Effects of Climate Change on Tree Crop Phenology in California

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Notes

- Need to add chill and heat sums over time
- Need to run linear models and then extract the interesting numbers
- Need to find a good way to plot all the things without having massive amounts of space in the graph (ex scaling the data)
- To be honest I my want to scale the data anyway for model fitting.

Introduction

Tree crops, like almonds and walnuts, made up 35% of the California agricultural sector by income in 2012 and that percentage is increasing (Ag stats 2012). Almonds individually are the second highest valued commodity California produces, second only to milk and cream (Ag Stats 2015). Unlike field crops and other annuals that are replanted every spring, tree crops stay in the same place for multiple decades. They also require more upfront investment as most trees do not fruit until a couple years after planting. Because of this, they are more vulnerable to changes in climate.

The effects of climate change in California are fairly well documented, especially with respect to drought (citations). However, the potential for groundwater based irrigation systems protects many agricultural systems from significant water stress during all but the most severe droughts (Citation?). Temperatures in California are also changing due to climate change and this has already impacted the phenology for more sensitive crops (Luedeling 2012b). Many papers have has also been demonstrated temperature to be one of the key, if not the key climatic variable when predicting crop phenology (citations).

The majority of variation in California temperatures over the past 100 years is not due to climate change, but rather is inter-annual. Since temperature variablility between years is so great, we can use crops' phenological responses over many years to fit models relating temperature and crop phenology (citation). The effects of temperature on thermal time and flowering and leaf out have also been investigated for many crops in the Central Valley using this method (Luedeling 2012). The effects on harvest however, are not as well studied.

Almost all phenological models of plant development depend on the calculation of thermal time, or the temperature that the plant experiences over a given length of time. Thermal time comes in two main types: chill units and heat units. Chill units count the amount of time a plant experiences temperatures above freezing (0°C) but below some threshold temperature (commonly 7°C) (citation). The sum of all the chill units experienced over a winter is called a chill sum. Heat units count the number of degrees above a certain threshold (base) temperature the plant experiences over a set amount of time, generally an hour or day. Heat sums represent the total number of heat units experienced over a set amount of time. These sums are collectively referred to as thermal time accumulation.

Flowering models frequently use a combination of chill and heat sums to predict flowering (Fishman 1987b). Once a plant has accumulated enough thermal time, it blooms. However, estimating the amount of thermal time accumulation required to produce flowering in a given species is difficult to determine experimentally. Determining when the plant accumulates chill units and heat units is also a challenge. Luedeling *et al.* (2012)

used partial least squares to estimate the flowering thermal time accumulation requirements For walnuts in California in order to capture potential non-linear rel.

Models of harvest readiness only use heat sums to predict fruit and nut maturity dates. This is because most relevant chemical reactions slow to a crawl near 0°C, so the plant develops very little. The most common model of calculating heat units assumes no development below the base temperature (T_b), maximum development at some optimal temperature (T_o) and no at a critical temperature (T_c) above the optimal temperature (citation). The exact functional form this can vary quite a bit. However, it seems more complex models may not gain that much in over simpler ones (Hellwig 20??).

For most fruit and nut trees, including almonds, prunes and walnuts, there are two primary stages of fruit development: the cell division and differentiation stage and the cell enlargement stage (Micke 1996; Buchner 2012; Ramos 1997). The cell division and differentiation stage begins right after pollination and continues for a month or so into development (Micke 1996). After the cell division stage is over, most of the changes to the size of the fruit are due to enlargement of already existing cells (Micke 1996; Buchner 2012; Ramos 1997). Of the two phases, cell division is much more responsive to differences in temperature (Warrington et al. 1999; Bertin 2005; C. Zhang et al. 2006). Consequently, the amount of thermal time accumulated during the cell division stage is generally a much better indicator of how quickly the fruit or nut is developing than the amount of thermal time accumulated later in the growing season (T. DeJong and Goudriaan 1989, Mimoun and DeJong (1998), Warrington et al. (1999), Lopez and DeJong (2007), Tombesi et al. (2010), Ruml et al. (2011)).

This paper extends those results to estimate not only the amount of thermal time required for bloom but also when that thermal time accumulation happens and what temperature thresholds to use. This paper also investigates the way changes in temperature over the past century have impacted harvest dates for almonds, walnuts and prunes at four sites across the California Central Valley.

When discussing fall phenology, the most commonly referenced development stage is maturity, the first possible harvest date (Mimoun and DeJong 1998; Tombesi et al. 2010; Ruml et al. 2011). However, maturity is correlated with flowering. Everything else being equal, a tree that bloomed earlier will also be ready to harvest earlier. Consequently, changes in harvest readiness date can be due to changes in flowering dates and/or changes in temperature after flowering dates. To avoid confounding these two phenomena, we use season length (time from flowering to maturity) as the fall phenological response, instead of harvest date.

Methods

Data

Climate Data

Climate data for each of the focal orchard sites was obtained from the National Climatic Data Center (NCDC, Menne and Houston 2015) and from California Irrigation Management Information System (CIMIS, California Department of Water Resources 2015). The NCDC provided daily minumum and maxiumum temperature data going back to 1906, and CIMIS provided hourly data back to 1983. Several climate stations were chosen for each orchard location to ensure there would be data for every day in the time span of the orchard datasets for each location (Table X). The closest station to the site with at least 85% completeness was chosen as the primary station (indicated by a *). Temperature data from other stations was related to temperature data from the primary station via a linear regression. This model was then used to fill in gaps in the primary station's data. In cases where there were nearby NCDC and CIMIS weather stations, one primary station was chosen for each data source.

Source	Location	Orchard Location	Start	End	
NCDC	Chico University Farm	Chico	1982	2014	Primary
NCDC	Oroville Municipal Airport	Chico	1906	2014	NA

Source	Location	Orchard Location	Start	End	
NCDC	Orland CA	Chico	1998	2014	NA
CIMIS	Durham CA	Chico	1982	2014	Primary
NCDC	Davis Experimental Farm	Davis	1893	2014	Primary
NCDC	Winters CA	Davis	1942	2014	NA
NCDC	Woodland CA	Davis	1911	2014	NA
CIMIS	Davis CA	Davis	1982	2014	Primary
NCDC	Modesto City Co Airport	Modesto	1906	2014	Primary
NCDC	Stockton Metropolitan Airport	Modesto	1948	2014	NA
CIMIS	Manteca CA	Modesto	1987	2014	Primary
CIMIS	Parlier CA	Parlier	1983	2014	Primary
NCDC	Visalia CA	Parlier	1895	2014	NA

Phenological Data

Though the almond and walnut datasets have records for a large number of cultivars, only three will be analyzed – the earliest and latest cultivars to bloom and/or leaf-out, and the current most popular variety, which blooms in the middle. It is expected that if there is variability in response to warming, examining cultivars that cover the spectrum of phenological timing is the most likely way to reveal that variability. The prune industry in California is planted almost exclusively with one cultivar and thus only one cultivar will be analyzed.

Almond bloom records from the National Weather Service Fruit Frost Service (FF) and the University of California (UC) Regional Almond Variety Trial (RVT) were used. We report data for cultivars 'Sonora', 'Nonpareil', and 'Mission' which represent the range of bloom timing in commercially cultivated almonds.

Bloom dates reported by the National Weather Service Fruit Frost Service for the North Sacramento Valley Region, based in Chico, were derived by National Weather Service employees querying growers in the Chico area and Butte County UC Cooperative Extension.

Data from the UC Regional Almond Variety Trial were recorded in Chico and Modesto by UC Cooperative Extension advisors assigned to the county where the data was recorded. The bloom record in a given year represents the average bloom of a number of trees of similar age in the same orchard. Records are from two separate trials revisited annually. For Chico, the FF and RVT records were combined. Records spanned approximately 10-80 years, depending on the location and variety. Variety-specific data was not recorded by the FF network in Modesto, so only the more recent UCRVT data was used for Modesto.

Almond harvest records were from the UC Regional Variety Almond Trials which spanned 10 years. Similar to the almond bloom data, we report on the 'Sonora', 'Nonpareil', and 'Mission' cultivars grown in Chico, California. Prune bloom and harvest timing data was recorded by the University of California Prune Breeding, provided by current breeder Sarah Castro. Both the leaf-out and the harvest data for walnuts came from the UC Davis Walnut Improvement Program, currently headed by Charles Leslie (See Appendix).

We investigated variation and trends in the four locations in the Central Valley: Chico, Davis, Modesto, and Parlier. Temperature time series going back to 1931 were analyzed to match up with the duration of the longest phenological time series (almond bloom in Chico). While most of the phenological time series do not extend this far back, it is necessary to examine a long time series for climate data to ensure that the trends we find are robust.

We looked at four different classes of climate metrics and their correlation with phenological observations: minimum, maximum and mean average monthly temperatures, winter chill accumulation, heat accumulation following winter chill accumulation, and the amount of thermal time accumulated during the cell division stage of fruit development (T. DeJong and Goudriaan 1989; Mimoun and DeJong 1998).

Phenological trends

Changes in bloom or leaf-out dates over time were analyzed using both linear regression and segmented (broken-line) models. Using this dual approach can be illuminating for long-term datasets in which there are no trends or changes early in the dataset but changes do occur later in the dataset. For example, given a hundred year record of an annual event, if there has only been a change in the last 30 years, linear analysis may not pick up this change, because the consistency of the first 70 years would dilute the statistical signal of change from the last 30 years. Segmented analysis can break up this record into two trends, giving one trend line for the first 70 years and a second trend line for the 30 years after that, if this gives a more robust statistical explanation of the data.

