Historic Effects of Climate Change on Tree Crop Phenology in California

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Notes

** Thesis: Temperature increases due to climate change vary by region in California. By looking at tree response to interannual temperature variation we can explain past phenological trends and predict future ones. **

- 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 many already have 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).

However, it is not enough to just look at the predictors of flowering and harvest dates when assessing climate risk. It is also necessary to compare these predictors to actually flowering and harvest dates, and investigate changes to these dates over time.

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.

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.

This paper documents temperature changes in California over the past century and relates those changes to changes in almond, prune and walnut phenology in the Central Valley. Realized temperature increases due to climate change vary by region in California. By looking at tree response to interannual temperature variation, we can explain past phenological trends and predict future ones.

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 the early 1900s, and CIMIS provided hourly data back to 1983. A number of 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. 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.

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.

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 and harvest records came from the University of California (UC) Regional Almond Variety Trial (RAVT). 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. We report data for cultivars 'Sonora', 'Nonpareil', and 'Mission' which represent the range of bloom timing in commercially cultivated almonds. Prune bloom and harvest timing data was recorded by the University of California Prune Breeding, provided by current breeder Sarah Castro. Because the 'Improved French' cultivar makes up almost all of the prune acreage in California, it is the only prune cultivar analyzed. We used walnut

Table 1: Table 1. NCDC and CIMIS weather station information by orchard location.

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

phenology data from the University of California at Davis Walnut Breeding Program. Leaf out dates (LD) and Harvest readiness dates (HRD) were collected by Charles Leslie, Gale McGranahan and the members of the Walnut Improvement Program. The cultivars 'Chandler', 'Payne', and 'Franquette' were chosen as cultivars that both span the range of flowering and harvest dates as well as having long data records (>30 years).

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.

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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In Davis, annual minimum temperatures have risen an average of 0.21°C per decade over the past 80 years

