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Nut crop yield records show that budbreak-based chilling requirements may not reflect yield decline chill thresholds

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Abstract Warming winters due to climate change may critically affect temperate tree species. Insufficiently cold winters are thought to result in fewer viable flower buds and the subsequent development of fewer fruits or nuts, decreasing the yield of an orchard or fecundity of a species. The best existing approximation for a threshold of sufficient cold accumulation, the “chilling requirement” of a species or variety, has been quantified by manipulating or modeling the conditions that result in dormant bud breaking. However, the physiological processes that affect budbreak are not the same as those that determine yield. This study sought to test whether budbreak-based chilling thresholds can reasonably approximate the thresholds that affect yield, particularly regarding the potential impacts of climate change on temperate tree crop yields. County-wide yield records for almond (*Prunus dulcis*), pistachio (*Pistacia vera*), and walnut (*Juglans regia*) in the Central Valley of California were compared with 50 years of weather records. Bayesian nonparametric function estimation was used to model yield potentials at varying amounts of chill accumulation. In almonds, average yields occurred when chill accumulation was close to the budbreak-based chilling requirement. However, in the other two crops, pistachios and

walnuts, the best previous estimate of the budbreak-based chilling requirements was 19–32 % higher than the chilling accumulations associated with average or above average yields. This research indicates that physiological processes beyond requirements for budbreak should be considered when estimating chill accumulation thresholds of yield decline and potential impacts of climate change.

Keywords Chilling requirement · Climate change · Yield · Bloom · Budbreak · Bayesian

Introduction

Chilling requirements have been central to the discussion of the impacts of climate change on temperate tree crops and forest ecosystems (Campoy et al. 2011). The reproductive and vegetative buds of temperate trees become dormant in autumn and require exposure to winter chill, of an amount specific to species and variety, to exit this state (Westwood 1993). Trees that are not exposed to enough winter cold, i.e., do not meet their “chilling requirement,” have been reported to experience delayed, protracted, and weak leafing and flowering, formation of bare shoots, shortage of flower bud-bearing spurs, poor fruit development, and irregular ripening (Saure 1985). Lack of sufficient chill can cause structurally underdeveloped flower buds, undersized pistils, abortion of flower primordia, and abscission of flower buds in various stages of development (Black 1952).

There are essentially two approaches taken to estimate chilling requirements—forcing and modeling. Both approaches use the timing of when a specific percentage of reproductive or leaf buds break, bloom, shed pollen, or leaf out (henceforth collectively referred to as “budbreak”). The forcing approach manipulates amounts of chill accumulation, either in controlled settings or by collecting shoots from the

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field at accumulation intervals, then “forcing” buds to break under spring-like temperatures in a greenhouse or growth chamber. The lowest amount of chill necessary to cause a specific percentage of buds to break after a specific amount of exposure to warm temperatures is considered the chilling requirement (Dennis 2003). Variations of the forcing approach use single-node cuttings (Champagnat 1989), shoot cuttings (Barba and Melo-Abreu 2002), rooted shoots, or small trees (Couvillon et al. 1975) as the experimental units.

The modeling approach pairs temperature records with records of the timing of budbreak. Chilling requirements and subsequent requirements of spring heat that results in budbreak are then statistically fit to many years of data. The most common approach is some variation on Ashcroft et al. (1977), selecting the chilling accumulation that results in the least variation of heat accumulations that precede budbreak (Ramirez et al. 2010; Rattigan and Hill 1986) or the chilling and heating accumulation that minimizes the error in the predicted day of budbreak (Chuine et al. 1998; Legave et al. 2008).

These budbreak-based estimates of chilling requirements are the primary means of quantification of species—or variety-specific chill accumulation needs—and have served as a starting point for identifying species or varieties that may be vulnerable to the warmer winters associated with climate change (Campoy et al. 2011; Hatfield et al. 2008; Jackson et al. 2009). As the only widely quantified measurement of the relationship between orderly emergence from dormancy and winter temperatures, it is important to determine if budbreak-based estimates of chilling requirements are equivalent to the chilling accumulation thresholds necessary for sustainable yields and can thus continue to be used as a reasonable proxy for estimating the impacts of climate change to temperate trees. If these thresholds are not equivalent, reliance on budbreak-based requirements may lead to mistaken conclusions regarding climate change vulnerability and priorities for climate change adaptation.