Monthly temperatures

We considered the monthly average minimum, maximum, and mean temperatures for November through July as simple climate metrics. These eight months are deemed to have the most influence over tree crop flowering and fruit development (Ramos 1997). Temperatures in November, December and January are generally associated with the amount of chill accumulation, as well as February, if a tree blooms later in the spring (e.g. prunes, walnuts). In contrast, February and March are associated primarily with heat accumulation, as well as January for early blooming crops (e.g. almond). That is, given that vernalization requirements are at least partly met, trees will generally flower earlier if temperatures are higher during February and March (Micke 1996; Buchner 2012; Ramos 1997).

By the end of April almost all of the tree crops have bloomed (Ramos 1997), so temperatures during May, June, and July only affect season length. In addition, early flowering crops (e.g. almonds) may start fruit or nut development as early as March. The Aikaike Information Criterion (AIC) was used to select the months with the best ability to predict flowering date and season length for each cultivar. These groups of months were then modified to remove collinearity.

We analyzed both the monthly and annual temperature time series with a first degree autoregressive linear model, due the presence of autocorrelation in the data. A first degree autoregressive linear model is a statistical model where the value of the dependent variable for time t is a predictor for the value of the dependent variable at time $t+1$ (Cressie and Wikle 2015).

For plots that show data from multiple months or multiple locations, we used deviation from mean temperature, instead of just the raw temperature value, as the variable on the x-axis. So if the mean temperature value for February was 4° C, points at 6°C would be plotted at 2° and points at 1°C would be plotted at -3°. This ensures that the data for any number months can be plotted together without data from the hotest or coldest month (or location) being pushed to the edge of the graph.

Chill and heat metrics (flowering)

Chill accumulation was calculated using the Dynamic Model (S. Fishman, Erez, and Couvillon 1987). This model is more complex than the often cited Chill Hours thermal time model, which gives the same value to any temperature under a particular threshold. However, it has been found to model the timing of spring phenological events better than the chill hours model in Mediterranean climates (Alburquerque et al. 2008; Luedeling et al. 2009; Ruiz, Campoy, and Egea 2007). Chill accumulation was then compared with chill requirements, as measured in chill portions, to determine with the chill requirement was met.

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 (Table 1). Temperatures between 6°-8°C (43°-47° F) have the most chill value. The chill value on either side of that range are lower, dropping to no value at 0° C (32° F) and 12°C (54° F). This accumulation can be reduced given high temperature. Second, the chill intermediate accumulates to a threshold and is counted as one chill portion

(CP), which cannot be negated by later warm temperatures (Table 2). Accumulation of new chill intermediate starts again from zero (Erez and Fishman 1997). Chill accumulation was calculated beginning November 1.

Spring heat accumulation was calculated using the Growing Degree Hours (GDH) Anderson model from Anderson and Kesner (1986), with a base, optimal, and critical temperatures of 4° C, 25° C, and 36° C respectively (Figure 2, Table 1). Trees will accumulate the most GDH at temperatures near 25° C, and will not accumulate any spring heat thermal time below temperatures of 4° C or above temperatures of 36° C.

Table 2: Table 1. Cardinal temperatures for flowering thermal time accumulation. Temperatures in degrees C.

Variable	Model	Base Temp	Optimal Temp	Critical Temp
Chill	Dynamic Model	0	7	12
Heat	Anderson	4	25	36

Table 3: Table 2. Cardinal temperatures for fruit development thermal time accumulation.

Crop	Cultivar	Chill Req.	Ag. Chill Req.	Heat Req.
Almond	Sonora	21	41	3210
	Nonpareil	20	38	3142
	Mission	32	56	2786
Prune	French	38	49	6994
Walnut	Payne	33	46	6782
	Chandler	42	53	8091
	Franquette	51	60	8887

Fruit development thermal time metrics (season length)

The amount of fruit development thermal time accumulated during the cell division stage is, in theory, the best metric to use to predict season length (T. DeJong and Goudriaan 1989; Micke 1996; Buchner 2012; Ramos 1997). However, determining the exact length of the cell division and differentiation stage is difficult, if not impossible to do experimentally. Many studies use 30 days after flowering as an estimate of the length of cell division (Mimoun and DeJong 1998; Marra et al. 2001; Day, Lopez, and DeJong 2007; DeBuse, Lopez, and DeJong 2008). However, it is not clear that this length of time is appropriate across cultivars and crops (Tombesi et al. 2010). Because of the intractability of estimating the length of the cell division stage, we focus instead on estimating what we call the optimal length of fruit development thermal time accumulation. This is the length of time after bloom that produces thermal time accumulation sums that correlate the strongest with the season length.

For this report, we used an optimization process to determine optimal values for both the cardinal temperatures, and the length of fruit development thermal time accumulation for each cultivar. Sets of parameter values were scored based on the root mean squared error (RMSE) of the statistical linear model relating thermal time accumulation and season length. Parameter sets with lower RMSE values were considered to be more optimal. The length of thermal time accumulation and accompanying cardinal temperatures with the lowest RMSE value were selected for each cultivar and used for the rest of the analysis (Table 3). We conducted this optimization for the Anderson model and the Simplified model of fruit development thermal time accumulation separately.

Table 4: Table 3. Cardinal temperatures for fruit development thermal time accumulation. TTAL: thermal time accumulation length. Temperatures in degrees C.

Crop	Cultivar	Model	TTAL	Base Temp	Optimal Temp	Critical Temp	RMSE
almond	Mission	Anderson	134	1	43	43	2.71
		Simplified	135	6	43	NA	2.78
	Nonpareil	Anderson	62	3	33	36	5.27
		Simplified	135	0	42	NA	4.82
	Sonora	Anderson	124	20	32	65	3.36
		Simplified	125	16	37	NA	2.89
prune	French	Anderson	99	18	36	36	3.81
		Simplified	117	20	24	NA	3.67
walnut	Chandler	Anderson	30	11	24	51	7.09
		Simplified	30	13	21	NA	7.08
	Franquette	Anderson	37	10	25	38	5.60
		Simplified	67	17	21	NA	5.57
	Payne	Anderson	63	2	41	42	5.47
		Simplified	63	7	38	NA	5.46

Results

Temperature Trends

Over the past 80 years, annual temperatures minimum temperatures have stayed roughly the same in Chico but the annual maximum temperature has increased by 0.085 °C (Table 5, Figures 2-3). No monthly minimum temperatures in Chico exhibit any significant trends. However, January, February, and December monthly maximum temperatures show significant increasing trends (Table 5).

Modesto minimum temperatures show the strongest warming trends of all the locations, with a mean increase of 0.2 °C per decade (Figure 3, Table 2). In addition, all mean minimum temperatures show significant increases in all months except for January and the means from eight months increased at over 0.3°C per decade (Table 2). The annual maximum temperature in Modesto is also increasing, but not as rapidly (Figure 4, Table 5). Also, only seven months exhibit significant positive thrends in temperature (Table 5).

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Table 5: Table 5. Average change per decade of Modesto minimum, maximum, and mean monthly temperatures from 1931-2014. Change is considered significant and given in bold if p-values are under 0.05.

Month	Minimum	p-value	Maximum	p-value	Average	p-value
January	**-1.2e-16**	**1.3e-03**	**1.2e-16**	**4.3e-06**	**-1.6e-16**	**2.3e-04**
February	**-1.2e-16**	**1.1e-09**	**1.6e-16**	**7.3e-04**	**2e-16**	**4.8e-09**
March	**1.6e-16**	**5.8e-04**	**3.9e-17**	**0.028**	**-1.2e-16**	**2e-06**
April	**-7.9e-17**	**2.3e-09**	5.9e-17	0.31	0	1

Month	Minimum	p-value	Maximum	p-value	Average	p-value
May	**-1.6e-16**	**1e-08**	-1.2e-16	0.12	**-2e-16**	**1.4e-05**
June	**-7.9e-17**	**3e-06**	**-1.2e-16**	**1.6e-03**	0	1
July	**-2.4e-16**	**4.6e-08**	-9.8e-18	0.63	**1.6e-16**	**2.1e-08**
August	**-4.7e-16**	**3.1e-12**	2e-17	0.057	**7.9e-17**	**7.5e-11**
September	**-7.9e-17**	**7.7e-07**	-3.9e-17	0.085	**7.9e-17**	**3.2e-08**
October	0	1	-2e-17	0.26	**3.9e-17**	**2.5e-28**
November	**-8e-17**	**1.3e-17**	1.5e-17	0.78	**4e-17**	**8.8e-07**
December	-4e-17	0.092	**-2e-17**	**7.2e-04**	**2e-17**	**0.034**
Annual	**-8e-17**	**6.6e-25**	**-6e-17**	**5.3e-03**	**8e-17**	**1.1e-08**

In Davis, annual minimum temperatures have risen an average of 0.21°C per decade over the past 80 years based on an autoregressive linear analysis (Figure 2). Annual maximum temperatures, however, have stayed fairly constant (Figure 3). Davis monthly minimum temperatures exhibit strong warming trends in the spring, summer and fall, with temperatures increasing between 0.15°C and 0.26°C per decade in months where a significant change was detected (Table 16). January maximum temperatures in also show a significant warming trend (0.17°C per decade), but it is the only month we have strong evidence of maximum temperatures increasing. In addition, mean maximum temperatures in July display a slight cooling trend (Table 7).

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Table 6: Table 16. Average change per decade of Davis minimum, maximum, and average monthly temperatures from 1931-2014. Change is considered significant and given in bold if p-values are under 0.05.