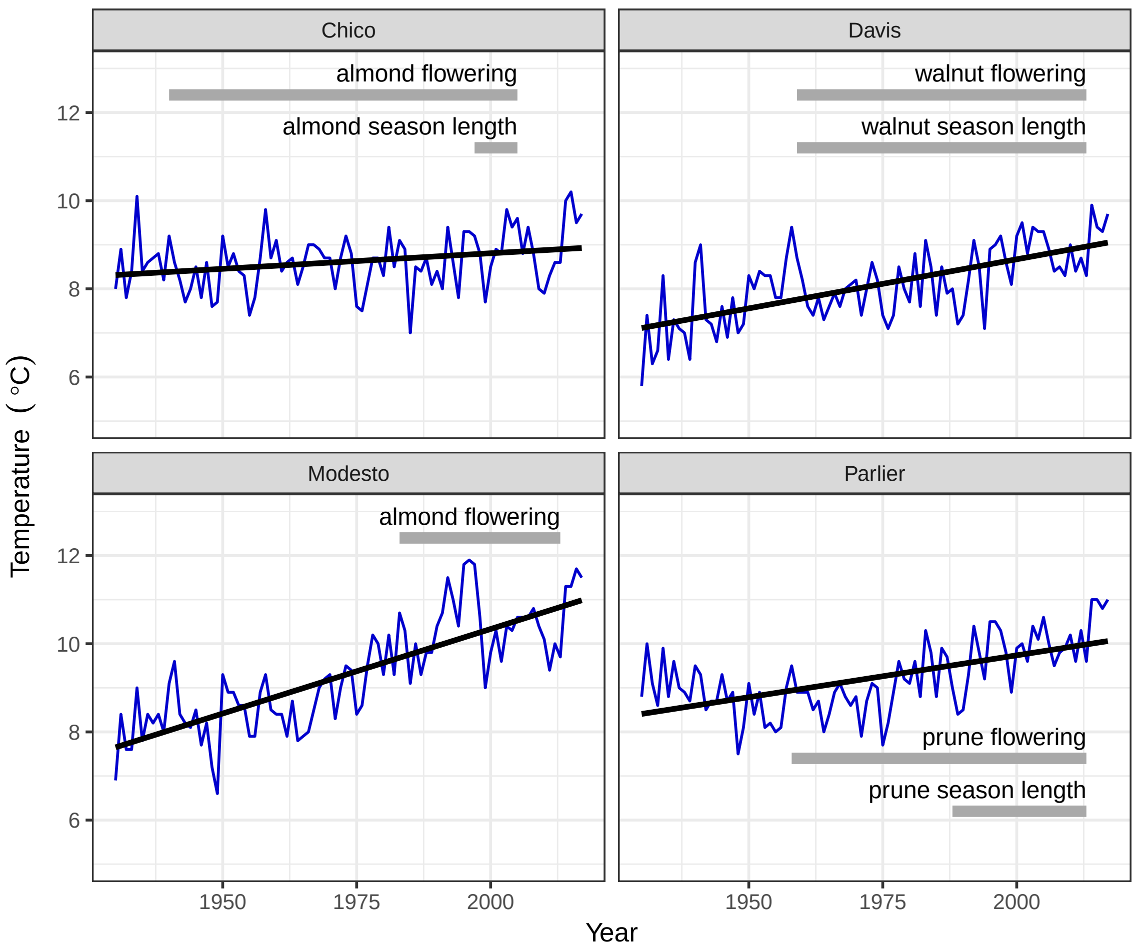

Figure 1: Mean Annual Minimum Temperatures from 1930 to 2017, duration of phenology record shown with grey lines.

Table 2: Average change per decade of Chico 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	0.11	0.19	\textbf{0.31}	\textbf{0.00032}	\textbf{0.24}	\textbf{0.00054}
February	0.11	0.18	\textbf{0.26}	\textbf{0.0014}	\textbf{0.2}	\textbf{0.0016}
March	\textbf{0.14}	\textbf{0.025}	\textbf{0.19}	\textbf{0.048}	\textbf{0.17}	\textbf{0.014}
April	0.053	0.28	0.065	0.55	0.062	0.39
May	\textbf{0.14}	\textbf{0.01}	0.041	0.67	0.09	0.19
June	\textbf{0.11}	\textbf{0.019}	-0.024	0.77	0.041	0.49
July	-0.014	0.78	\textbf{-0.17}	\textbf{0.009}	\textbf{-0.11}	\textbf{0.044}
August	0.036	0.46	-0.13	0.063	-0.052	0.32
September	0.023	0.65	-0.0067	0.93	0.0079	0.88
October	-0.018	0.73	0.12	0.16	0.047	0.38
November	0.11	0.12	0.014	0.87	0.064	0.23
December	-0.015	0.86	\textbf{0.2}	\textbf{0.017}	0.096	0.11
Annual	0.052	0.055	0.043	0.17	0.04	0.088