There are reasons to suspect that budbreak-based chilling requirements may be substantially higher than the amount of chill necessary for sustainable yields. Researchers often use a high percentage of budbreak as the threshold that signals the end of bud endodormancy, generally 50 % of buds on a shoot (Dennis 2003). Even given sufficient chill, many flowers of commercial almond, pistachio, and walnut trees do not develop into harvested nuts, due to lack of flower fertilization or fruitlet abortion from resource competition, a phenomenon popularly referred to as “June drop” (Iwanami et al. 2012). In “Nonpareil” and “Mission” almond cultivars, only 25–40 % of flowers develop into harvested nuts given adequate chill and high initial fruit set (Kester and Griggs 1959b, a). In “Kerman” pistachio, only 10 % of individual pistils develop into harvested nuts given favorable chill and bloom conditions (Crane 1986). After pistillate flower abortion, which results

from an overabundance of pollen, and June drop, only about 65 % of “Vina” pistillate flowers developed into nuts (Polito et al. 2002). The low-to-moderate percentage of flowers that develop into nuts given sufficient chill indicates that, to a certain extent, a low-chill winter could reduce the number of viable flowers without impacting yield, provided that a larger percentage of remaining flowers result in harvested nuts. Indeed, when researchers removed almond flowers at bloom, mimicking the failure of a percentage of buds due to inadequate chill, 25 % of the buds could be removed in Nonpareil and up to 75 % in Mission without significantly effecting final set (Kester and Griggs 1959a).

The objectives of this study were to model the relationship between yield and chill accumulation during the preceding winter in California’s Central Valley in order to identify yield-based chill requirements of almonds, pistachios, and walnuts and compare those with chilling requirements based on budbreak. County yield records beginning in 1960 were modeled with respect to winter chill accumulation for almonds, pistachios, and walnuts. Nut tree crops are ideal for these analyses because trees are managed to maximize the number of nuts on a tree, unlike fruit crops which are thinned to increase the size of the remaining fruit (Kester and Griggs 1959a). Yield numbers thus represent the maximum potential productivity of the trees under a given year’s conditions. Annual county yields were examined for the counties in California that grew at least 1 % of the state’s acreage of the given crop during the period studied. Yields were then compared with chill accumulation from the preceding winter. In order to account for yield increases due to improvements in technology, *relative yield* was calculated by normalizing yield relative to the 7-year average for each county. This work does not attempt to model the yield in each county each year based solely on chill accumulation, but rather to model the greatest yield that could be expected at each amount of chill if all other conditions affecting yield were optimal. To achieve this, the *potential relative yield*, the highest relative yield at each amount of chill accumulation within the recorded range, was determined for each crop.

It was anticipated that this analysis would show no relationship between chill and yield above a specific threshold, when chill was sufficient and thus not yield-limiting. On the other hand, it was expected that, below a specific chill accumulation, potential relative yield would decline to below average and that this change point would reflect the yield-based chilling requirement. Following the approach of Pope et al. (2013), Bayesian nonparametric function estimation was used to estimate this yield-based chilling requirement for each crop. Because the chilling requirement in almond is quite low (Ramirez et al. 2010), it was doubted that there would be years in the record with chill low enough to impact yield. Thus, the relationship between almond yield and chill was analyzed as a proof of concept, expecting to find no relationship between

chill and yield. Given the moderately high chilling requirement of pistachio (Zhang and Taylor 2011; Ferguson et al. 2008), and the fact that it is grown mainly in the warmer southern part of the Central Valley, we expected to find a chill accumulation threshold below which yield declined. Because of the high chilling requirement of walnuts (Aslamarz et al. 2009; Luedeling et al. 2009a), we expected to find a few years in which chill had been low enough to decrease yield. Because, even in a normal chill year, many flower buds do not fully develop into fruit or nuts; it was anticipated that the yield-based chilling requirements estimated for pistachio and walnut would be lower than the chilling requirements estimated from budbreak analyses.