Month	Minimum	p-value	Maximum	p-value	Average	p-value
January	**5.9e-17**	**1.8e-03**	**-3.9e-17**	**8.5e-03**	3.9e-17	0.07
February	**-1.2e-16**	**0.028**	0	1	**2e-17**	**0.024**
March	**2.4e-16**	**7.2e-04**	9.8e-17	0.17	0	1
April	**3.9e-17**	**5.5e-05**	4.9e-18	0.37	2.9e-17	0.46
May	**-1.2e-16**	**1.4e-05**	2e-17	0.36	**-3.9e-17**	**4.7e-04**
June	**-1.2e-16**	**4.8e-07**	-9.8e-18	0.32	0	1
July	**7.9e-17**	**4e-04**	**-9.8e-17**	**8.5e-03**	4.9e-18	0.61
August	**-3.9e-17**	**7.1e-05**	3.9e-17	0.28	**5.9e-17**	**3.1e-03**
September	0	1	-5e-18	0.74	0	1
October	**-1.2e-16**	**1.2e-09**	9.8e-18	0.52	2e-17	0.24
November	**-1.2e-16**	**1.2e-04**	**4e-17**	**0.019**	0	1
December	5e-17	0.4	1e-17	0.77	1e-17	0.19
Annual	**-8e-17**	**4.2e-06**	-3.7e-18	0.9	0	1

Annually Parlier exhibits warming minimum temperatures and cooling maximum temperatures (Figures 2-3) based on an autoregressive linear model of data since 1931. While the cooling trend in the mean annual maximum temperature is stronger (-0.36°C per decade), the warming trend in the mean annual minimum temperature is still highly significant (Table 8). Minimum monthly temperatures are increasing year round based on autoregression analysis, but only spring, summer, and fall maximum temperatures are cooling significantly (Table 8).

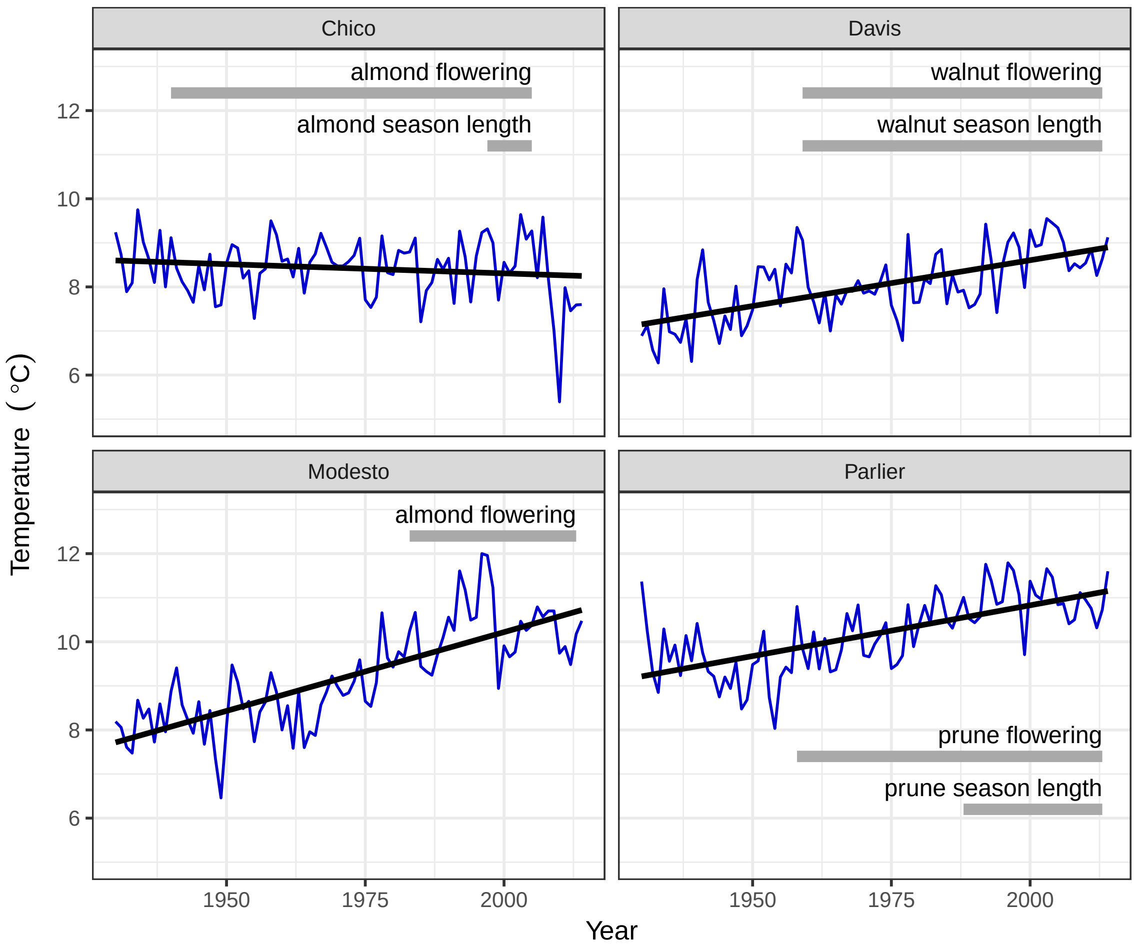

Figure 1: Figure 3. Mean Annual Minimum Temperatures from 1931 to 2014, duration of phenology record shown with grey lines.

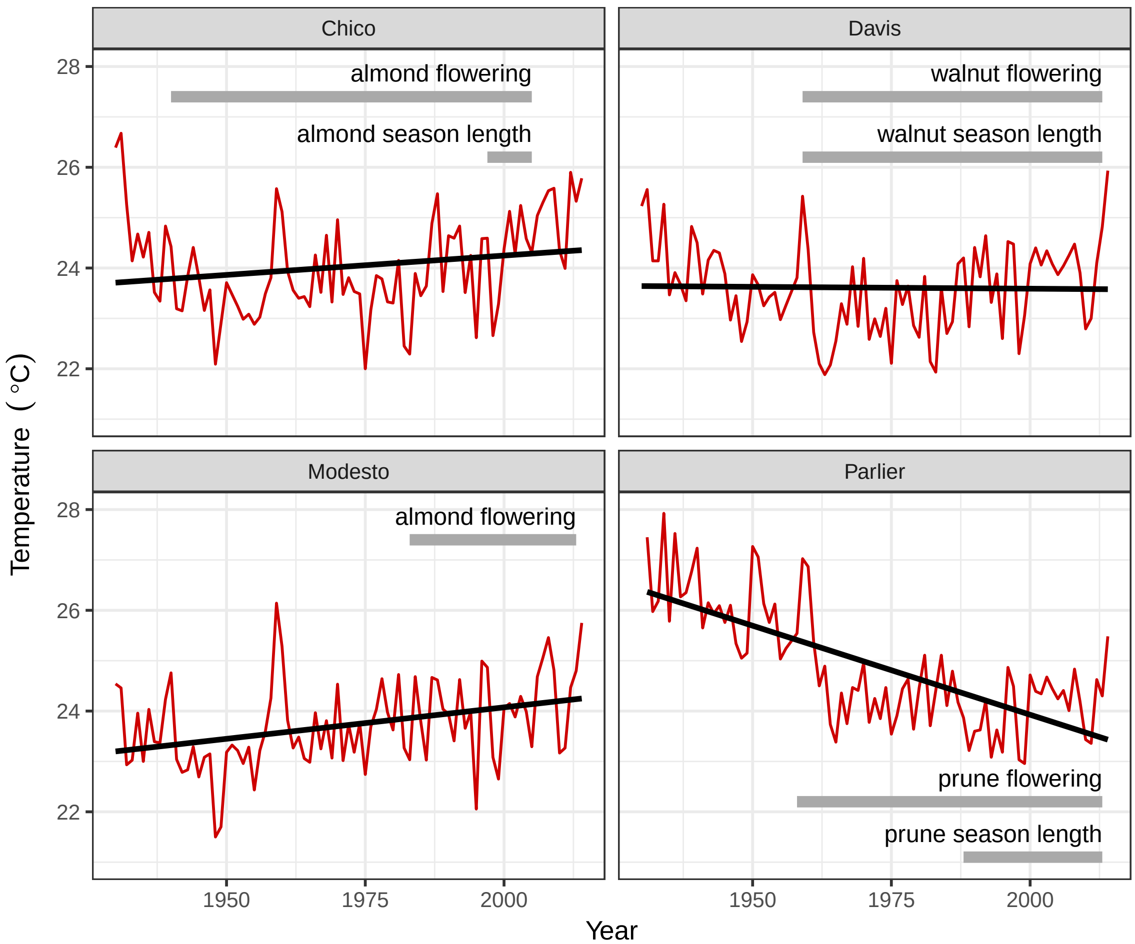

Figure 2: Figure 3. Mean Annual Minimum Temperatures from 1931 to 2014, duration of phenology record shown with grey lines.

Table 7: Table 12. Average change per decade of Parlier minimum and maximum monthly temperatures from 1931-2014. Change is considered significant and given in bold if p-values are under 0.05.

Month	Minimum	p-value	Maximum	p-value	Average	p-value
January	**-1.6e-16**	**5.5e-04**	3e-17	0.61	4e-17	0.15
February	**-3.9e-17**	**1.1e-12**	2e-17	0.088	-2.5e-17	0.47
March	**3.1e-16**	**3.4e-04**	-7.9e-17	0.13	-2e-17	0.092
April	-2e-17	0.32	0	1	3.9e-17	0.13
May	**-3.9e-17**	**0.016**	**2.4e-16**	**1.2e-07**	9.8e-18	0.11
June	**1.6e-16**	**1.7e-07**	**7.9e-17**	**1.8e-13**	-2.5e-18	0.9
July	**7.9e-17**	**2e-22**	0	1	**3.9e-17**	**3e-04**
August	**-1.6e-16**	**5.3e-19**	**-1.6e-16**	**3.9e-08**	**2e-17**	**4.6e-03**
September	**1.6e-16**	**1.3e-14**	**-7.9e-17**	**6.1e-05**	-4.9e-18	0.5
October	**-7.9e-17**	**4.2e-14**	**7.9e-17**	**1.1e-04**	9.8e-18	0.25
November	**4e-17**	**3.7e-03**	**-8e-17**	**0.001**	-6e-17	0.11
December	1e-17	0.21	-1.2e-16	0.055	2e-17	0.4
Annual	**8e-17**	**3.2e-07**	**8e-17**	**4.4e-07**	**-5e-17**	**0.038**

Spring Phenology

Almonds

Mean flowering dates has not changed significantly ($p<0.05$) for Sonora, Nonpareil, or Mission almonds over the study period in either location (Figure 5-6, Table 6). When analyzed with linear regression, the data for Nonpareil almonds in Chico showed some support for change ($p=0.075$); but the change was very small. The change in bloom is 0.07 days later every year (1 day every 14 years, 7 days over 100 years). The segmented analysis for Sonora almonds in Chico did detect a significant changepoint in 2006. However, this is too close to the end of the time series to be meaningful (Figure 5).