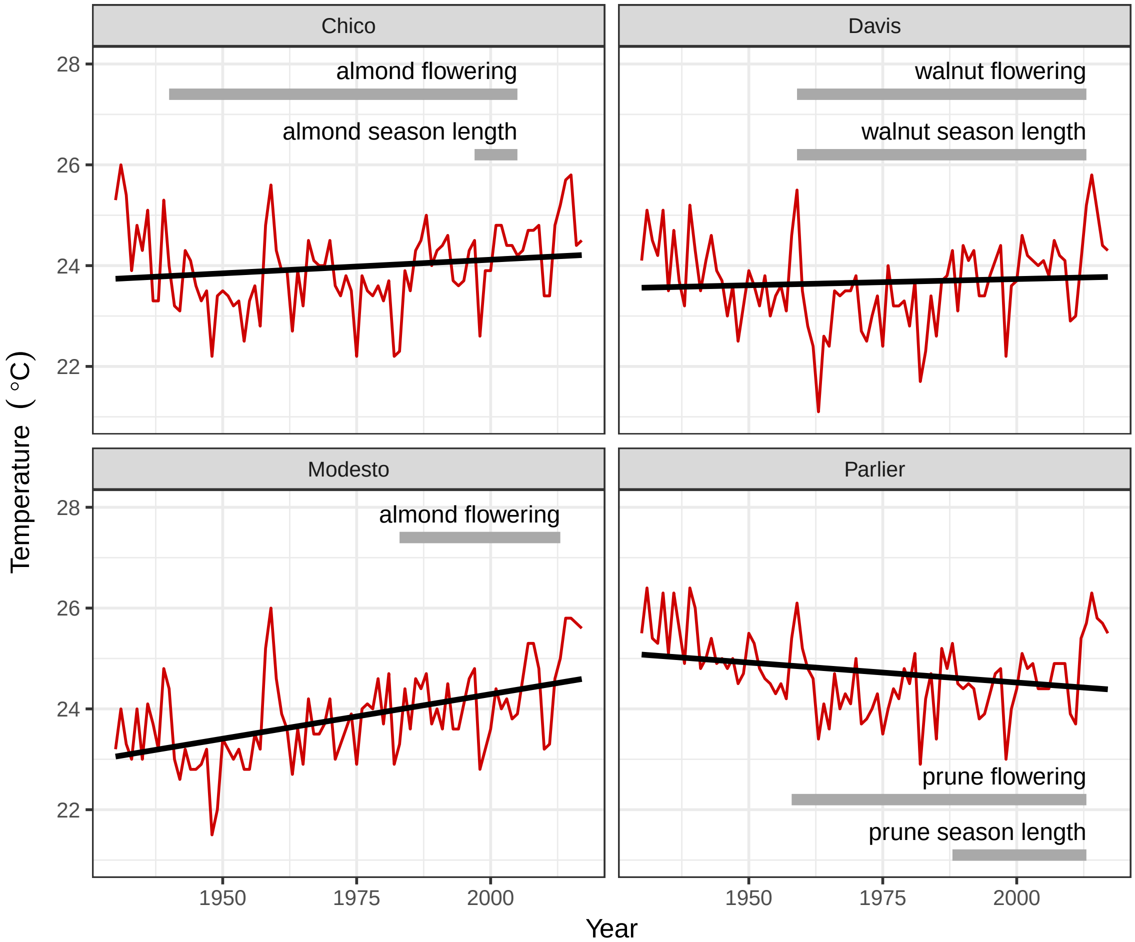

Figure 2: Mean Annual Minimum Temperatures from 1930 to 2017, duration of phenology record shown with grey lines.

Table 3: 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	\textbf{0.19}	\textbf{0.028}	\textbf{0.3}	\textbf{0.00027}	\textbf{0.26}	\textbf{7e-04}
February	\textbf{0.26}	\textbf{0.0024}	\textbf{0.27}	\textbf{0.00015}	\textbf{0.26}	\textbf{0.00013}
March	\textbf{0.33}	\textbf{8.8e-06}	\textbf{0.27}	\textbf{0.0031}	\textbf{0.32}	\textbf{2.7e-05}
April	\textbf{0.22}	\textbf{4e-04}	0.13	0.18	\textbf{0.22}	\textbf{0.0026}
May	\textbf{0.36}	\textbf{9e-07}	\textbf{0.22}	\textbf{0.015}	\textbf{0.33}	\textbf{2.8e-05}
June	\textbf{0.39}	\textbf{8.3e-08}	\textbf{0.2}	\textbf{0.012}	\textbf{0.3}	\textbf{2.2e-05}
July	\textbf{0.39}	\textbf{3.5e-07}	0.073	0.21	\textbf{0.25}	\textbf{4.8e-05}
August	\textbf{0.5}	\textbf{7.4e-10}	\textbf{0.15}	\textbf{0.012}	\textbf{0.34}	\textbf{9.1e-08}
September	\textbf{0.36}	\textbf{1.2e-06}	\textbf{0.17}	\textbf{0.0051}	\textbf{0.3}	\textbf{1.6e-06}
October	\textbf{0.3}	\textbf{4.9e-05}	0.11	0.11	\textbf{0.22}	\textbf{0.00034}
November	\textbf{0.37}	\textbf{1.5e-05}	0.046	0.57	\textbf{0.22}	\textbf{0.00054}
December	0.15	0.077	0.14	0.074	\textbf{0.15}	\textbf{0.024}
Annual	\textbf{0.21}	\textbf{2.6e-05}	\textbf{0.11}	\textbf{0.0026}	\textbf{0.16}	\textbf{2.5e-05}

Table 4: 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	0.14	0.11	0.16	0.058	**0.17**	**0.012**
February	**0.16**	**0.041**	**0.13**	**0.037**	**0.15**	**0.009**
March	**0.27**	**3.2e-05**	0.13	0.16	**0.19**	**3.8e-03**
April	**0.19**	**6.1e-04**	-0.016	0.87	0.11	0.12
May	**0.29**	**5.1e-06**	0.086	0.36	**0.2**	**5.8e-03**
June	**0.24**	**2.6e-06**	0.078	0.29	**0.15**	**6.1e-03**
July	**0.22**	**9.7e-06**	-0.12	0.064	0.032	0.5
August	**0.24**	**1.5e-06**	-0.062	0.31	**0.089**	**0.034**
September	**0.17**	**1.4e-03**	0.0085	0.9	0.091	0.067
October	**0.19**	**5.4e-04**	0.039	0.64	**0.13**	**0.018**
November	**0.23**	**1.2e-03**	-0.09	0.31	0.074	0.18
December	0.061	0.49	0.056	0.49	0.053	0.4
Annual	**0.16**	**1e-05**	0.019	0.55	**0.078**	**4.4e-03**

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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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).