Materials and methods

Data origins

County yield

The cultivars grown in California nut production have been relatively consistent for the last several decades, allowing the effects of chill on yield to be assessed for the same cultivars with county aggregated crop records. Nonpareil almond accounts for 37 % of California almond acreage 134 years after it was first planted (California Agricultural Statistics Service 2013; Asai et al. 1996). Because Nonpareil is self-sterile, it requires pollinizer cultivars (planted on a 1:1 or 1:2 Nonpareil to pollinizer ratio) with similar bloom timing and thus similar chilling requirements (Egea et al. 2003). Kerman pistachio makes up the overwhelming majority of California acreage, 84 years after being introduced to California (Kallsen et al. 2009). Of the six most popular walnut cultivars, one (“Hartley”) has been grown commercially since 1915, two (“Serr” and Vina) since 1968, and two others (“Chandler” and “Howard”) since 1979 (McGranahan et al. 1998). All bloom within 17 days of each other (Hendricks et al. 1998).

County yield data were gathered from the US Department of Agriculture (www.nass.usda.gov) for data after 1980 and from County Agricultural Commissioners’ crop reports for years prior to 1980, available through each county’s Agricultural Commissioner Web site. Data were used from counties with at least 1 % of the state’s planted area for each crop for the period examined (Online Resource 1). The period of examination was determined by the quality of weather data, the consistency of reporting protocols, and the land area cultivated. Prior to 1970s, counties reported almond weight in-shell, shelled (kernel only), or did not specify. Only shelled almond records were used. In the few “not specified” cases, if there was a clear trend of high yields for decades which plummeted then slowly rose again, it was assumed that the high yield measurements were in-shell, the plummet marked

the shift to shelled reporting, and the base of that curve was the first year of the record used. Pistachio and walnut yields were consistently reported as in-shell. All yields were given as tons per acre. The data were examined for transcription or calculation error outliers and culled if three or more standard deviations from the mean of 3 years before and after the year in question. Colusa County walnut data was also culled before 1983, because 9 years between 1970 and 1982 inexplicably achieved yields not again achieved until 1994.

Data were normalized to account for management and technological advances that led to increased yields. Yield was normalized based on a running average, not a simple linear regression, because yield increases were nonlinear. Environmental conditions, management practices, and the resulting yield vary enough across the approximately 700-km length of the study area in which yields were normalized within each county instead of against the state average. Yield in a given year and county was compared with the 7-year running mean. The mean was subtracted from that year’s yield, and the result was divided by the mean and multiplied by 100 to calculate relative yield, Y_R , the percent yield changes that year from the running average. Negative values represented below average yields, positive values above average. Potential relative yield, Y_{PR} , was the highest value of Y_R at each amount of chill accumulation. This was taken to approximate the greatest yield that could be expected at each amount of chill if all other conditions affecting yield were optimal.

Local winter weather

Weather data were retrieved from the National Climate Data Center (NCDC) (www.ncdc.noaa.gov) from 1959 to the mid-1980s and from the California Irrigation and Management Information System (CIMIS) (www.cimis.water.ca.gov) for the mid-1980s to present. One NCDC and one CIMIS station were chosen per county based on proximity to nut production areas, completeness of the dataset, and distance from areas which became heavily urbanized over the course of the record. NCDC daily minimum and maximum temperatures were used until the CIMIS station recording hourly data was established (Online Resource 2).

All temperature data were screened for errors. Values were not used if flagged by the source as likely erroneous or if temperatures from November through February were below $-10\text{ }^{\circ}\text{C}$ or above $30\text{ }^{\circ}\text{C}$. Missing (including erroneous) values were replaced differently depending on the duration of the gap. If 1–3 consecutive days or 1–2 h were missing, the data were interpolated by averaging the previous and next nonflagged records. If 3–72 consecutive hours were missing, the same hour from the previous and next day were averaged. If 4–6 consecutive days or 73–144 h were missing, the record for the same period was copied from the nearest station. All

backup stations were within 30 miles of the primary stations. If 5 % of a winter's consecutive records were missing, or more than 10 % of the total winter record had to be interpolated or copied from the backup station, that winter and its associated harvest year were omitted from the analysis (Online Resource 2).

