Effects of Climate Change on Tree Crop Phenology in California

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Introduction

In this report we evaluate the effects of recent climate change on crop tree phenology in selected fruit and nut growing regions of California. Phenology refers to timing of developmental stages in plants and animals. In perennial plants, many of these stages occur every year and include phenomena such as the emergence of leaves, flowering, and maturation of fruits.

We first provide some general background on the effects of temperature on the phenology of tree crops. We then describe observed trends in temperature in the California Central Valley over the past decades. This is followed by three sections, each focusing on one of the following tree crops, almonds, prunes (dried European plum), and walnuts. Within each section, we first look at the long term temperature trends for the locations under consideration. Then we investigate temporal trends in flowering or leaf-out, as well as climate metrics that might affect flowering and leaf out. Then we investigate temporal trends in season length as well as climate metrics that might affect season length. For both flowering and season length we assess whether climate variation explains variation in phenology and wither future warming should be expected to influence tree crop development.

Temperature and phenology data are from four sites in the Central Valley of California: Chico, Davis, Manteca-Modesto, and Parlier.

Tree Crop Phenology

Spring Phenology: flowering and leaf-out

Many plants, including temperate tree crops, have mechanisms to ensure that leaf growth or flowering starts when conditions are favorable. Ideally, flowering should happen as early as possible after winter conditions (cold and wet) are generally diminishing. This ensures the longest possible growing season, optimizing resource use and yield. The two main mechanisms to ensure this timing are referred to as the "chill requirement"" (or vernalization) and the "heat requirement". Another mechanism commonly found in plants is daylength sensitivity (photoperiodism), but it is not considered to be an important mechanism in California tree crops.

The chill requirement is the amount of cold (low temperatures for a certain amount of time) a plant must experience before its flower or leaf buds will open. Typically, these temperatures need to be below 7°C (45°F) but not below 0°C 32°F). This mechanism helps ensure that the plant does not flower during a warm spell in the middle of winter. If the plant only gets the bare minimum amount of chill necessary for flowering (100% of chill requirement), bloom will still occur, but may be late, straggled and prolonged, resulting in decreased yield and production problems for farmers, such as needing to harvest an orchard multiple times because later bloomed flowers resulted in later-maturing nuts, or having fruit at slightly different stages of development vulnerable to pest attacks at different times. The agronomic chill requirement is a metric developed for this report to confront this issue of orchard trees needing more than 100% of their chilling requirement for prime production. It is approximately 150% of the chill requirement, and is meant to estimate the amount of chill needed for bloom that will not create production problems for farmers.

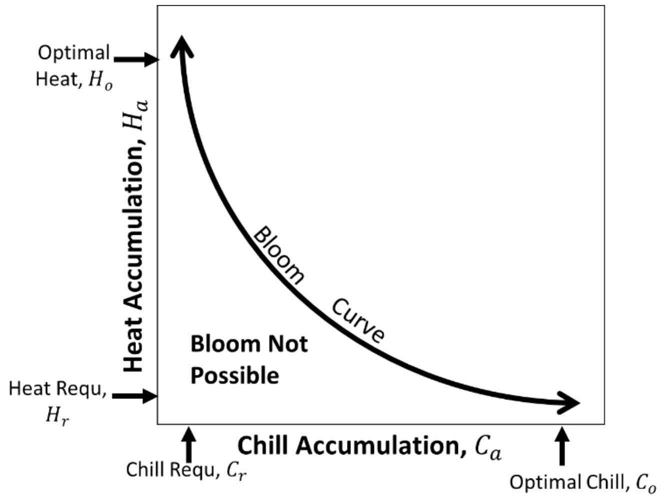

Figure 1: Figure 1. Chill and Heat Accumulation Curve

Many plants, including almonds, prunes and walnuts, also have a heat requirement: they need to experience warm temperatures over a certain amount of time before they start to flower. This ensures that the cold season is over when flowering starts. The amount of chill and/or heat required varies strongly between species and cultivar.

Heat and chill requirements are typically expressed in thermal time accumulation. In its simplest form, thermal time is the number of degrees below (for chill accumulation) a certain threshold (base) temperature that an organism experiences in a day or other unit of time. For example, if a plant with a base temperature of 50°F was in a greenhouse that was at 40°F, it would accumulate 10 degree days of chill accumulation over a one day period (40°F x 1 day = 10 degree days). Heat accumulation works the same way, except instead of counting the degrees below a threshold temperature a plant experiences, you count the degrees above a threshold temperature.

The total chill or heat accumulation is computed by summing all of the daily or hourly thermal time. Thermal time has units of °d (degree-days) or °h (degree-hours). When the necessary amount of chill and heat have accumulated the plant buds open. The phenology of plants that have both chill and heat requirements, including those investigated here, is complex because these two mechanisms depend on one another. As temperatures have warmed globally and chilling requirements in particular have become an area of increasing concern, this interdependence between chill and heat accumulation has been gaining attention and research. This report interprets and applies the current understanding of these requirements and relationships, but this understanding will continue to develop as research continues and our global and local climate changes. The amount of chill and heat accumulation necessary for bloom or leaf-out in a given year is not fixed (Figure 1).