Almonds

Mean almond season lengths appear to have decreased by varying degrees based on cultivars (Figure 3). However because the time series are so short, it is unclear whether these trends will continue into the future. Almond season lengths respond fairly strongly to

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).

Table 5: 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	**0.18**	**0.025**	0.019	0.82	0.13	0.057
February	**0.19**	**0.013**	0.043	0.48	**0.12**	**0.03**
March	**0.24**	**3.2e-04**	0.069	0.43	**0.16**	**0.019**
April	0.091	0.082	-0.15	0.12	-0.014	0.84
May	**0.25**	**6.2e-05**	-0.075	0.35	0.098	0.13
June	**0.24**	**2.6e-05**	0.037	0.59	**0.14**	**0.013**
July	**0.22**	**2.2e-04**	**-0.11**	**0.043**	0.046	0.33
August	**0.23**	**4.7e-05**	-0.063	0.27	0.075	0.12
September	**0.2**	**5.2e-04**	-0.046	0.44	0.078	0.12
October	0.092	0.15	**-0.16**	**0.022**	-0.024	0.67
November	0.096	0.12	**-0.24**	**5.5e-03**	-0.059	0.28
December	-0.035	0.65	-0.11	0.18	-0.075	0.22
Annual	**0.11**	**4.3e-04**	-0.033	0.25	0.037	0.12

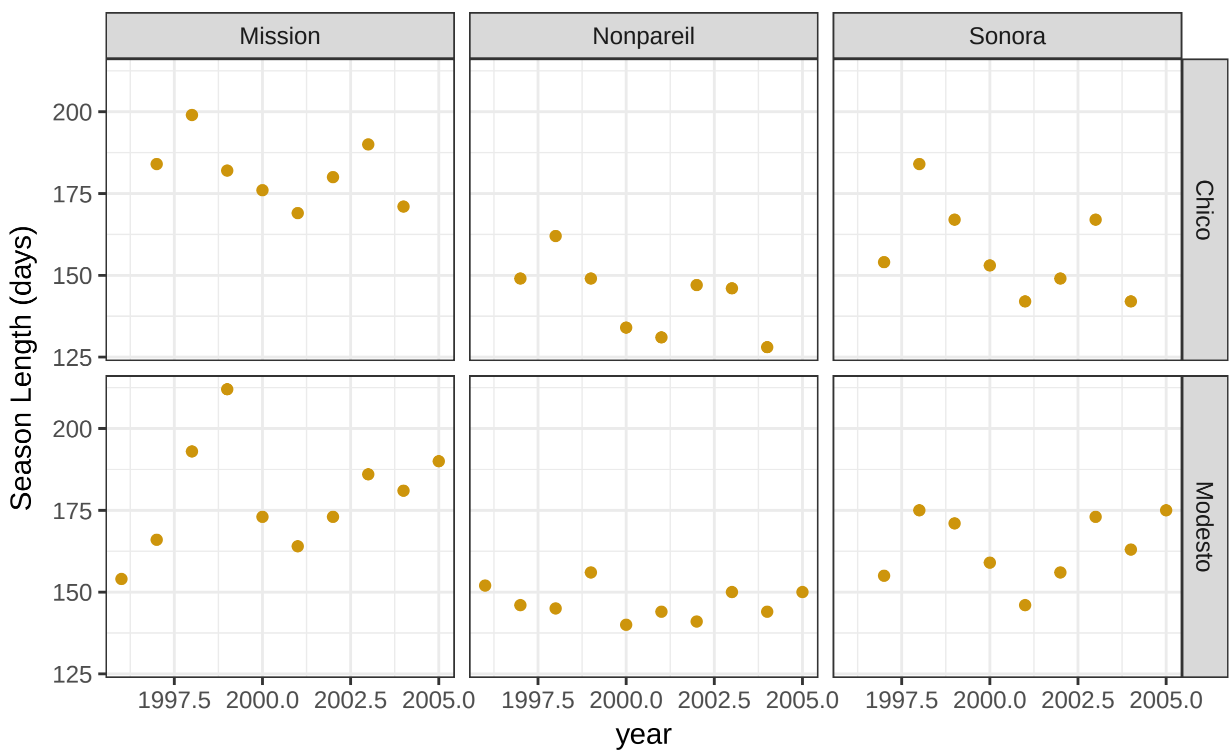

Figure 3: Almond season lengths over 10 years in Chico, California.