Spring bloom and heat sums were analyzed for Chico and Modesto, CA. California State University, Chico hosts the longest known bloom and harvest timing records for almonds, and is part of the long-time commercially important Northern Sacramento Valley almond growing district. Spring heat predicts flowering for both Nonpareil and Mission cultivars in Chico and Modesto. Heat sums explain more variation in Nonpareil almond bloom in both locations. January precipitation also explains some variation in Nonpareil flowering dates in Chico bringing the R^2 value for the final flowering model to 0.43 (Table X).

In addition to examining chill accumulation, we analyzed when chill and heat requirements were met for almonds for the duration of the phenology records for Chico and Modesto for any potential changes. No significant changes were detected in the timing of the chill requirement being met for any of the three almond cultivars in Chico and Modesto, using either linear modeling or segmented linear modeling (Figures 13-18, Table 8-9 for p-values). The agronomic chill requirement also did not show change over time using linear or segmented regression (Figures 13-18, Tables 8-9).

The timing of the post-chill heat requirement being met did change significantly over time for the Sonora cultivar in both Chico and Modesto and for the Nonpareil cultivar in Modesto according to the linear models (Figures 13-18, Tables 8-9). On average the heat requirement for these cultivars was being met 0.7-0.9 days earlier every year over the course of the bloom record. . Note that in the figures below that zero is January 1st, as with Julian days. Negative numbers on the y-axis signify days in the previous calendar year. For example, Day of Year: -10 is December 22nd. Bloom data are the same as those given in Figures 5 & 6.

The fact that the heat metrics for Sonora and Nonpareil almonds have shown significant change but that there has been no change detected in the timing of bloom points to the complex inter-relatedness of a number

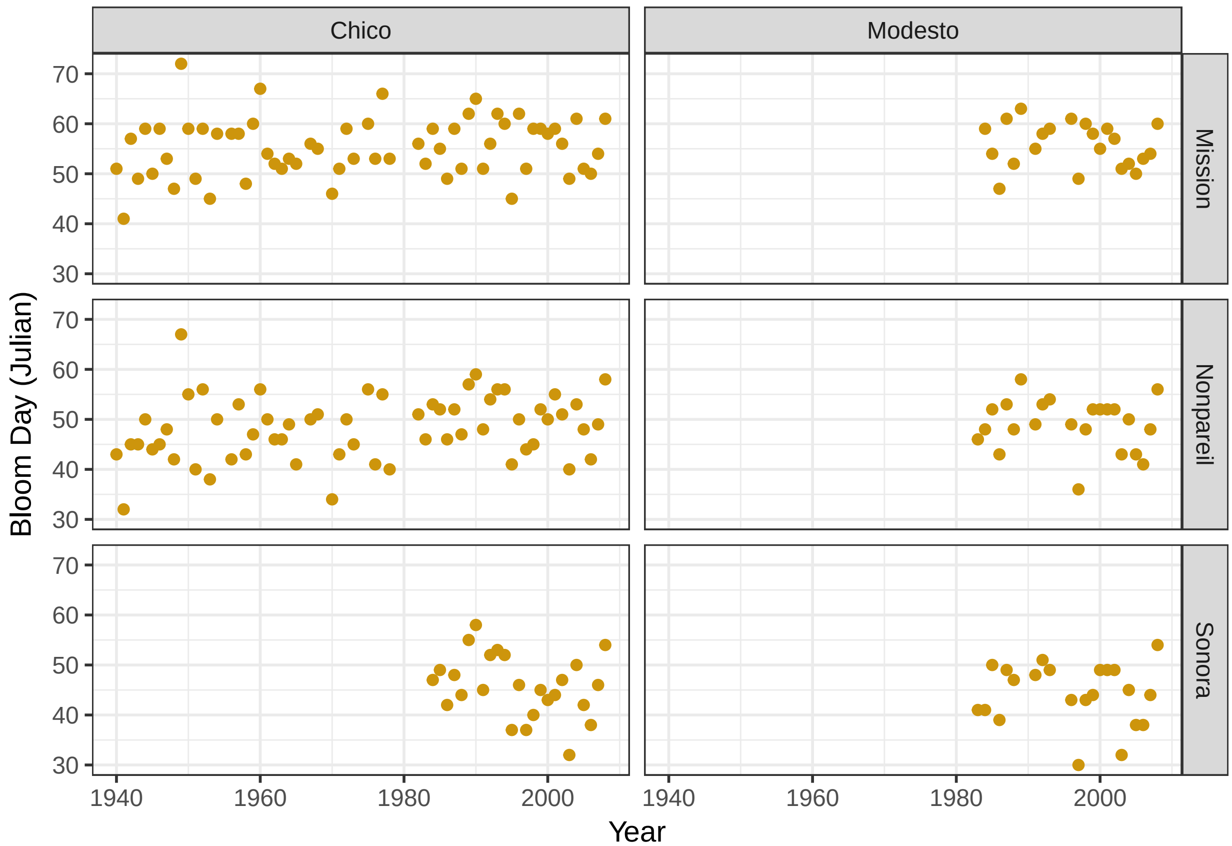

Figure 3: Almond bloom over the past 70 years in Chico and Modesto, California.

of determinants of bloom, and requires further research to be more adequately explained.

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Prunes

Flowering dates in Parlier increased markedly between 1988 and 2014 (Figure 35). On average, bloom has moved 0.4315 days later each year. This trend explains 41% of the variability in bloom date and was highly significant (R^2 = 0.41, p=0.00006).

In addition to examining chill accumulation, we analyzed when chill and heat requirements were met for prunes from 1988-2014, for any potential changes (Figure 40). No significant changes were detected in the timing of the chill requirement being met for prune (linear model p=0.69). The agronomic chill requirement also did not show change over time (Figure 40, p=0.465). The timing of the post-bloom heat requirement being met also did not change significantly over time either (Figure 40, p=0.879).

However, prune flowering dates are getting later instead of earlier, which is contradictory to what the chill and heat accumulation, as well as the monthly temperatures imply. The fact that none of these metrics on their own explain the changing timing of bloom suggests that the influence of temperature on bloom is more complex than previously thought, or that something else entirely is influencing the flowering dates. More research is necessary to adequately explain this phenomenon.

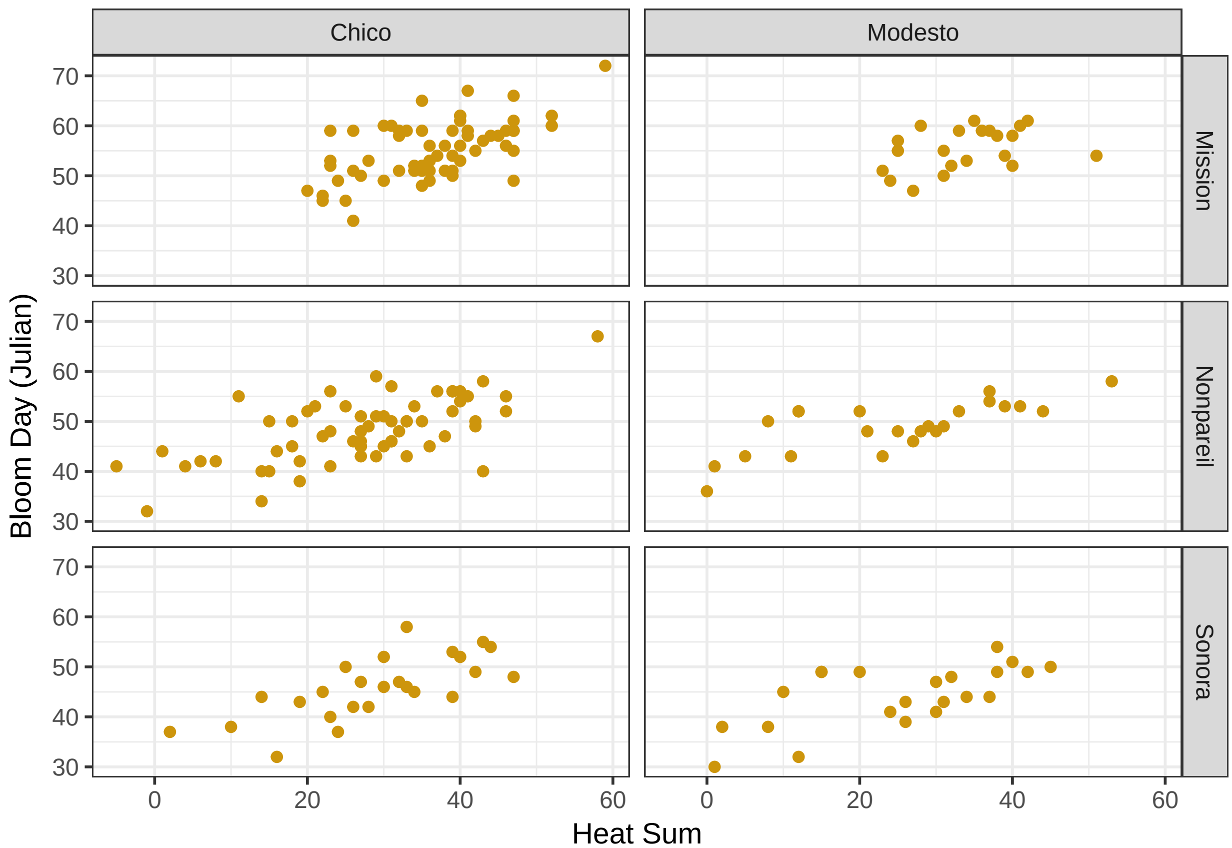

Figure 4: Bloom day by heat sum for two cultivars in Chico and Modesto, California.

