results clearly demonstrate that chill requirement is variety-specific as was seen in a Chilean study (Cortes and Gratacos, 2008) but also confounded by quantification method. Hence, although targeted quantification is warranted for all varieties, it is also important to undertake such quantification with a fixed, consistent, and easily recognized start point (Andreini et al., 2012; Brown, 2011; Gaal et al., 2011) such as 100% leaf fall, which may not occur on the same date for each variety. This study did not address seasonal variation in chill responses. Further exploration of visible cues for dormancy initiation would enable more comprehensive studies to advance the process of aligning chill accumulation to tree phenology. The difficulties in controlled environment

chill quantification (Luedeling, 2012) emphasize the need to accurately define chill accumulation periods by phenology.

Quantification using different models, with different units, and with undefined accumulation periods can also provide unclear information and impact on subsequent decision-making on variety suitability. Both varieties used in this study, 'Kordia' and 'Sweetheart', have been regarded by growers as having significantly different chilling requirements (James, 2011). Matching varietal chilling requirements to orchard meso- and microclimatic conditions is important for uniformity of budburst and overall tree productivity (Charrier et al., 2011; Luedeling et al., 2011). Interestingly, the comparatively prolonged BB seen in this study, for 'Kordia', did not result in a prolonged period of fruit ripening. Harvest maturity was uniform in both varieties with the difference in fruit size an observed and supported varietal characteristic (De Franceschi et al., 2013; Measham et al., 2009). The crop should not have experienced any loss of size as a result of cropload or yield because the threshold for size reduction was not reached (Bound et al., 2013; Measham et al., 2009, 2012).

This study confirms varietal differences (Albuquerque et al., 2008). Varietal difference may also explain grower confusion around winter chill requirement (Albuquerque et al., 2008; Charrier et al., 2011; Gaal et al., 2011; Mounzer et al., 2008). Traditionally (for sweet cherry in Australia), growers consider a general chilling requirement that approximates 800 h of exposure to temperatures between 2 and 12 °C (James, 2011). Relying on chill requirements, as determined by different models, to optimize management of crops still carries some risk (Darbyshire et al., 2011; Luedeling, 2012; Luedeling and Brown, 2011) because descriptions of chill can vary in generic terms such as "high" or "moderate." Awareness and understanding of exact chill requirement, the alignment of categorical descriptions, and clear presentation of value origins (chill hours or portions) are required. This would help bridge the gap between scientific progress and practice and guide the development of options for industry. Quantifying chill requirements for a greater number of Australian varieties would assist decisions regarding potential climate risk and the options available for adaptation or change. Information could then be communicated (with industry in mind) based on knowledge that can be understood and assimilated and would then be more likely to be implemented (Fleming and Vanclay, 2010; Juana et al., 2013; Koenig et al., 2012; McEvilly and Fischer, 2010).

This study reinforces that some current cherry-producing regions in Australia may become marginal in terms of achieving sufficient chill exposure for specific varieties. This can be concluded from the chill values calculated based on phenology, values that would be lower than expected if calculated using traditional chill model accumulation periods. Higher values potentially obtained

using the May through August period could have additional areas deemed as marginal. Providing accurate chill values and risk to growers is essential. Strategies that ensure cherry trees meet their chill requirements are needed for marginal areas (Brunt, 2012; Kapp, 2008; Ruiz et al., 2007) in the short term. It has been suggested that future warming in some regions of central Hungary may have positive impacts on cherry production (Gaal et al., 2011), whereas other regions have started investigating induced breaking of endodormancy in apples resulting from insufficient chill (El-Yazal and Rady, 2012). Chemical dormancy breakers, however, still require significant inputs and increases costs (El-Yazal and Rady, 2012; Erez et al., 1988). Assessing the effects of low-input orchard practices on cherry trees may elucidate some impacts on success of budburst and overall flowering uniformity after chill requirement is met (Campoy et al., 2011; Clairmaczulajtys et al., 1994; Usenik et al., 2008).

## Conclusions

This study demonstrated the difference in chill requirement between the sweet cherry varieties 'Kordia' and 'Sweetheart'. The distinct difference in chill requirement was evident in BB response, but not at harvest. Chill into the future was deemed insufficient in some regions using the chill values produced in this study. That these values would be lower than expected with traditional chill accumulation periods highlighted the need for clarification of chill accumulation commencement. The complexity of quantifying chill in line with tree phenology, and the difficulty for growers in implementing chill information, is demonstrated in this study.

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