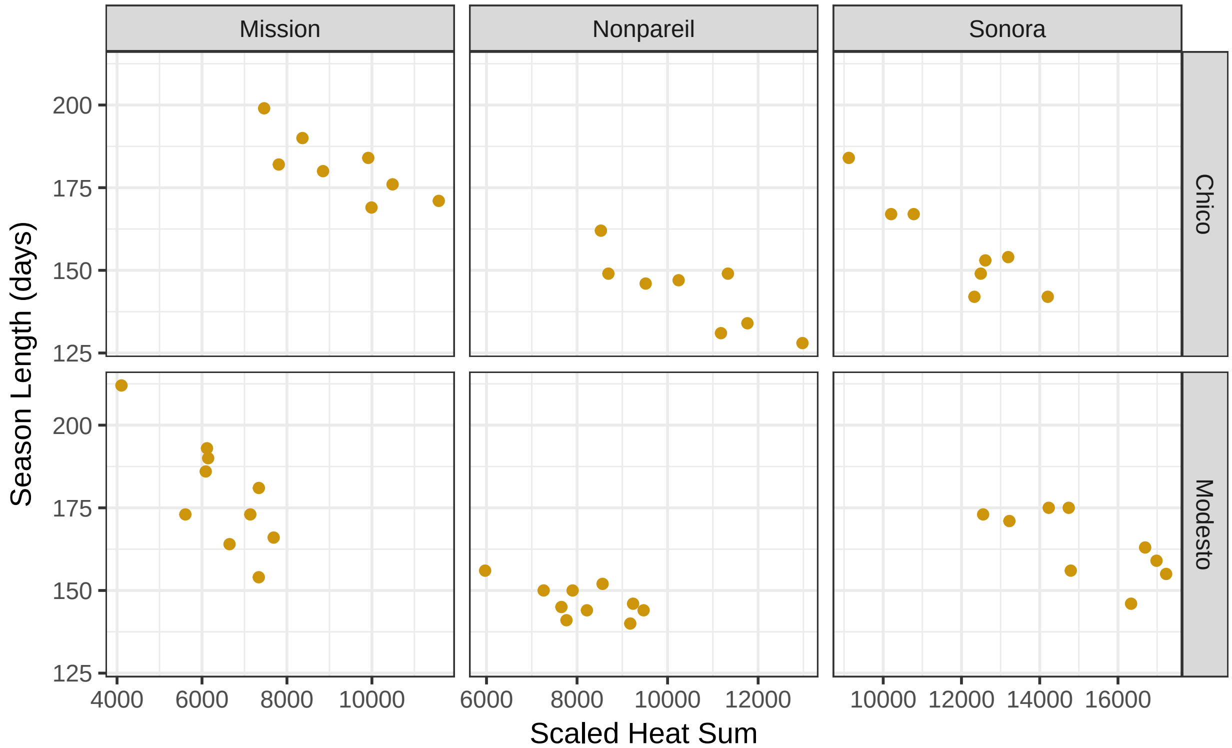

Figure 4: Almond season length by heat sum in Chico, California.