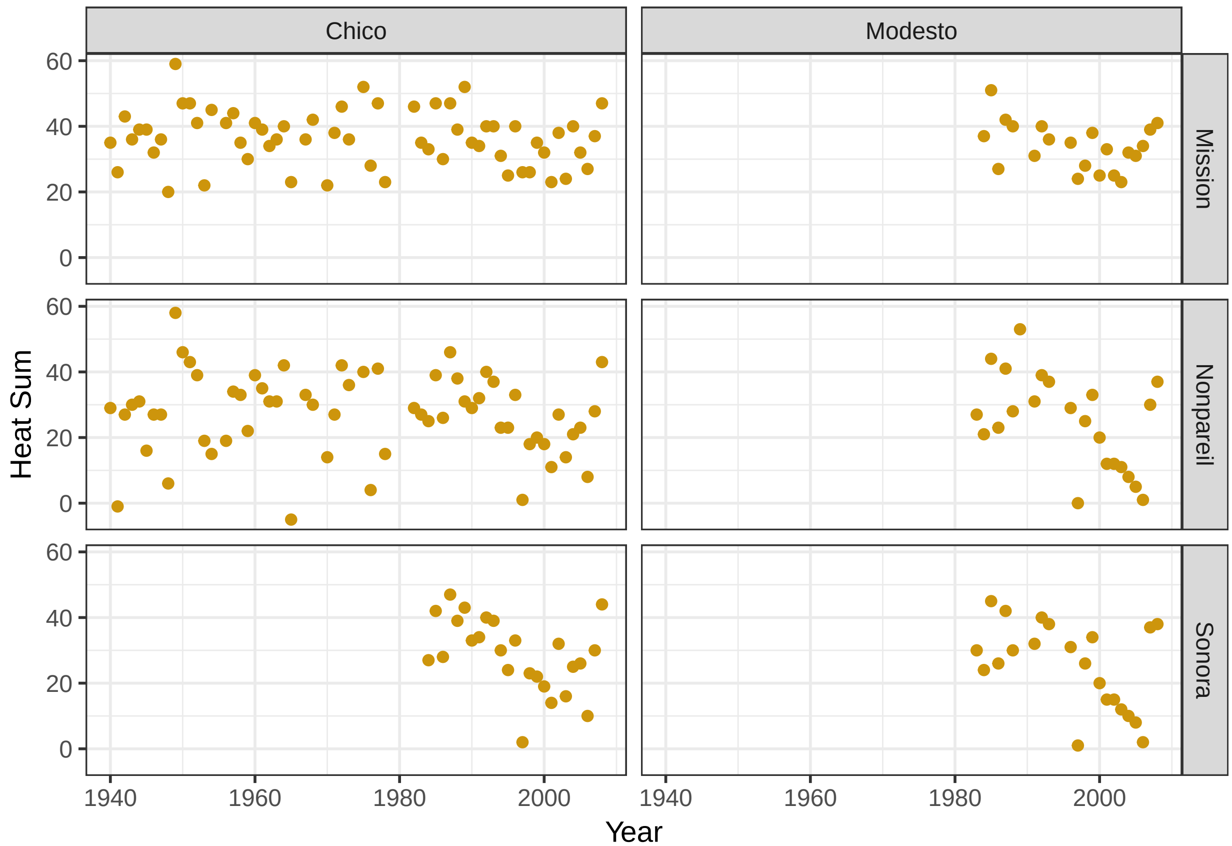

Figure 5: Change in head sums over time for two cultivars in Chico and Modesto, California.

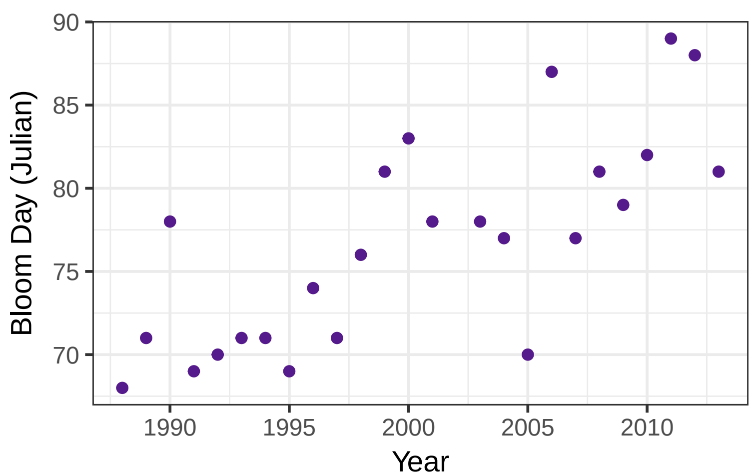

Figure 6: Improved French prune bloom over 25 years in Parlier, California.

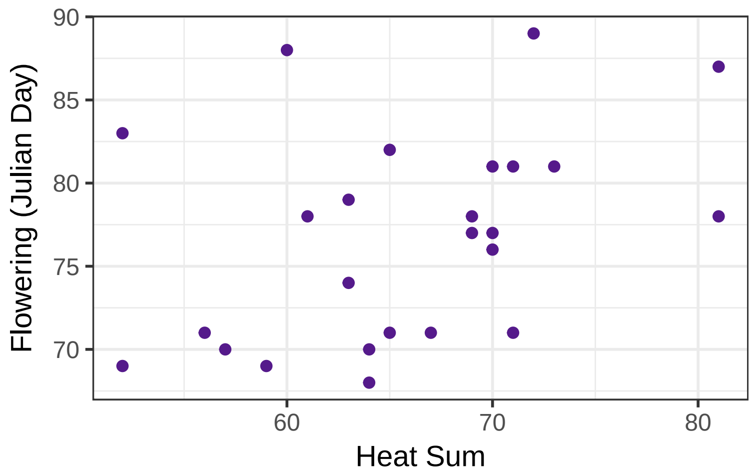

Figure 7: Prune flowering day by winter heat sum in Parlier, California.

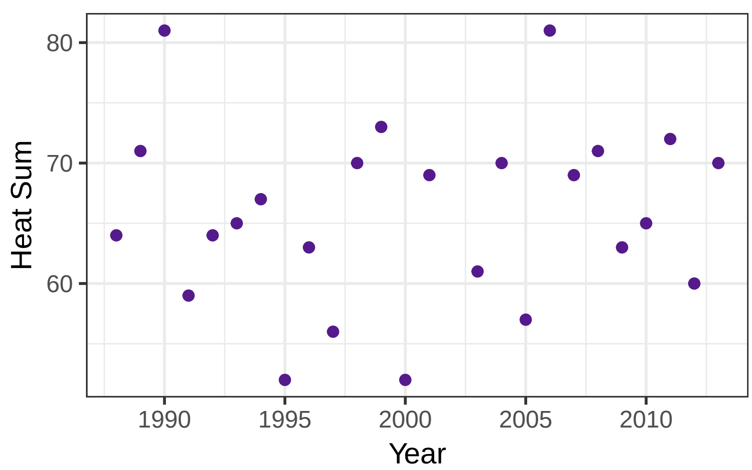

Figure 8: Improved French prune bloom over 25 years in Parlier, California.

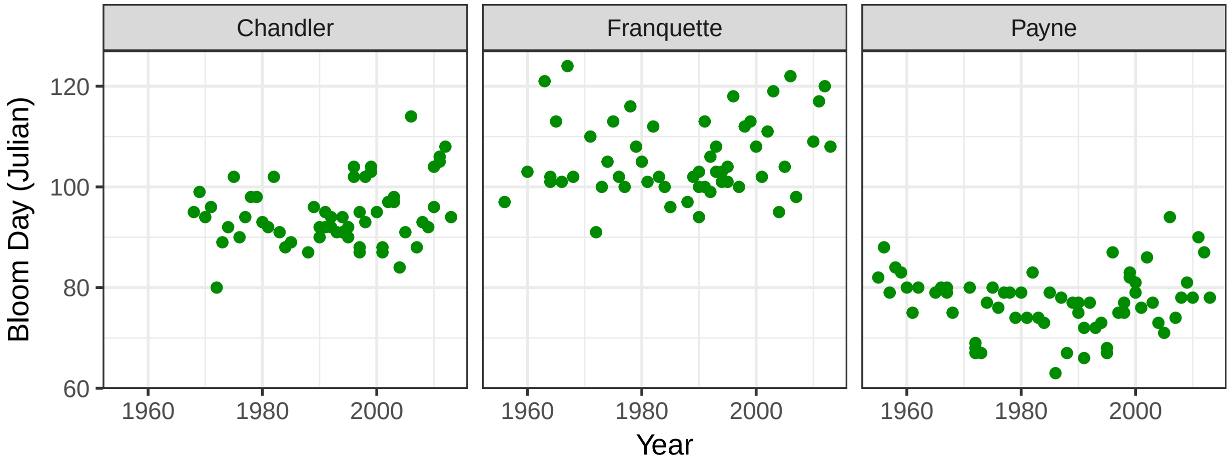

Figure 9: Walnut leaf out over the past 60 years in Davis, California.