Because winter chill and spring heat work together to determine the timing of spring phenological events, warming can, in principle, lead to either an earlier onset or a delay in flowering. There is a bare minimum amount of winter chill that trees must experience to bloom (Fig 1, 'Chill Requ'). If tree buds only experience that minimum, they must be exposed to warm conditions for longer to bloom or leaf-out ('Optimal Heat'). There is an optimal amount of chill accumulation ('Optimal Chill') that, when experienced by the trees, subsequently requires only brief exposure to warm temperatures ('Heat Requ') to trigger bloom.

The three crops studied, almond, prune and walnut, have different bud types. Almond and prune trees have vegetative buds that produce leaves and flower buds that produce flowers with both male and female parts. In both species, flowering occurs before vegetative bud break. Walnuts have male buds that produce pollen and mixed buds that produce leaves and then female flowers. In walnuts, leaf emergence precedes the opening of the female flowers (Ramos 1997).

Because of this difference in biology, different phenological stages were examined for almond and prune than

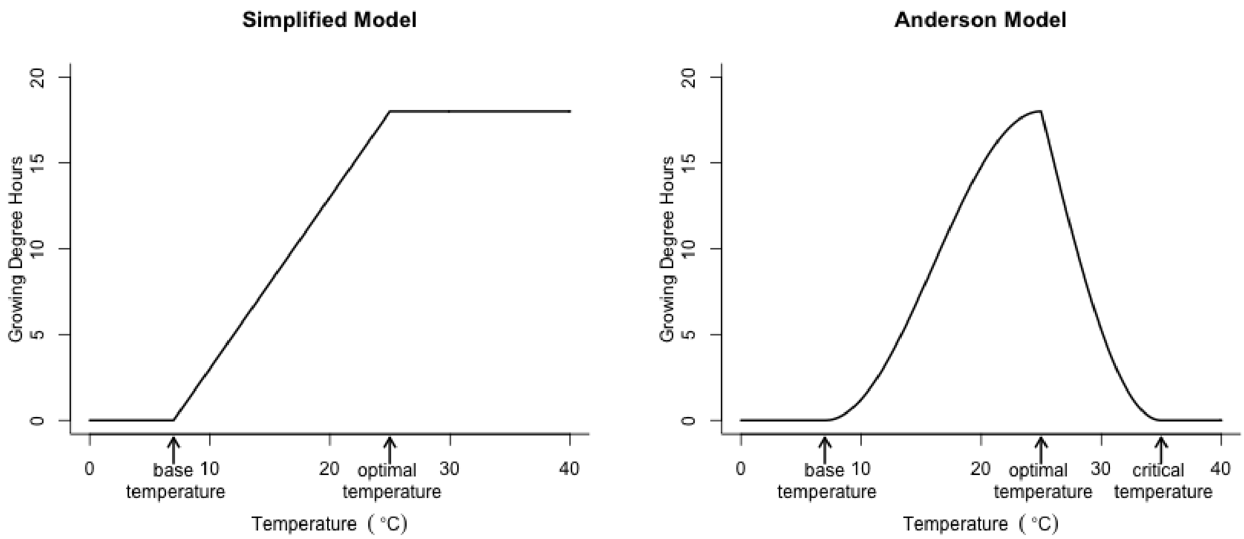

Figure 2: Figure 2. Models of thermal time for crop development

for walnut. For almonds and prune this was the onset of flowering, defined as when about 1% of the flowers have opened in the case of almond and 5-10% for prune. For walnut we used leaf-out, measured as 50% of mixed (vegetative and female flower parts) buds opening,as the spring phenological stage.

Fall Phenology: maturity and season length

Temperature can also influence how fast the fruits on a plant develop. As ambient temperatures rise, key chemical reactions (like photosynthesis) proceed more quickly. This causes the fruit or nut to develop more quickly. Like the chill and heat requirements, fruit development is measured in thermal time. When a fruit or nut has accumulated enough thermal time, it is ready to harvest (Fisher 1962). While in general warmer conditions mean faster development, temperatures that are too high can also slow development down. This is especially relevant in the Central Valley. If the weather is too hot, trees will divert energy from fruit development towards increasing respiration costs, and preventing or repairing heat damage. Thus, a fruit may develop more over a 3-day period where the average temperature was 25°C, than over a 7-day period where the average temperature was 10°C or over a 5-day period with an average temperature of 40°C.

The amount of fruit development thermal time a tree accumulates can be modeled using a number of different functions (Anderson and Kesner 1986; Marra et al. 2001). In this report, we investigate two: a three parameter model developed by Anderson and Kesner (1986) we refer to as the Anderson model, and two parameter model called the simplified model (Figure 2). In these models, the base temperature is the temperature at which the tree starts accumulating fruit development thermal time. The optimal temperature is the temperature at which the tree is accumulating thermal time at its maximum rate. At the critical temperature, the tree stops accumulating thermal time because it is too hot. Together, these temperatures are called the cardinal temperatures. The fact that the Anderson model has a critical temperature while the simplified model does not represents a fundamental difference in the assumptions of the two models. The simplified model assumes that while fruit development may slow or stop due to heat stress at some temperature, that critical temperature is above the range of temperatures the tree experiences. The Anderson model assumes that the tree does experience a meaningful slowing of fruit development at temperatures it encounters.

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)).