Chill accumulation

Chill accumulation was calculated using the Dynamic model (Fishman et al. 1987), which has modeled the timing of spring phenological events as well as, or better than, other horticultural models in Mediterranean climates (Luedeling et al. 2009a; Albuquerque et al. 2008). Accumulation of chill according to the Dynamic model is a two-step process. First, a chill intermediate is accumulated based on a bell-shaped relationship of hourly temperature to chill value. This accumulation can be reduced by subsequent high temperatures. Second, the chill intermediate reaches an accumulation threshold and is counted as one chill portion (CP), which cannot be negated by later warm temperatures. Accumulation of a new chill intermediate starts again from zero (Erez and Fishman 1998). The Dynamic model requires hourly temperature data. Daily minimum and maximum temperatures were used to estimate hourly temperatures following Cesaraccio et al. (2001), which was developed for conversion of NCDC data in California.

Almond chill accumulation was calculated for November and December because the best estimation of the chilling requirement for almond (Ramirez et al. 2010) is generally fulfilled by mid-December in California. Based on the best estimates of the chilling requirement of California's pistachio cultivars (Ferguson et al. 2008), pistachio's chill needs are met in mid-to-late February. In walnut, estimates of both the chilling requirement and the average date when the chilling requirement is met indicate that the chilling requirement is usually met by mid-February (Luedeling and Gassner 2012; Luedeling et al. 2009a). Thus, chill accumulation from November 1st through the last day of February was used for pistachios and walnuts.

Bayesian nonparametric function estimation

Potential relative yield was modeled using Bayesian nonparametric function estimation. Data analysis was based on Pope et al. (2013), comparing the probability of six models: a constant model, a linear model, and change point models with up to four change points (Fig. 1). A constant model (no relationship between chill and yield) would indicate a dataset that did not contain years with low enough chill to affect yield (Fig. 1a). A linear model would fit well if there was an incremental chill response, suggesting that the threshold framework of a chill requirement was inaccurate (Fig. 1b). A one change point model would be most probable if the threshold framework were accurate, with a flat line during stable, adequate chill years, and a drop in yield in response to low chill (Fig. 1c). A high probability of a model with more than one change point (not shown) would indicate influence of factors correlated with high chill on yield.

The six base models used for this analysis consisted of allowing for polygons with an arbitrary number of sections. The data model at year t_i for $t_k \leq t_i \leq t_{k+1}$ was

$$d_i - f_k * \frac{(t_{k+1} - t_i)}{(t_{k+1} - t_k)} + f_{k+1} * \left(\frac{t_i - t_k}{t_{k+1} - t_k} \right) = \varepsilon_i \quad (1)$$

where f_k and f_{k+1} were the functional values at change points t_k and t_{k+1} , d_i the observation in year t_i and ε_i the uncertainty of d_i .

Application of Bayesian methods to this model was very different from conventional least square fitting. While the least square result for a one change point model would have been a triangle with a peak at the change point t_{ML} and in the generalized case a polygon with change points t_{ML} , the Bayesian treatment considered not only the most likely change points but also neighboring points, hence less optimal configurations. The probability of a particular configuration was calculated within the Bayesian theory. The analysis yielded the parameters of each model that resulted in the lowest residual sum of squares (RSS), the RSS value itself and the probability

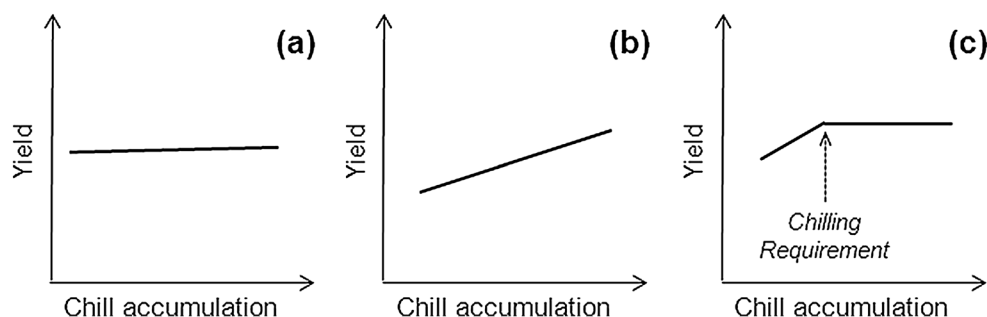


Fig. 1 Theoretical framework of detecting changing spring phenology based on spring heat and winter chill accumulation using Bayesian change point analysis. **a** Constant model—no years in data below chill requirement; **b** linear model—yield response to chill is incremental.