Walnuts

Analysis of leaf-out dates in Davis illustrate the difference in results that can be obtained if one uses linear or segmented regression with long datasets. Of the three cultivars examined (Payne, Chandler, and Franquette), only one, Chandler, showed a significant change in leaf-out timing when analyzed with a linear regression (Figure 47). However, Payne also showed low p-values when analyzed with a segmented model with a break point at 1988 (Figure 48, Table 17).

A more conceptually simple way to look at these results is by limiting the years we analyze. If we only examine the leaf-out timing for Payne and Franquette since their respective break points (1988 and 1990), we see leaf out dates getting significantly later. For 1988-2013, Payne has a p-value of 0.003 (R^2=0.24), showing leaf-out coming later by 0.47 days/year. For data between 1990 and 2013, Franquette has a p-value of 0.015 (R^2=0.17), showing leaf-out coming later by 0.47 days/year.

In addition to examining chill accumulation, we analyzed when chill and heat requirements were met for walnuts from the course of the leaf-out record (starting 1959 for Payne and Franquette, 1968 for Chandler), for any potential changes.

For Payne, linear regression detected a significant decrease in the day of the year when the chill requirement was met (i.e. was met earlier) (p=0.04), by 0.11 days per year (Figure 55). Not surprisingly, linear regression also detected a significant change in when the agronomic chill requirement was met (p=0.04), 0.12 days earlier. Linear regression analysis did not detect a change in the timing of the heat requirement being met (p=0.59), but the segmented regression did detect change (p=0.08). According to the segmented regression, the heat requirement was met 0.22 days earlier every year until 1995. Then it was met 0.54 days later every year. This later meeting of the heat requirement may explain the later leaf-out date trend seen in Payne in recent years.

For Chandler, linear regression did not detect a significant change in the day of the year when the chill requirement or the agronomic chill requirement was met (p=0.75 and 0.73, respectively, Figure 56). The segmented model was significant (p=0.09) for the chill requirement but results were erratic, showing a change point at 1973 and 1977, indicating these are spurious results. No change was detected in the timing of meeting the heat requirement by linear regression or segmented regression.

For Franquette, linear regression did not detected a significant change in the day of the year when the chill requirement was met (Figure 57) by linear regression (p=0.13) or segmented regression (0.17). For the agronomic chill requirement, however, linear regression did detect a significant change in the day of the year that the agronomic requirement was met (p=0.07), coming 0.16 days earlier every year. The timing of meeting the heat requirement was not detected as changing by simple liner regression (p=0.24) or segmented

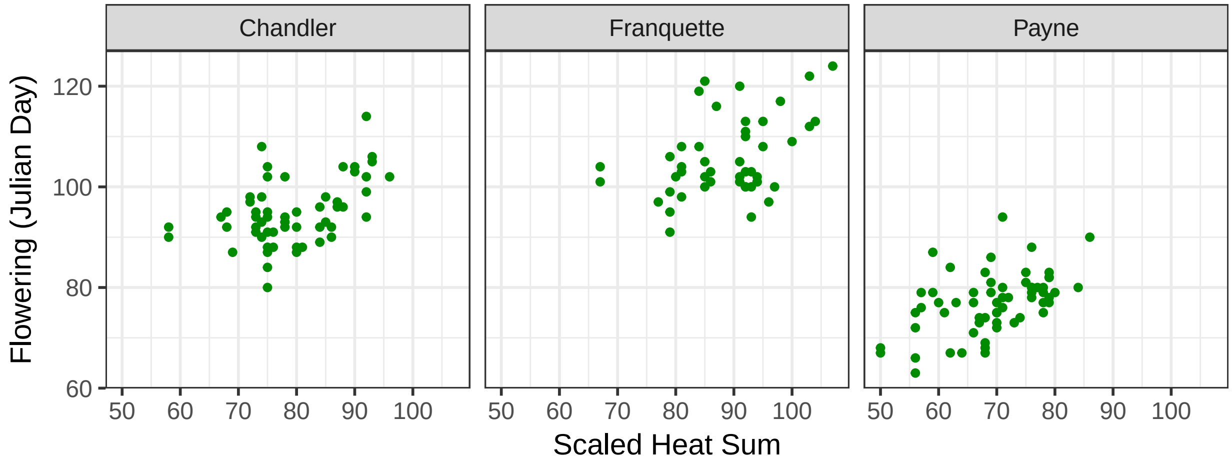

Figure 10: Walnut leaf out by winter heat sum for three cultivars in Davis, California.

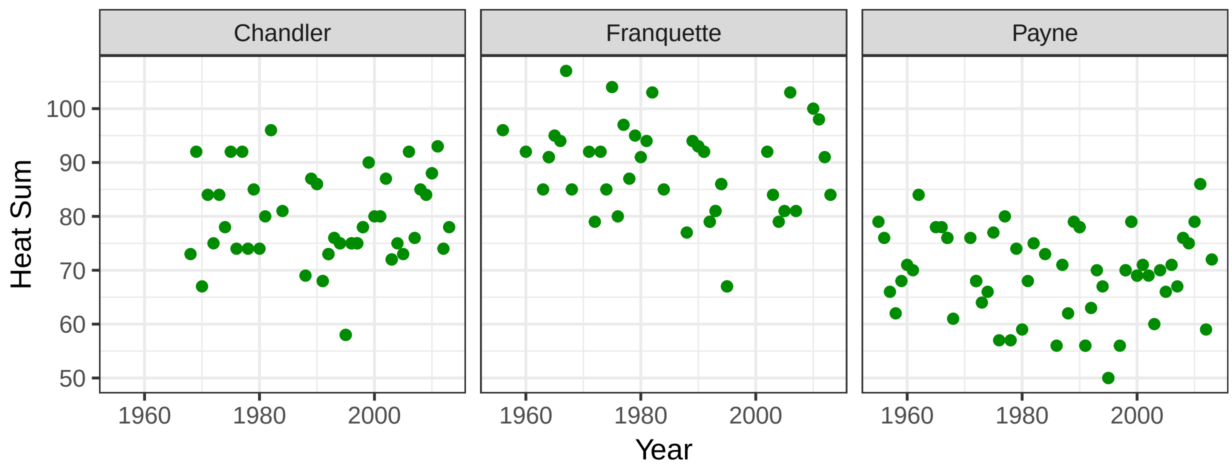

Figure 11: Changes in walnut heat sums over the past 60 years in Davis, California.

regression (p=0.15). In other words, no changes in chill or heat accumulation were detected that would adequately explain the later leaf-out trends since 1990.

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Fall Phenology

Almonds

Harvest dates were not available for Modesto almonds, so this section will only contain data from Chico. Mean almond season lengths appear to have decreased by varying degrees based on cultivars (Figure 23). However because the time series are so short, it is unclear whether these trends will continue into the future.

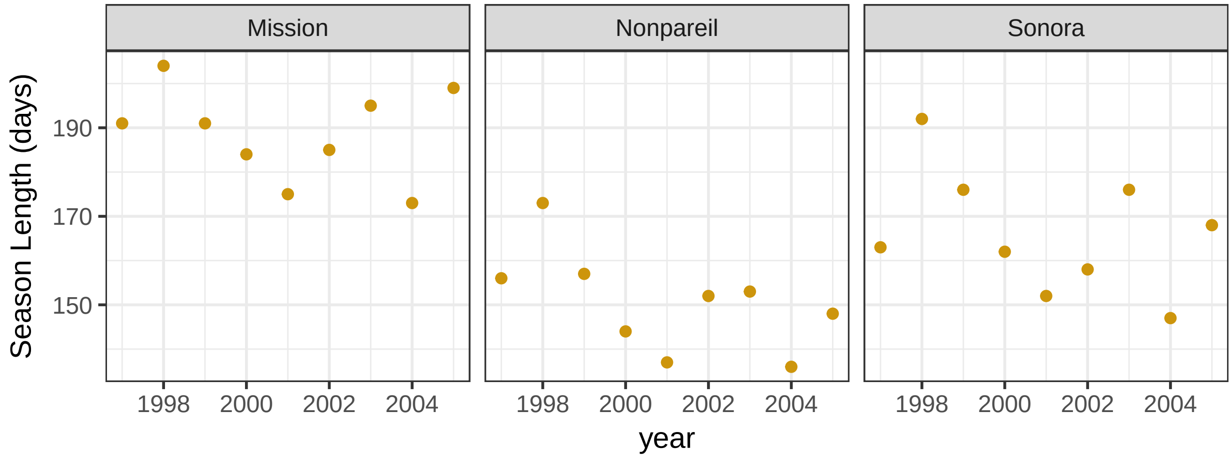

Figure 12: Almond season lengths over 10 years in Chico, California.

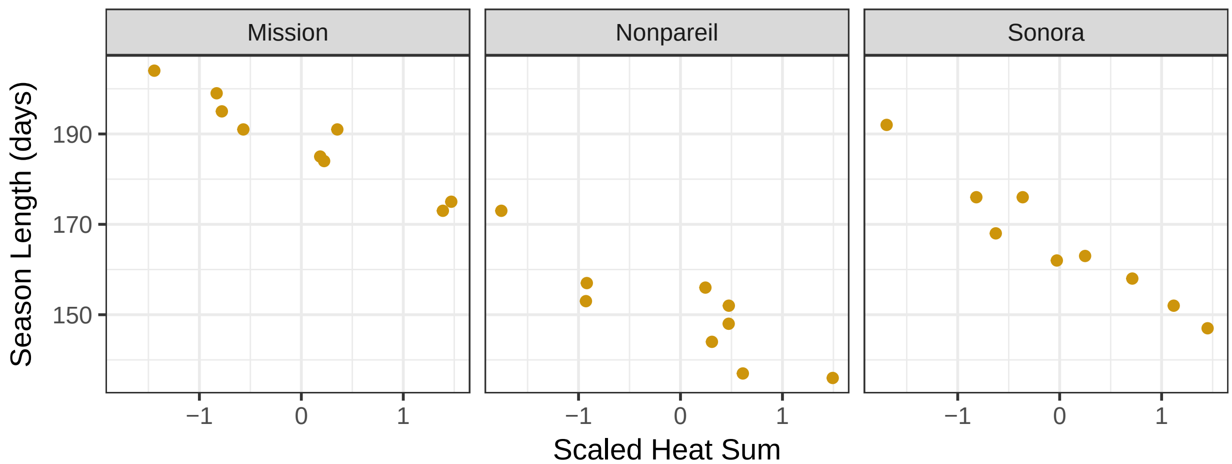

Figure 13: Almond season length by heat sum in Chico, California.