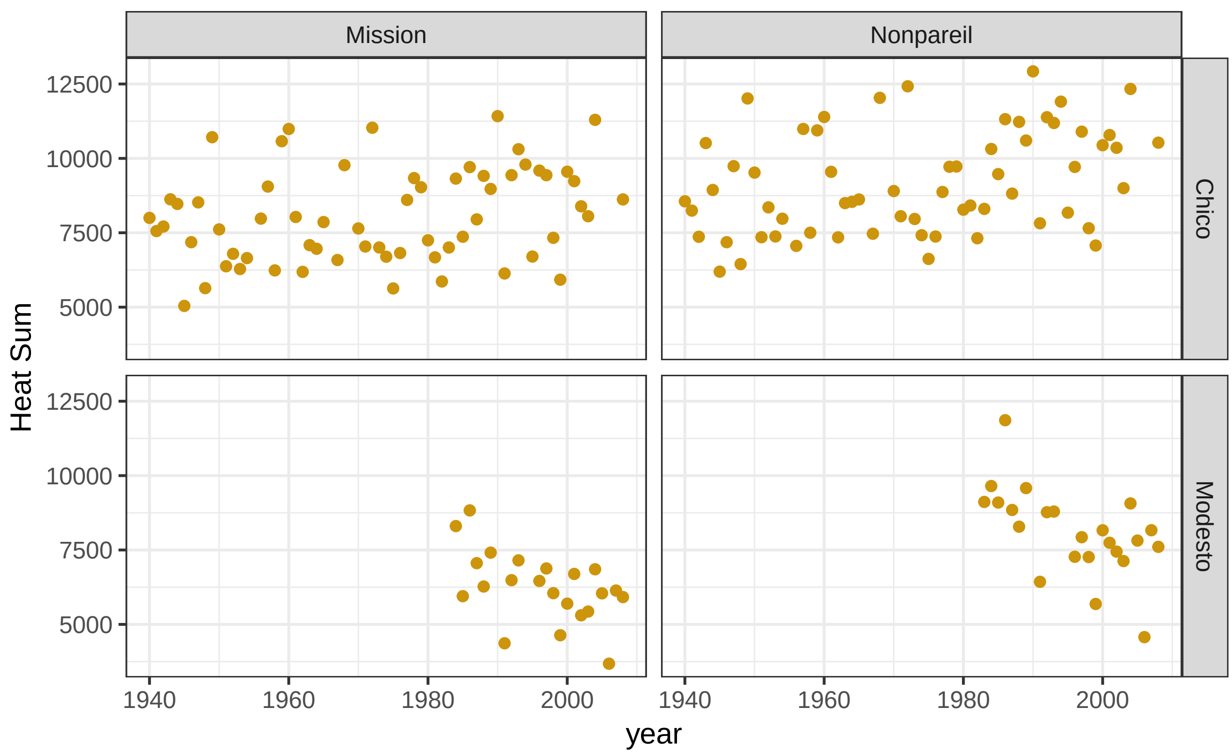

Figure 5: Almond heat sums over 80 years in Chico and Modesto, California.

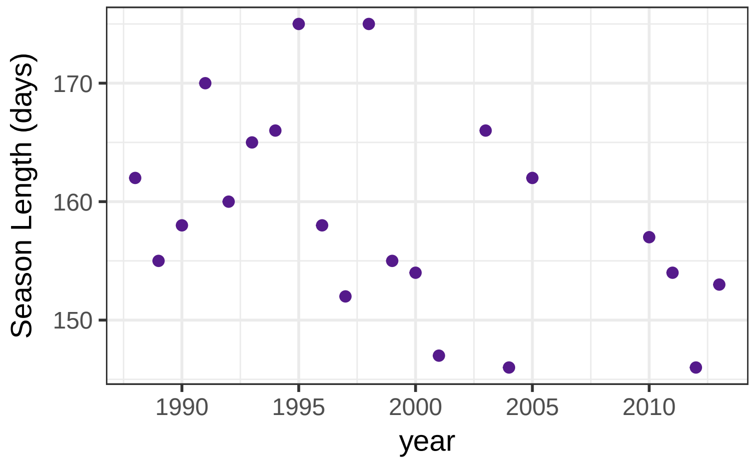

Figure 6: Prune season lengths over 25 years in Parlier, California.

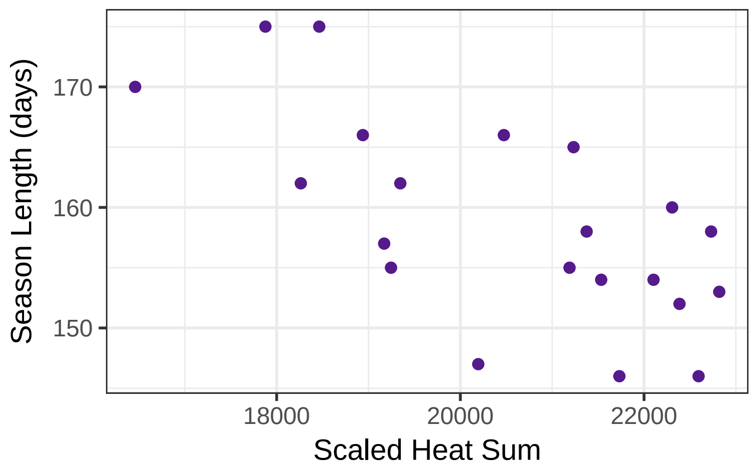

Figure 7: Prune season lengths by heat sum in Parlier, CA.