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

We used climate data 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). 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 (See Appendix). These stations are the closest stations to the monitored orchards that had at least 85% record completeness. Stations indicated with a "*" are the closest stations with reliable data records are be the primary source of data. Additional stations listed were to supplement information when data from the primary station was missing.

Location: Chico (Almonds)
- CIMIS
  - Durham*, CA: 1982 – 2014
- NCDC
  - Chico University Farm*, CA: 1906 – 2014
  - Oroville Municipal Airport, CA: 1998 – 2014
  - Orland, CA: 1903 – 2014

Location: Davis, CA (Walnuts)
- CIMIS
  - Davis*, CA: 1982 – 2014
- NCDC
  - Davis Experimental Farm*, CA: 1893 – 2014
  - Winters, CA: 1942 – 2014
  - Woodland, CA: 1911 – 2014

Location: Modesto, CA (Almonds)
- CIMIS
  - Manteca*, CA: 1987 – 2014
- NCDC
  - Modesto City Co Airport*, CA: 1906 – 2014
  - Stockton Metropolitan Airport: 1948 – 2014

Location: Parlier, CA (Prunes)
- CIMIS

Parlier*, CA: 1983 – 2014
NCDC
Visalia, CA: 1895 – 2014

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 1: 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

Variable	Model	Base Temp	Optimal Temp	Critical Temp
Heat	Anderson	4	25	36

Table 2: 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 3: 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

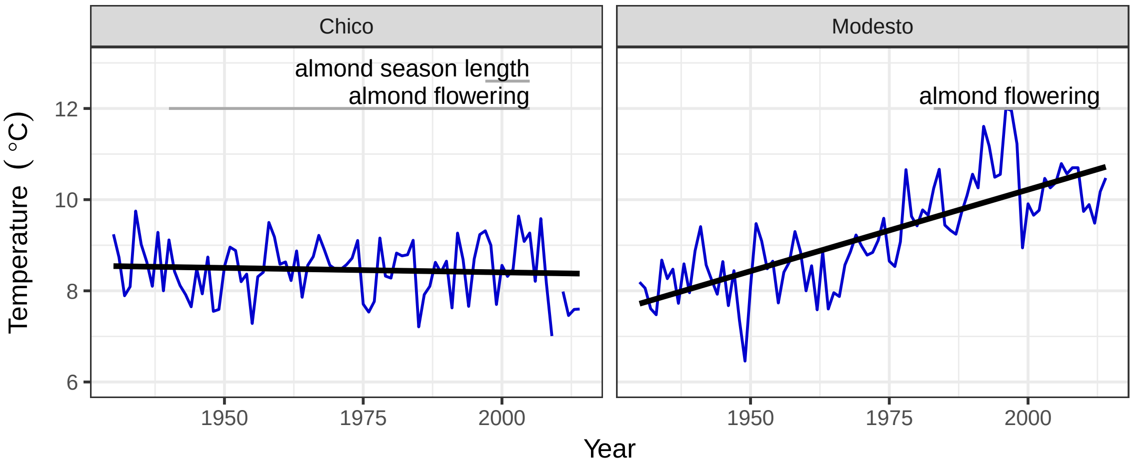

Figure 3: Figure 3. Mean Annual Minimum Temperatures from 1931 to 2014, duration of phenology record shown with grey lines.

Crop	Cultivar	Model	TTAL	Base Temp	Optimal Temp	Critical Temp	RMSE
		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

Almonds

Average temperatures, flowering and fruit development thermal time accumulation, spring bloom, and season length were analyzed for Chico, California. This is the location of 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. Additionally, average temperatures, thermal time metric accumulation, spring bloom and season length were analyzed for Modesto, California.

Temperature Context: Chico and Modesto

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 4, Figures 3-4). No monthly minimum temperatures in Chico exhibit any significant trends. However, January, February, and December monthly maximum temperatures show significant increasing trends (Table 4).

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).