Threshold framework of chill requirement is invalid, **c** one change point model—yield is stable above a threshold, the chill requirement, then drops incrementally

of each parameterized model relative to the other five models. As in least square fitting, residuals diminished with increased parameters (increased change points). In calculating model probability, Bayesian theory penalized increased model complexity not accompanied by a sufficiently substantial decrease in the residuals.

Rather than drawing conclusions from that model with the highest probability, disregarding the nonnegligible probability of other models, the Bayesian approach drew conclusions from a model-averaged function, averaging the function and derivative of the respective models with their probabilities as weights. This model-averaged function was the final product of the analysis.

Results

Almond

After screening the almond data from 12 counties over 46 years for errors in yield and temperature records, 312 of the initial 374 data points remained for analysis. Chill accumulation ranged from 22 to 47 CPs. Relative yield ranged from 63 % below average to 49 % above average (Online Resource 1). Potential relative yield ranged from 40 % below average to 49 % above average (Online Resource 3). The six model options fit the almond yield data with varying amounts of probability, with the one change point model fitting the data the best, followed closely in probability by the two change point model (Table 1). The number of pivots of each model was n_p . The change point models had $n_p - 2$ change points, with $n_p \geq 3$. Note that the residuals diminished with rising n_p , while the model probability passed through a maximum for $n_p = 3$ (i.e., the one change point model). This is a demonstration of how Bayesian theory follows Ockham's razor (Garrett 1991).

The Bayesian analysis allowed for drawing conclusions from a model-averaged function. The probability of the one change point model was the highest for almond potential relative yield, but the probabilities of a two and three change point models were high enough to also affect the shape of the model-averaged function (Fig. 2). This can be seen in the

changing slope below 25 CPs and above 44 CPs. The model-averaged function indicated a potential yield of 5 % above average at 22 CPs, an increase to 38 % above average at 35 CPs, and then a decrease again to 14 % below average at 47 CPs.

Pistachio

After screening the pistachio data from six counties over 34 years for errors in yield and temperature records, 137 of the initial 161 data points remained for analysis. Chill accumulation ranged from 55 to 85 CPs. Relative yield ranged from 67 % below average to 74 % above average (Online Resource 2). Potential relative yield ranged from 42 % below average to 74 % above average (Online Resource 4). The six model options fit the pistachio potential relative yield data differently. The one change point model was most probable, followed by the two change point model (Table 1). Since the probabilities of the one and two change point models were both high, the model-averaged function was a composite of the two models, a curve with a sharp peak like almond and a slight change in slope at 81 CP (Fig. 3). The model-averaged function had a potential relative yield of 26 % below average at 55 CPs, increasing to 56 % above average at 67 CPs and decreasing again to 2 % below average at 85 CPs.

Walnut

After screening the walnut data from 11 counties over 51 years for errors in yield and temperature records, 429 of the initial 461 data points remained for analysis. Chill accumulation ranged from 52 to 87 CPs. Relative yield ranged from 54 % below average to 46 % above average (Online Resource 3). Potential relative yields ranged from 18 % below average to 46 % above average (Online Resource 5). The six model options fit the walnut potential relative yield data differently, with the one change point model having by far the highest probability (Table 1). The one change point model dominated the model-averaged function, though the nonnegligible probability of the two change point model was also manifested in the change in slope at approximately 68 CPs (Fig. 4). The model-averaged function had a potential yield of 2 % below