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.

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.

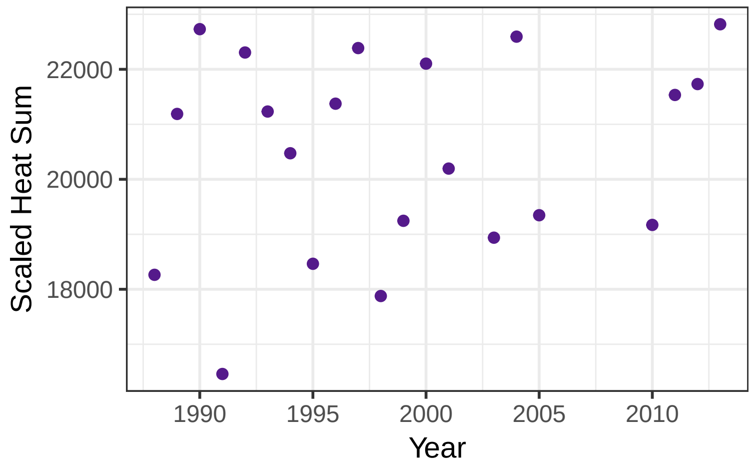

Figure 8: Prune heat sum over 25 years in Parlier, CA.

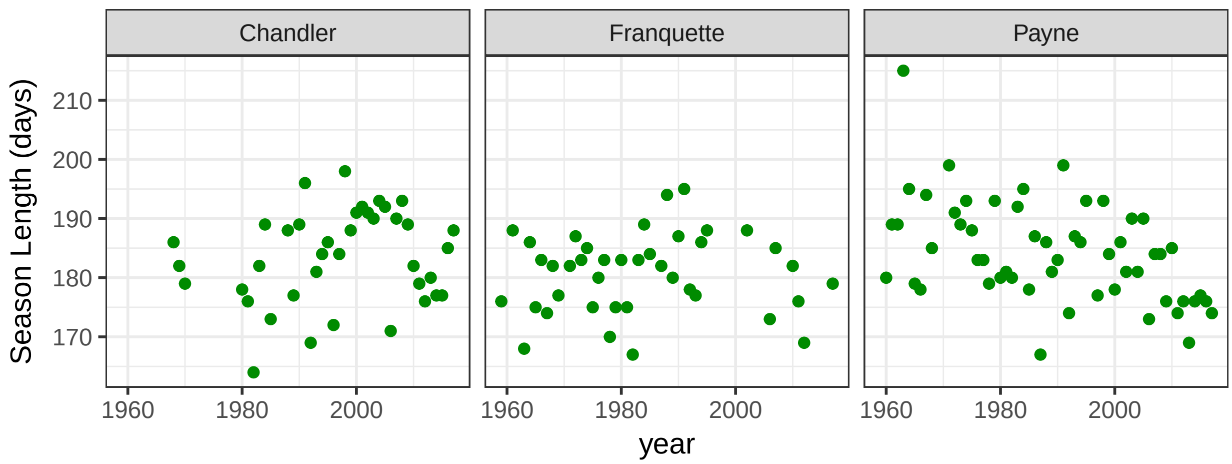

Figure 9: Walnut season lengths over the past 60 years for Chandler, Franquette and Payne Cultivars.

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 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