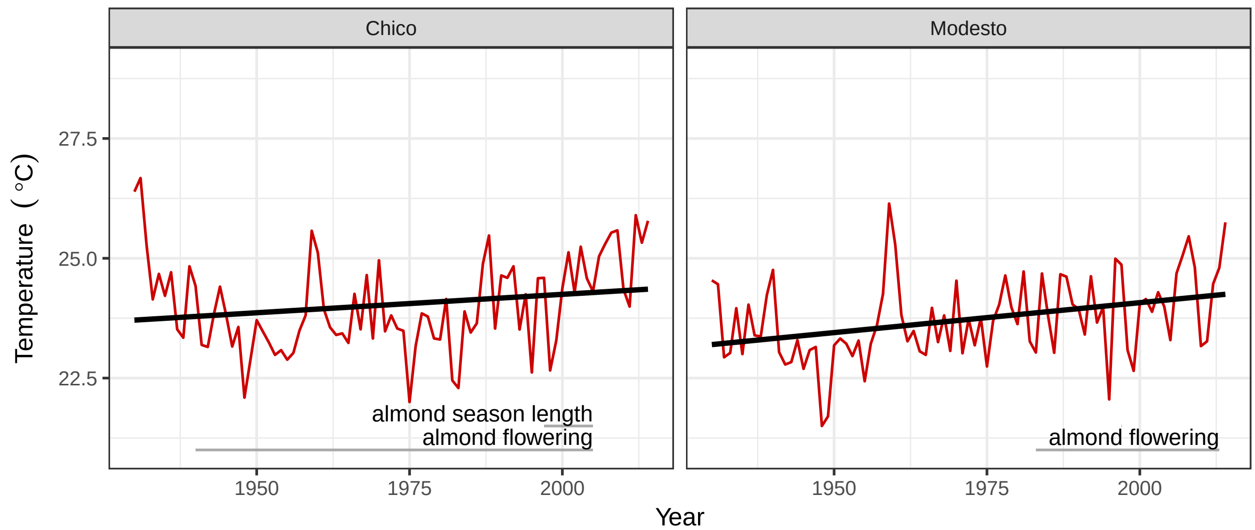

Figure 4: Figure 4. Mean Annual Maximum Temperatures from 1931 to 2014, duration of phenology record shown with grey lines.

Table 4: Table 4. 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	-0.06	0.51	**0.35**	**5.3e-04**	**0.19**	**5.2e-03**
February	-0.032	0.71	**0.28**	**7.9e-04**	**0.15**	**0.017**
March	0.042	0.54	0.19	0.059	0.12	0.081
April	-0.023	0.67	0.048	0.67	0.0032	0.97
May	0.09	0.14	0.035	0.74	0.065	0.4
June	0.037	0.49	-0.026	0.77	0.004	0.95
July	-0.029	0.6	-0.1	0.14	-0.072	0.19
August	0.018	0.76	-0.038	0.61	-0.012	0.83
September	-0.031	0.6	0.076	0.35	0.028	0.62
October	-0.12	0.067	**0.26**	**0.019**	0.073	0.29
November	0.001	0.99	0.11	0.27	0.062	0.28
December	-0.14	0.14	**0.29**	**2.9e-03**	0.11	0.11
Annual	-0.026	0.39	0.069	0.061	0.027	0.27

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	0.17	0.055	**0.29**	**6.3e-04**	**0.24**	**1.8e-03**
February	**0.26**	**4.9e-03**	**0.26**	**2.2e-04**	**0.26**	**2.6e-04**
March	**0.32**	**2.5e-05**	**0.25**	**7.4e-03**	**0.31**	**7.2e-05**
April	**0.21**	**0.001**	0.12	0.24	**0.2**	**0.006**
May	**0.34**	**5.7e-06**	**0.21**	**0.029**	**0.31**	**1.1e-04**
June	**0.4**	**8.5e-08**	**0.19**	**0.024**	**0.29**	**3.6e-05**
July	**0.38**	**8.2e-07**	0.042	0.48	**0.23**	**1.7e-04**
August	**0.48**	**2.7e-09**	**0.13**	**0.039**	**0.33**	**4.5e-07**
September	**0.35**	**2.8e-06**	**0.16**	**9.9e-03**	**0.3**	**3.7e-06**
October	**0.31**	**2.4e-05**	0.11	0.13	**0.23**	**3.3e-04**
November	**0.36**	**4.8e-05**	0.026	0.77	**0.21**	**1.7e-03**
December	**0.18**	**0.048**	0.12	0.16	**0.15**	**0.034**