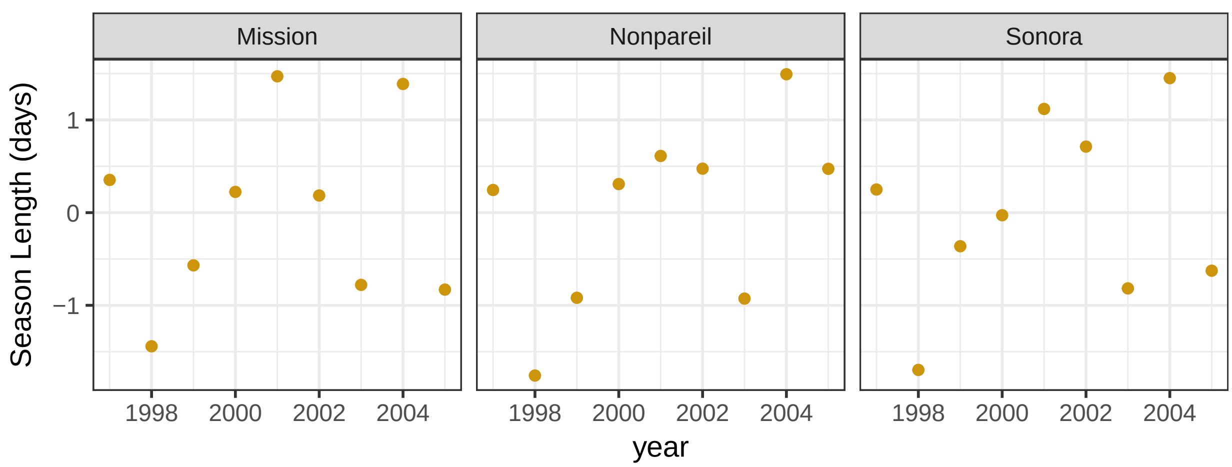

Figure 14: Almond heat sums over 10 years in Chico, California.

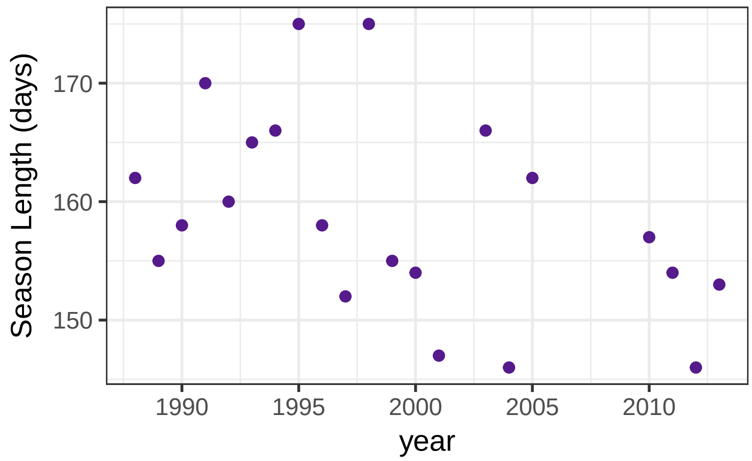

Figure 15: Prune season lengths over 25 years in Parlier, California.

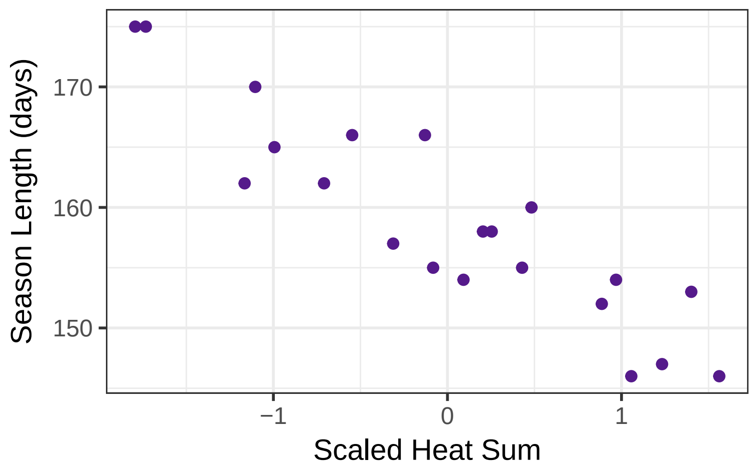

Figure 16: Prune season lengths by heat sum in Parlier, CA.

Prunes

French Prune season lengths in Parlier shortened by an average of 0.49 days per year over the past 25 years (Figure 41). Improved French prune season length was significantly correlated with average maximum May temperatures (Figure 42, Table 13). In addition, prune season length responded very strongly to fruit development thermal time accumulation calculated using both models (Figure 43, Table 14).

Fruit development thermal time accumulation values for French prunes in Parlier exhibit increasing trends using both models (Figure 44, Table 14). However, there is too much variation in the data to make any strong conclusions. Given the trends present in the monthly data though, it is likely that spring thermal accumulation values will continue to increase. Conversely the mean maximum May temperatures appear to be decreasing slightly (Table 12), which would indicate that prune season lengths will get longer based on the model in Figure 30. However, given that the thermal time accumulation model is more biologically accurate, it is likely to be more reliable. In this case, using monthly temperatures as an indicator of season length is misleading.

Given the trend of increasing fruit development thermal time accumulation in Parlier (Figure 44), Improved French prune season lengths will most likely continue to shrink with increasing climate change.

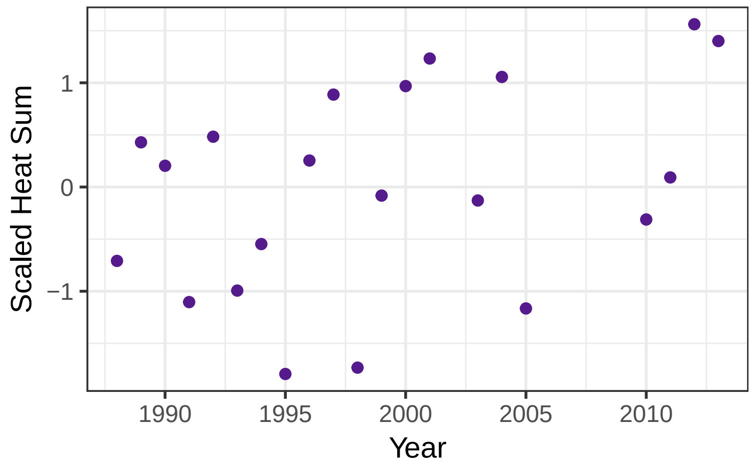

Figure 17: Prune heat sum over 25 years in Parlier, CA.

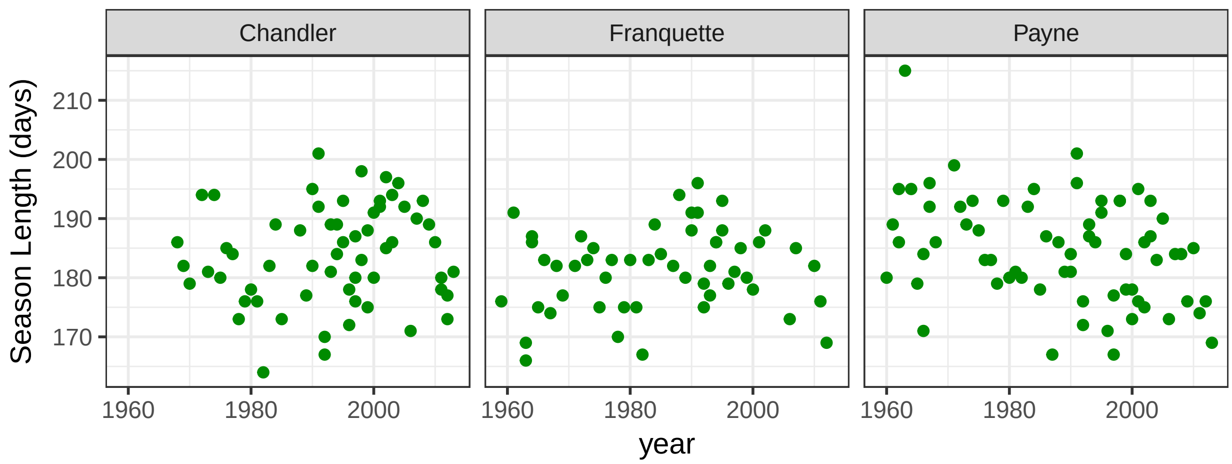

Figure 18: Walnut season lengths over the past 60 years for Chandler, Franquette and Payne Cultivars.

Walnuts

Mean season length in Payne walnuts decreased significantly over the past 50 years (Figure 58). Chandler and Franquette season lengths seem to have stayed fairly stable. However, because of the variability in the data, it is possible that a longer time series will exhibit a significant trend. This is particularly relevant for Chandler walnuts, as they were only developed in the last 50 years.