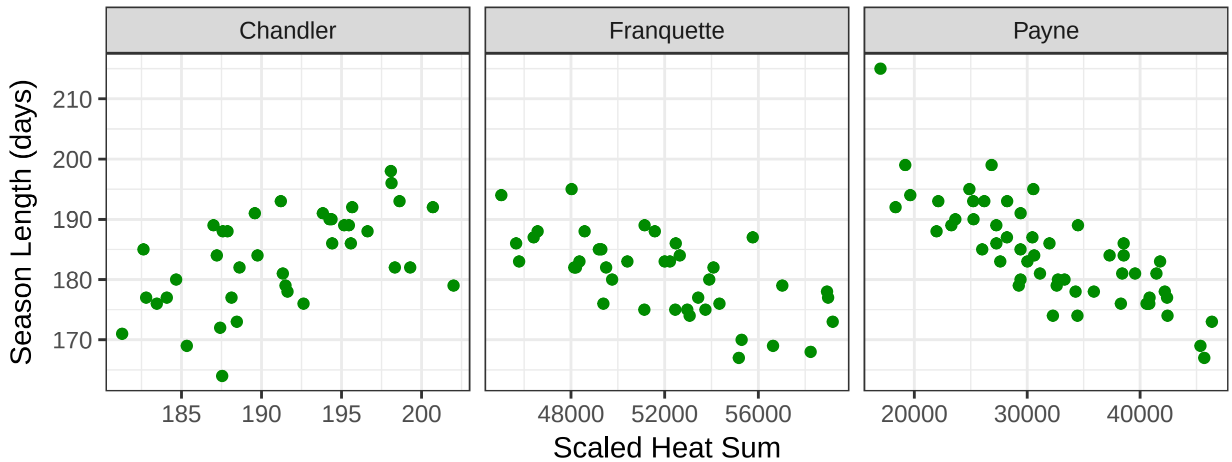

Figure 10: Heat sum correlation with walnut season lengths over the past 60 years in Davis.

(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

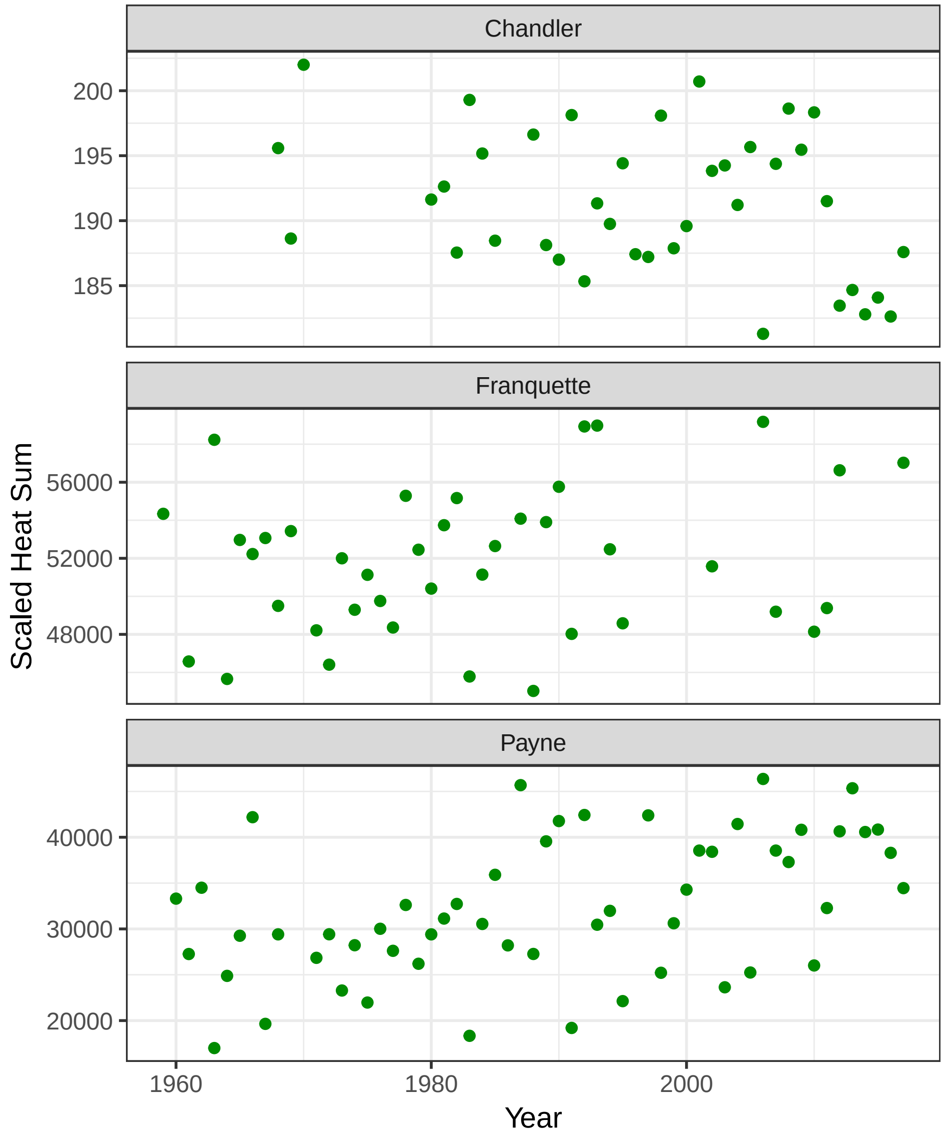

Figure 11: Walnut heat sums over the past 80 years.

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).

References

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