Table 1 Model residuals (RSS) and probability for potential relative yield

Number of pivots (n_p)	Almond		Pistachio		Walnut	
	RSS	Probability	RSS	Probability	RSS	Probability
1	12,608	0.000	32,859	0.000	7,859	0.000
2	11,132	0.000	32,859	0.000	6,844	0.000
3	4,501	0.325	20,949	0.528	4,760	0.632
4	3,796	0.293	19,734	0.309	4,361	0.265
5	3,203	0.201	19,019	0.120	4,060	0.080
6	2,501	0.181	18,508	0.042	3,812	0.023

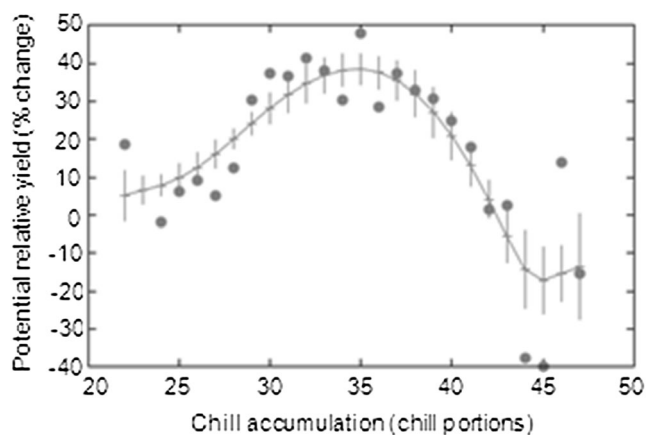


Fig. 2 Almond potential relative yield versus accumulated chill

average at 52 CPs, increasing to 28% above average at 78 CPs and dropping to 5% above average at 87 CPs.

Discussion

Attempting to project the potential impact of climate change on temperate perennial trees, chilling requirements have been provisionally utilized as the best available quantification of the threshold of chill below which negative impacts such as yield declines may occur (Campoy et al. 2011; Hatfield et al. 2008; Jackson et al. 2009). However, the low percentage of flowers fertilized in normal years and June drop resulting from early resource competition indicates that budbreak-based chilling requirements may be greater than the chill accumulation necessary for sustainable yields. The yield-based chilling requirement gleaned from analyses of decades of yield and chill data varied in their relationship to budbreak-based chilling requirements. Because chilling requirements are not precisely transferable from one location to another (Luedeling and Brown 2011), every attempt was made to compare yield-based requirement estimates with budbreak-based requirements

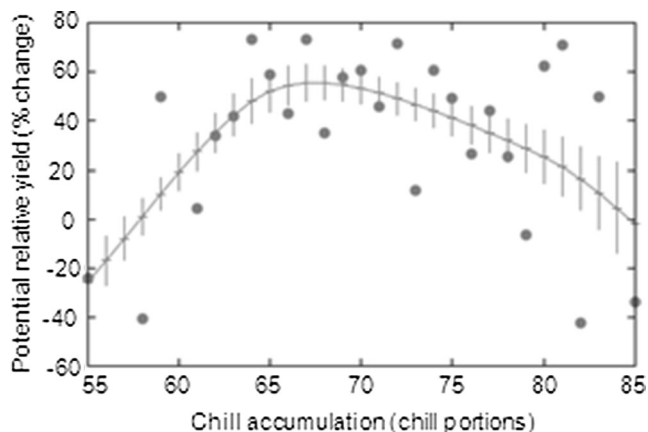


Fig. 3 Pistachio potential relative yield versus accumulated chill

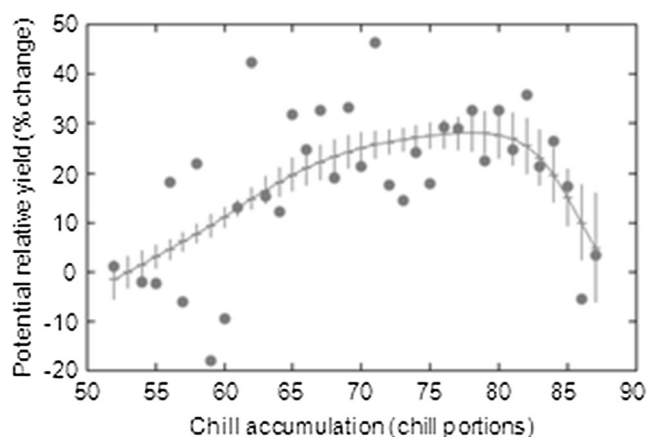


Fig. 4 Walnut potential relative yield versus accumulated chill

generated with California data and/or cultivars. The budbreak-based chilling requirements were similar to those required for average yield for almond. However, the best approximation of the budbreak-based chilling requirements for California pistachios was 19% higher than the yield-based chilling requirement and 28–32% higher than that of walnut.