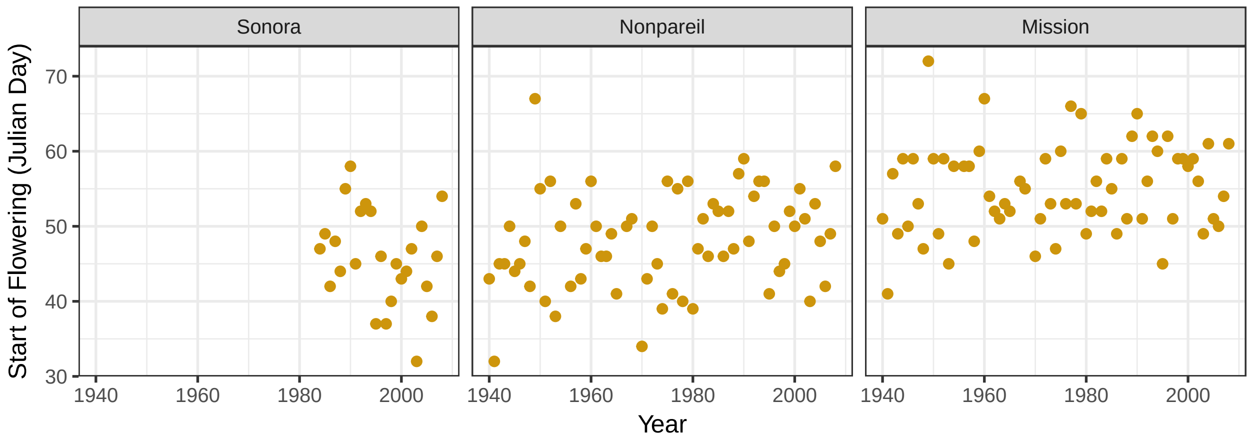

Figure 5: Figure 5. Almond flowering dates in Chico, CA

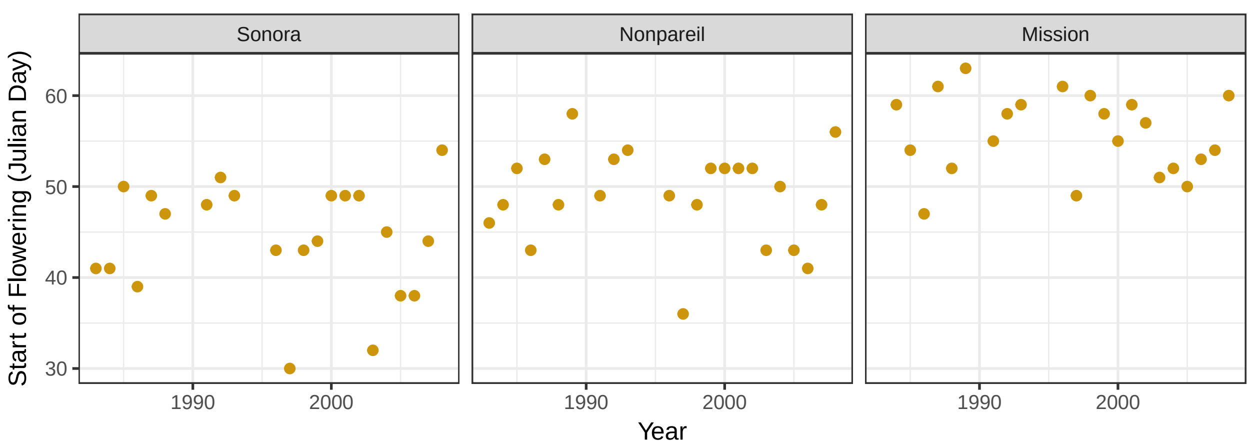

Figure 6: Figure 6. Almond flowering dates in Modesto, CA

Flowering dates of all three cultivars of almonds in Chico correlated strongly with average January and February temperatures, with flowering date getting earlier if temperatures in these months were warmer (Figure 7-9, Table 7). There was also correlations between flowering date and November and December monthly temperatures for cultivars Nonpareil and Mission. Only warmer November temperatures correlated with later bloom.

Given the current data, it is likely that almonds in Chico generally meet their chill requirement in November (Figures 7-9). Consequently, warming December and January temperatures allow the almonds to meet their heat requirement sooner, which causes them to bloom earlier. Based on the December and January temperature trends in Chico (Table 3), it seems likely that almond flowering dates will continue to get earlier as long as November temperatures stay stable.

In Modesto, flowering dates for all almond cultivars correlate negatively January temperatures and positively with November temperatures. (Figure 10-12, Table 7). Because both November and January temperatures in Modesto may potentially be increasing, it is not currently possible to tell what affect warming will have on Almonds in Modesto (Table 4). It will depend on the strength of the warming in both months, as well as the strength of the trees response to that warming.

Winter Chill Accumulation

Time Heat Requirements are met

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

Table 6: Table 8. P-values for change in the timing of meeting chill and heat requirements over the course of the phenology record for almonds in Chico using linear models.

Cultivar	Chill	Agronomic Chill	Heat
Sonora	0.75	0.47	**0.02**
Nonpareil	0.41	0.48	0.46
Mission	0.65	0.7	0.28

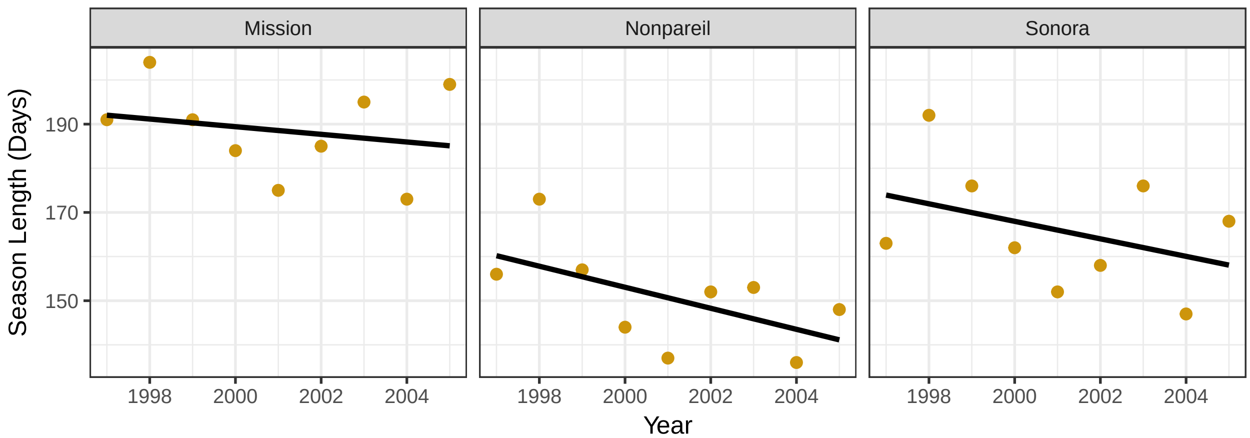

Figure 7: Figure 23. Almond season length by cultivar in Chico, CA

Table 7: Table 9. P-values for change in the timing of meeting chill and heat requirements over the course of the phenology record for almonds in Modesto using linear models.

