Title: Nut crop yield records show bud-break based chilling requirements may not reflect yield decline chill thresholds

KATHERINE S. POPE[1], VOLKER DOSE[2], DAVID DA SILVA[3], PATRICK H. BROWN[1] AND THEODORE M. DEJONG[1]

[1] Department of Plant Sciences, University of California, Davis, CA USA

[2] Max-Planck-Institut für Plasmapysiks, EURATOM Association, Garching bei München, Germany

[3]INRA, UMR 1334 Plant Genetic Improvement and Adaption (AGAP), Montpellier, France

Correspondence: Katherine Pope, tel. +001 530 666 8733, Address: 70 Cottonwood Street, Woodland, CA 95695 USA, E-mail: kspope@ucanr.edu

Keywords: chilling requirement, climate change, yield, bloom, bud-break, Bayesian

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 buds breaking. However, the physiological processes that affect bud-break are not the same as those that determine yield. This study sought to test whether bud-break 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 bud-break based chilling requirement. However in the other two crops, pistachios and walnuts, the best previous estimate of the bud-break based chilling requirements were 19-32% higher than the chilling accumulations associated with average or above average yields. This research indicates that physiological processes beyond requirements for bud-break should to be considered when estimating chill accumulation thresholds of yield decline and potential impacts of climate change.

I. 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 ‘bud-break’). The forcing approach manipulates amounts of chill accumulation, either in controlled settings or by collecting shoots from the 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 bud-break. Chilling requirements and subsequent requirements of spring heat that results in bud-break 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 bud-break (Ramirez et al. 2010; Rattigan and Hill 1986), or the chilling and heating accumulation that minimizes the error in the predicted day of bud-break (Chuine et al. 1998; Legave et al. 2008).

These bud-break 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 bud-break 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 bud-break based requirements may lead to mistaken conclusions regarding climate change vulnerability and priorities for climate change adaptation.

There are reasons to suspect that bud-break based chilling requirements may be substantially higher than the amount of chill necessary for sustainable yields. Researchers often use a high percentage of bud-break 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 over-abundance 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 objective of this study was 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 bud-break. 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 seven 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 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 bud-break analyses.

II. Materials and Methods

A. Data Origins

1. 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 United States 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 website. 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 the 1970's, 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 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 three years before and after the year in question. Colusa County walnut data was also culled before 1983, because nine 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 non-linear. Environmental conditions, management practices and the resulting yield vary enough across the approximately 700 kilometer length of the study area that yields were normalized within each county instead of against the state average. Yield in a given year and county was compared with the seven-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 change 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.

2. 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° C or above 30° C. Missing (including erroneous) values were replaced differently depending on the duration of the gap. If 1-3 consecutive days or 1-2 hours were missing, the data were interpolated by averaging the previous and next non-flagged 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 hours were missing, the record for the same period was copied from the nearest station. All back-up 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 back-up station, that winter and its associated harvest year were omitted from the analysis (Online Resource 2).

B. 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; Alburquerque 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 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.

C. Bayesian nonparametric function estimation

Potential relative yield was modelled 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 (Figure 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 (Figure 1a). A linear model would fit well if there was an incremental chill response, suggesting the threshold framework of a chill requirement was inaccurate (Figure 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 (Figure 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.

[[Figure 1]]

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 squares fitting. While the least squares 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 $\mathbf{t}_{\mathbf{ML}}$, 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 of each parameterized model relative to the other five models. As in least squares 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 non-negligible 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.

III. Results

A. 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 CP. 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).

[[Table 1]]

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 (Figure 2). This can be seen in the changing slope below 25 CP and above 44 CP. The model averaged function indicated a potential yield of 5% above average at 22 CP, an increase to 38% above average at 35 CP, and then a decrease again to 14% below average at 47 CP.

[[Figure 2]]

B. 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 CP. 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 (Figure 3). The model averaged function had a potential relative yield of 26% below average at 55 CP, increasing to 56% above average at 67 CP, and decreasing again to 2% below average at 85 CP.

[[Figure 3]]

C. 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 CP. 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 non-negligible probability of the two change point model was also manifested in the change in slope at approximately 68 CP (Figure 4). The model averaged function had a potential yield of 2% below average at 52 CP, increasing to 28% above average at 78 CP, and dropping to 5% above average at 87 CP.

[[Figure 4]]

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

A. Almond

Recent quantification has estimated the bud-break based chilling requirement of ‘Nonpareil’ as 23 CP (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 chill portions (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 CP 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 CP 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 mid-range chill, it was more likely there would be some mid-chill data points with much higher or much lower relative yields than average, and less likely that extremely high relative yields (years in which most non-chill 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 CP were accumulated from November 1st to December 31st, indicating that the yield based chilling requirement of almond is somewhere below 22 CP. This suggests that the bud-break chilling requirement did not over-estimate the yield based chilling requirement of California almond cultivars.

B. 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 bud-break '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 translates to a chilling requirement of 69 CP. 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 CP and did not fall below average until 57 CP. There was a more moderate decline in potential relative yield above 67 CP, 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 CP 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 non-chill 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 CP, we can conclude that the yield based chilling requirement is

58 CP or below. Thus, though this analysis did not produce a definitive yield based chilling requirement it did show that the best approximation of the bud-break derived chilling requirement for California pistachio is at least 19% higher than the amount of chill needed for sustainable yields.

C. 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 CP.[1] Walnuts have a mixed vegetative-female bud with flowers borne on the apical end of vegetative shoots after pre-formed 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 CP, 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 CP, down to average at 53 CP.

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 bud-break 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 CP, meaning the previously estimated bud-break based requirement was at least 28-32% more than the chill yield threshold.

[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.

Overall, this study indicates substantial differences between bud-break 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 bud-break. One probable reason for this is that bud-break based estimates generally rely on 50% of buds 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% bud-break to achieve average yields.

The potential inaccuracies of relying on bud-break based chilling requirements to project climate change impacts can be illustrated by comparing the different potential conclusions based on bud-break versus yield based requirements for pistachio and walnut. Based on the chill accumulation projections of Luedeling et al. (2009b), under the IPCC A2 emissions scenario (unabated emissions), the bud-break based requirement indicates that there will be insufficient chill to cultivate 'Kerman' pistachios anywhere in California's Central Valley by mid-century. The yield based requirement estimation indicates cultivation would be possible in more than half of the Central Valley. Utilizing those same chill projections, by the end of the century bud-break based requirements project 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 bud-break 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 bud-break. 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.

Acknowledgements

We are indebted to the generations of employees of the California County Agricultural Commissioners, without whose meticulous record keeping this analysis would not have been possible. This work was supported by the California Department of Food and Agriculture (#SCB09044).

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Table Legend

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

Figure Legend

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

Fig. 2 Almond potential relative yield versus accumulated chill

Fig. 3 Pistachio potential relative yield versus accumulated chill

Fig. 4 Walnut potential relative yield versus accumulated chill

Supplementary Material Legend

Online Resource Figure 1. Chill accumulation and relative almond yield

Online Resource Figure 2. Chill accumulation and relative pistachio yield

Online Resource Figure 3. Chill accumulation and relative walnut yield

Online Resource Table 1. Harvest years used in analysis

Online Resource Table 2. Location of weather stations and years of temperature records used for each county.

Online Resource Table 3. Relative yield below 29 chill portions in almond

Online Resource Table 4. Relative yield below 40% above average yield in pistachio

Online Resource Table 5. Relative yield below 61 chill portions in walnut