Almond

Recent quantification has estimated the budbreak-based chilling requirement of Nonpareil as 23 CPs (Ramirez et al. 2010). The chilling requirements for pollinizer cultivars used in California have not been estimated using the Dynamic model but based on the quantification using other models, likely only differ from Nonpareil by a few CPs (Rattigan and Hill 1986; Alonso et al. 2005). Given this low requirement, below average potential yields were expected at CP < 23. The decline in potential relative yield below and above 35 CPs was unexpected.

There are many possible reasons why low or high chill might decrease yield. Because California's most grown cultivar, Nonpareil, is self-sterile, pollination is dependent on the bloom timing of pollinizer cultivars (Hendricks 1996). Analysis of bloom timing relative to Nonpareil shows that below 30 CPs, some cultivars that generally overlap in their timing bloom later than Nonpareil (Pope, unpublished). Change in timing of bloom may have decreased bloom overlap, decreasing pollination, fruit set, and nut yield. The potential yield decrease after high-chill accumulation may be due to decreased bloom duration. High chill coupled with favorable bloom temperatures can increase the rate of flower development, decreasing the bloom period and thus the pollination window (Ortega et al. 2004).

The low potential yields could also be an artifact of the analytical approach. Very low and very high chill years did not occur frequently. There were thus far more points in the middle range of chill accumulation than at the two ends of the range (Online Resource 1). Assuming an approximately

normal distribution of the errors and a common variance, with more data points at the midrange chill, it was more likely that there would be some midchill data points with much higher or much lower relative yields than average, and less likely that extremely high relative yields (years in which most nonchill conditions aligned to also favor high yield) would occur at high and low chill.

Despite these limitations, the data show that above average yields were possible when 22 to 42 CPs were accumulated from November 1st to December 31st, indicating that the yield-based chilling requirement of almond is somewhere below 22 CPs. This suggests that the budbreak chilling requirement did not overestimate the yield based-chilling requirement of California almond cultivars.

Pistachio

The chilling requirement of California's principal pistachio cultivar, Kerman, has not been estimated in the scientific literature using the Dynamic model. Ferguson et al. (2008) reported that to have even budbreak Kerman requires at least 900 chilling hours, a less accurate but more utilized method of chill quantification. Based on the chill model regional equivalency ratio of Luedeling and Brown (2011) for California's Central Valley, 900 chill hours translate to a chilling requirement of 69 CPs. If bud-based requirements reasonably approximated yield-decreasing chill thresholds, below average yields would be expected at $CP < 69$. Instead, potential relative yield was highest at 67 CPs and did not fall below average until 57 CPs. There was a more moderate decline in potential relative yield above 67 CPs, from 56 % above average to 2 % below average at 85 CP.

This disparity between estimated requirements is not likely to be due to the use of dormancy breaking oils. Nine of the 11 potential yield points below 69 CPs were from years before these oils were first researched in California for dormancy compensation (Beede et al. 1997). As with almonds, the decline in potential yield may have been representative of the response of the buds to lower chill or it may have been an artifact of the analysis (Online Resource 2). The potential skewing impact of the paucity of data points on the lower and upper end of the chill accumulation record was likely exacerbated by the strong alternate bearing behavior of Kerman, by which orchard yields oscillate from high yielding "on" years to low yielding "off" years (Spann et al. 2008). Normalizing the data for alternate bearing was prevented by occasional years of low yield when a high yield would have been expected which reset the oscillation. Alternate bearing complicates interpretation by increasing the odds of below average yields for nonchill reasons following low-chill winters.