Cultivar	Chill	Agronomic Chill	Heat
Sonora	0.98	0.34	**0.02**
Nonpareil	0.76	0.39	**0.01**
Mission	0.72	0.97	0.14

Fall Phenology

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.

The season lengths of Sonora, Nonpareil, and Mission all responded to May temperatures (Figure 24-26). May temperatures reduced season lengths for all cultivars. However, the lack of a detectable trend in May temperatures in Chico means it is not currently possible to determine what kind of an impact continued climate change will have on almond season lengths.

Table 8: Table 10. Summary of linear models comparing almond season length to monthly temperatures in Chico, CA.

Cultivar2	Adj. Rˆ2	Predictor	Coefficient	p-value
Mission	0.433	May_tmax	-2.974	0.032
Nonpareil	0.377	May_tmax	-2.318	0.046
Sonora	0.423	May_tmax	-2.213	0.034

In addition, all three cultivars showed strong correlation with fruit development thermal time accumulation during the first part of the season (~ the first four months) (Figures 27, 29, 31). However, there is not a significant trend in thermal time accumulation over time for any of the almond cultivars (Figures 28, 30, 32). While this could be because fruit developement thermal time accumulation is not changing, it is also possible that a longer time series is required to detect a trend in the data. This would be consistent with trend detection in other climate change affected variables. If there is an upward trend in almond thermal time accumulation, we can expect (with high confidence) that almond season lengths will get shorter.

Table 9: Table 11. Summary of linear models comparing almond season length to thermal time accumulated (GDH) for Anderson and simplified models in Chico, CA.

Cultivar	Predictor	Response	Coefficient	p-value	Adj. R^2
Sonora	Season Length	Year	-1.983	0.295	0.034
	Season Length	Anderson	-0.009	0.000	0.924
	Season Length	Simplified	-0.005	0.000	0.944
	Anderson	Year	147.447	0.494	-0.064
	Simplified	Year	216.546	0.545	-0.080

Prunes

Temperature Context: Parlier

Annually Parlier exhibits warming minimum temperatures and cooling maximum temperatures (Figures 33-34) 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 12). Minimum monthly temperatures are increasing year round based on autoregression analysis, but only spring, summer, and fall maximum temperatures are cooling significantly (Table 12).

Table 10: 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	**0.2**	**0.017**	-0.091	0.34	0.091	0.23
February	**0.19**	**0.013**	-0.13	0.051	0.034	0.56
March	**0.27**	**1.7e-04**	-0.15	0.1	0.071	0.3
April	0.081	0.18	**-0.4**	**4.3e-04**	-0.15	0.055
May	**0.27**	**7.5e-05**	**-0.39**	**7.9e-05**	-0.052	0.45
June	**0.27**	**1.6e-05**	**-0.26**	**0.002**	-0.0025	0.96
July	**0.31**	**3.2e-06**	**-0.49**	**4.7e-07**	**-0.11**	**0.033**
August	**0.35**	**3.5e-07**	**-0.46**	**9.9e-07**	-0.08	0.11
September	**0.34**	**3.7e-06**	**-0.29**	**3.3e-04**	-0.027	0.62
October	**0.28**	**1.6e-04**	**-0.4**	**2.9e-05**	-0.037	0.53
November	**0.26**	**3.6e-04**	**-0.44**	**3.6e-05**	-0.096	0.11
December	0.07	0.33	-0.19	0.074	-0.076	0.29
Annual	**0.18**	**1e-06**	**-0.18**	**5.5e-04**	-0.023	0.37

Spring Phenology

Flowering dates

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).

Flowering dates and monthly temperature

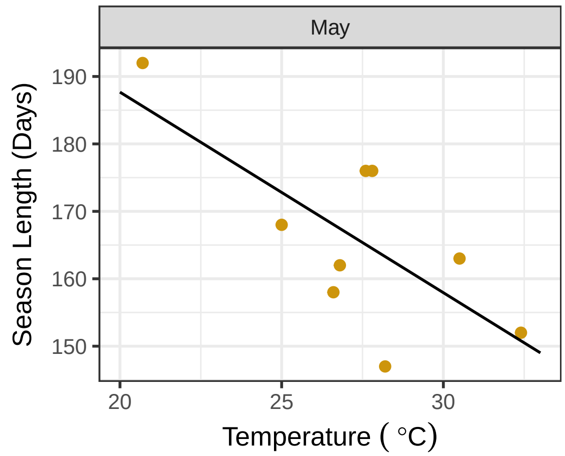

Figure 8: Figure 24. Sonora almond season length response to monthly temperatures in Chico, CA.

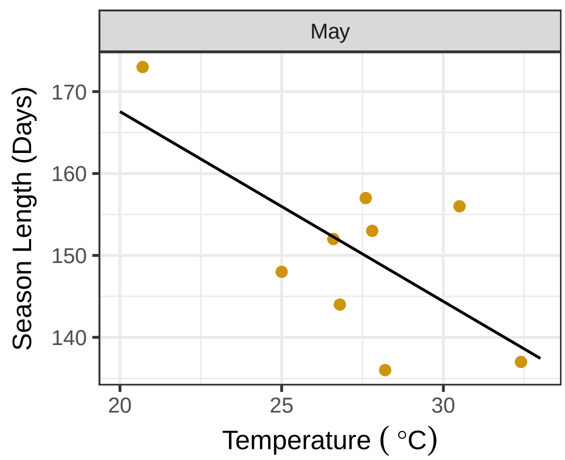

Figure 9: Figure 25. Nonpareil almond season length response to monthly temperatures in Chico, CA.