Payne is the only walnut cultivar whose mean season length shows significant change (decrease) over the past 60 years (Figure 58). Payne season length also responded to warmer April and May temperatures (Figure 59). As monthly minimum temperatures are increasing for both April and May in Davis (Table 16), it very likely that the season length of Payne walnuts will continue to get shorter over time. Additionally, Payne season length responded strongly to fruit development thermal time accumulation during the first two months after leaf-out (Figure 60, Table 19). The fact that Payne thermal time accumulation has been increasing over the past half-century is further evidence that mean season length for Payne walnuts will shorten with increasing climate change (Figure 61, Table 19).

While Chandler season length does not show a significant trend over time it does exhibit a complex response to monthly temperatures (Figure 62). Warmer temperatures in March lead to shorter seasons, while warmer temperatures in April and May correlate with longer ones. Because March, April, and May all show warming trends in Davis (Table 16), we cannot yet tell how climate change will effect Chandler season length based on

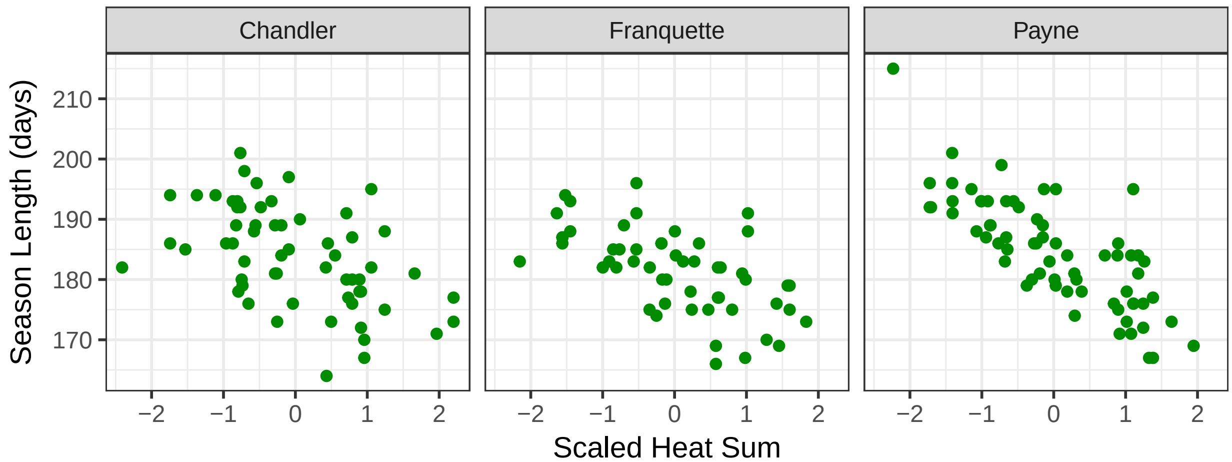

Figure 19: Heat sum correlation with walnut season lengths over the past 60 years in Davis.

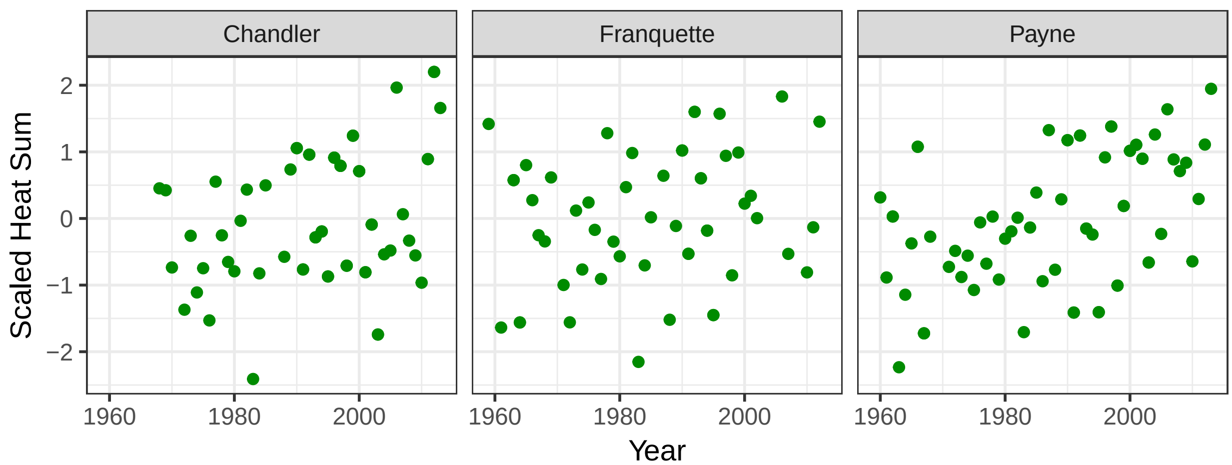

Figure 20: Walnut heat sums over the past 60 years.

monthly temperatures.

Chandler season length responds strongly to thermal time accumulation in the first thirty days after leaf-out as well (Figure 63). The trends in thermal accumulation in both models indicate that it is likely that Chandler season lengths will get shorter, even though a significant trend has not yet been detected (Figure 63-64, Table 19). It is unclear biologically why warmer temperatures in April correlate with longer season lengths, while fruit development thermal time accumulation in parts of March and April correlate with shorter season length (Figure 62-63). It may be that the correlation between April temperatures and season length is spurious.

While Franquette mean season length did not significantly correlate with mean temperatures from any month, it did respond to thermal time accumulation during the first 37 days after leaf-out (Figure 65, Table 19). As fruit development thermal time accumulation (calculated using the simplified model), is increasing (Figure 66, Table 19), we would expect that mean season length for Franquette walnuts will decrease as the climate warms. However, due to the amount of noise in the data, it may take a while before this trend becomes clear.

Conclusions

Climate

The climate of California has not changed uniformly across the state. Modesto, Parlier, and Davis have all experienced increases in minimum annual temperatures, but the trends in their annual maximum temperatures diverge. Modesto maximum temperatures are warming, though not as quickly as the minimum temperatures. In Davis, maximum temperatures are relatively stable, and in Parlier, annual highs are actually decreasing. Additionally, both minimum and maximum temperatures in Chico are fairly stable.

Spring Phenology

Almond

No changes were found in the timing of bloom, nor monthly or total chill accumulation for Chico or Modesto. The only change seen was in the timing of meeting the heat requirement for Sonora and Nonpareil, the two earlier blooming cultivars, in Modesto (the warmer location) and for Nonpareil in Chico.

It is not surprising that in Chico, where we found no change in minimum temperatures, there would be no change in chill accumulation or bloom timing. The earlier satisfaction of the heat requirement for Nonpareil in Chico is in keeping with the increased maximum temperatures in December, January and February in Chico. It is, however, difficult to explain why this was not reflected in the timing of meeting the heat requirement for the other two cultivars.

Mean monthly minimum and maximum temperatures increased every month in Modesto. It is more difficult to explain why no change was seen in bloom timing or chill accumulation in Modesto given these changes in temperature. The lack of change in chill accumulation was mirrored in the lack of change in the timing of the chill requirement being met. The increased temperatures were reflected in the earlier meeting of the heat requirement in the Nonpareil and Sonora cultivars. This may not yet have translated into a change in the timing of bloom due to the connection between chill and heat accumulation necessary for bloom.

Prune

Bloom was found to be coming later for prunes in Parlier since 1988. Chill accumulation was found to be increasing over time for January, February and winter as a whole. This is discordant with the finding of increased mean monthly minimum temperatures in November, January, February and March, unless increased temperatures have raised some temperatures into the range giving the most chill value - between 6°-8°C (43°-47°F). Despite this change in chill accumulation, no change was found in the timing of the chill and heat requirements being met. With increased winter chill accumulation and no change in heat accumulation, one would expect bloom to be coming earlier on average, not later. More research is needed to attempt to explain if and how the change in bloom timing is related to changing temperature.

Walnut

For walnuts in Davis, leaf-out, our marker of spring phenology, was detected as coming later for all three cultivars since 1988. No change was found for chill accumulation in November or December, however a potential increase in chill accumulation was detected towards the end of the century for January (since 1970) and February (1988). This change in chill accumulation does not synch with the lack of finding of significant change in minimum temperature in those months. It does, however, correspond with a finding of the chill requirement for Payne walnuts being met earlier. However, it is confusing that this was not also the finding regarding the timing of meeting the chill requirement for Chandler or Franquette. Furthermore, it is difficult to explain, in light of the increase in chill, why leaf-out has coming later in recent decades. With increased chill accumulation, one would expect leaf-out to come earlier with an earlier satisfaction of the chill requirement. More research is needed to attempt to explain if and how the change in leaf-out timing is related to changing temperature.

In short, while there is a clear signal of changing timing of spring phenology in prunes and walnuts, it is not clear if and how temperature is affecting that change.

Fall Phenology

Almonds

Given the length of the almond season length time series, we cannot draw any strong conclusions. However, if things continue as they have been over the ten years examined, Mission almond season lengths may potentially continue to shorten.

Prunes

French prune season lengths have gotten, on average, 12 days shorter since 1988. The trends in the May monthly temperatures (Table 7) and the relationship between the thermal time accumulation and season length (Figure 31) both point to a continuation of this trend with continued warming due to climate change.

Walnuts

Payne walnut season lengths have shortened by approximately 11 days since 1960. Based on the upwards trends in the thermal time accumulation (Figure 49) as well as April and May temperatures (Table 9), Payne season lengths will continue to get shorter as climate change intensifies. Chandler season lengths have not changed appreciably over the past 50 years. However, the increasing thermal time accumulation (Figure 52) indicates that season lengths will shorten in the future. Franquette season length shows a similar pattern to Chandler season length. It has yet to exhibit any trend, but the increasing trend in thermal accumulation for Franquette walnuts indicate that it is likely Franquette season lengths will get shorter in the future (Figure 54).

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