Without more data points at the low amounts of chill, it is difficult to estimate the minimum-chill accumulation necessary for average yield. However, given that the model-

averaged function indicated average yields at 58 CPs, we can conclude that the yield-based chilling requirement is 58 CPs or below. Thus, although this analysis did not produce a definitive yield-based chilling requirement, it did show that the best approximation of the budbreak-derived chilling requirement for California pistachio is at least 19 % higher than the amount of chill needed for sustainable yields.

Walnuts

Luedeling et al. (2009a) estimated chilling requirements for vegetative buds of two of California's most popular walnut cultivars, Hartley and Chandler, as 68 to 70 CPs.¹ Walnuts have a mixed vegetative-female bud with flowers borne on the apical end of vegetative shoots after preformed vegetative growth has unfurled (Polito 1998). Thus, the chilling requirement of the vegetative bud is what determines whether flowers open or not. In light of the estimated chilling requirement of 68–70 CPs, the yield results of this study were unexpected. The fit of the data indicated that potential relative yield began to decline from about 28 % above average at 78 CPs, down to average at 53 CPs.

As with almonds and pistachios, because the density of data points was lower at low- and high-chill accumulations (Online Resource 3), the minimum-chill requirement for average yields for California's walnut varieties could not be estimated from this dataset. However, the results did indicate that the budbreak-based requirement does not reflect the amount of chill needed for average yields. According to the data, the yield-based chilling requirement was at or below 53 CPs, meaning that the previously estimated budbreak-based requirement was at least 28–32 % more than the chill yield threshold.

Overall, this study indicates substantial differences between budbreak-based chilling requirement estimates and the yield-based chilling requirement in two out of three species examined. These results do not mean that the procedures or statistical approaches of previous chill requirement research were necessarily invalid or incorrect. Rather, they suggest that a direct correlation cannot be assumed between yield and the percentage or timing of budbreak. One probable reason for this is that budbreak-based estimates generally rely on 50 % of bud breaking. A substantial percentage of flowers that bloom do not result in harvested fruit or nuts because many flowers are not fertilized, and of those that are, many abort because of resource limitations (Kester and Griggs 1959b; Polito et al. 2002; Crane 1986). Thus, it may not be necessary to achieve 50 % budbreak to achieve average yields.

The potential inaccuracies of relying on budbreak-based chilling requirements to project climate change impacts can be

¹ Recent work by Luedeling estimating the chilling requirement of the cultivar 'Payne' is not compared here because of the cultivar's much earlier bud-break and much lower chilling requirement than common cultivars, and its sparse acreage.

illustrated by comparing the different potential conclusions based on budbreak versus yield-based requirements for pistachio and walnut. Based on the chill accumulation projections of Luedeling et al. (2009b), under the IPCC A2 emission scenario (unabated emissions), the budbreak-based requirement indicates that there will be insufficient chill to cultivate Kerman pistachios anywhere in California's Central Valley by midcentury. The yield-based requirement estimation indicates that cultivation would be possible in more than half of the Central Valley. Utilizing those same chill projections, by the end of the century, budbreak-based requirements project that walnut cultivation would be untenable in the whole Central Valley, whereas yield-based requirements indicate the area of cultivation shrinking to the Sacramento Delta and northern Sacramento Valley. Considering that many temperate fruit crops are thinned to increase fruit size, and thus that a smaller percent of fruit tree flowers result in harvested fruit than nut tree flowers (Lopez et al. 2010), the disparity between budbreak- and yield-based chilling requirements may be even greater in temperate fruit tree crops, increasing the disparity in climate change impact projections.

Because the above results are based on historic data, not a controlled experiment with statistically based sample sizes and replicates, it is impossible to say whether declines in yield below average denote the yield-based chilling requirement or are the fault of a smaller number of data points. However, results do show that estimates of bud-based chilling requirements for California's pistachio and walnut cultivars are 19–32 % higher than the amount of chill necessary for average or above average yields. Our findings thus indicate that speculation as to the impacts of the warmer winters of climate change on tree crops requires stronger consideration of processes that occur after budbreak. Closer examination of physiological changes to buds at different amounts of chill, as well as quantification of successful pollination, pollinizer overlap, set, June drop and fruit and nut size and quality at different levels of chill would help illuminate the causes of these differences in chill requirements and provide a more accurate estimation of the implications of reduced chill accumulation on crop yields.

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