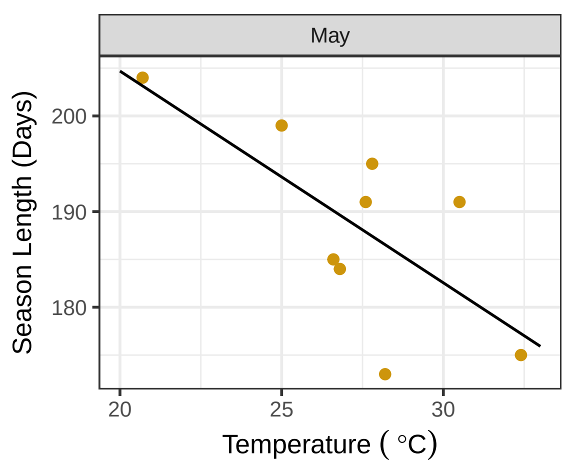

Figure 10: Figure 26. Mission almond season length response to monthly temperatures in Chico, CA.

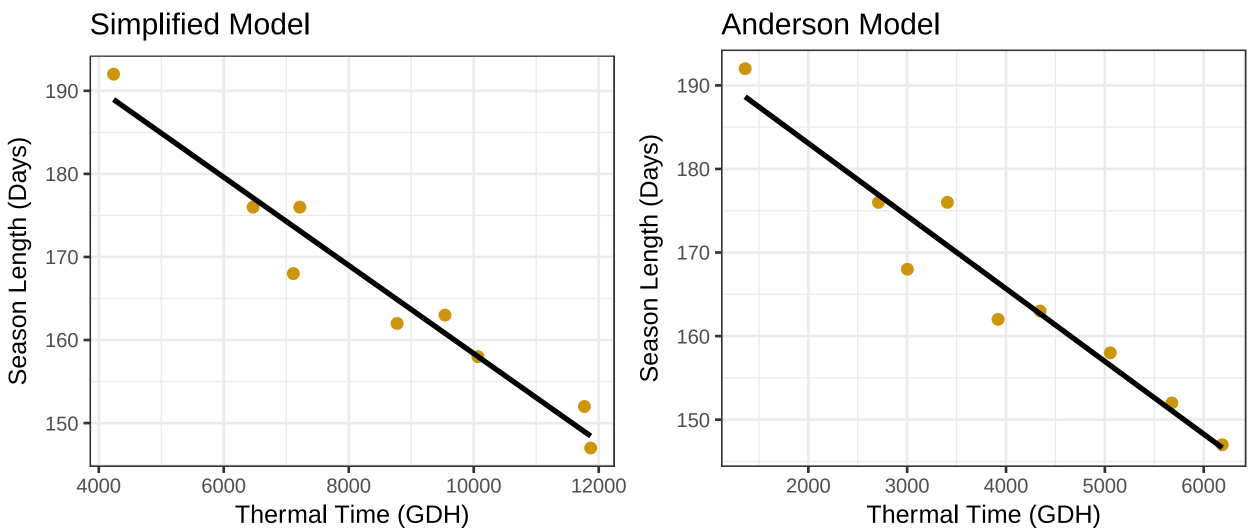

Figure 11: Figure 27. Season length vs. thermal accumulation for Sonora almonds in Chico, CA.

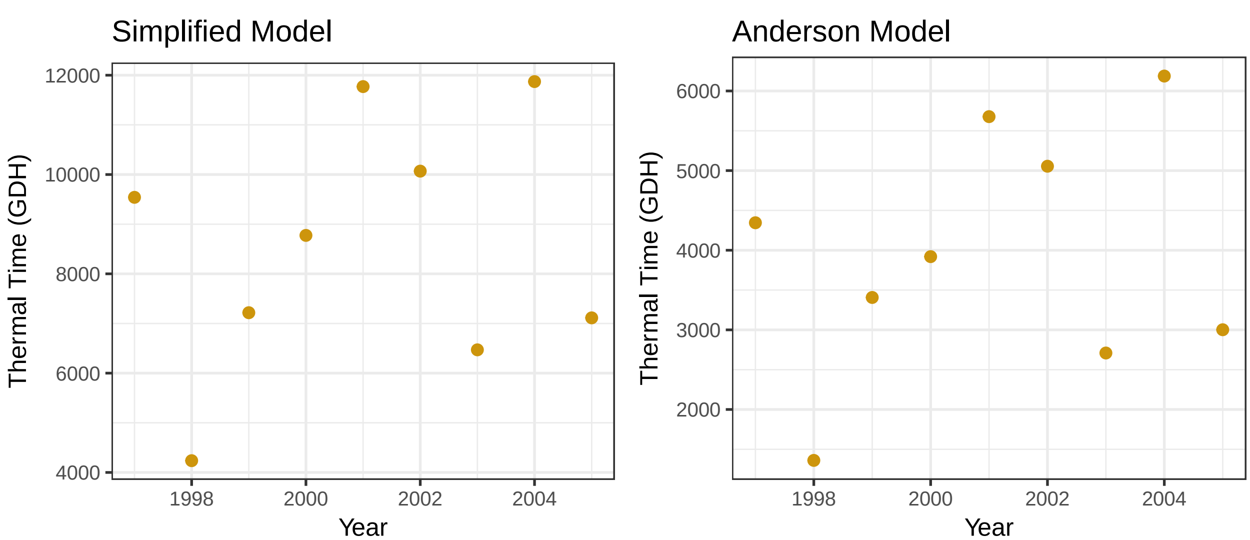

Figure 12: Figure 28. Thermal accumulation for Sonora almonds in Chico, CA.

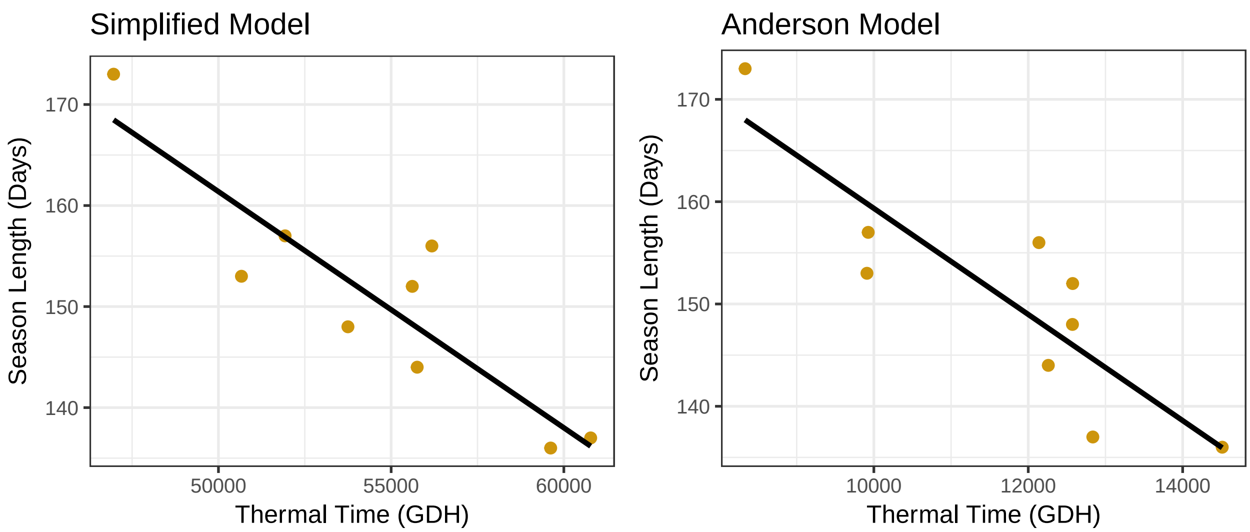

Figure 13: Figure 29. Season length vs. thermal accumulation for Nonpareil almonds in Chico, CA.

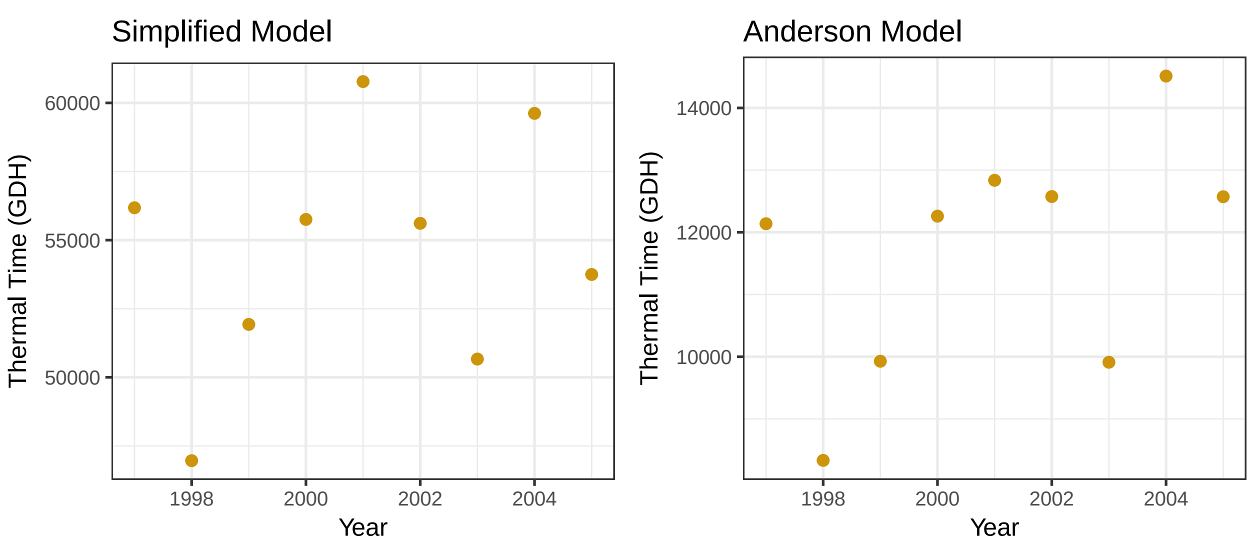

Figure 14: Figure 30. Thermal accumulation for Nonpareil almonds in Chico, CA.

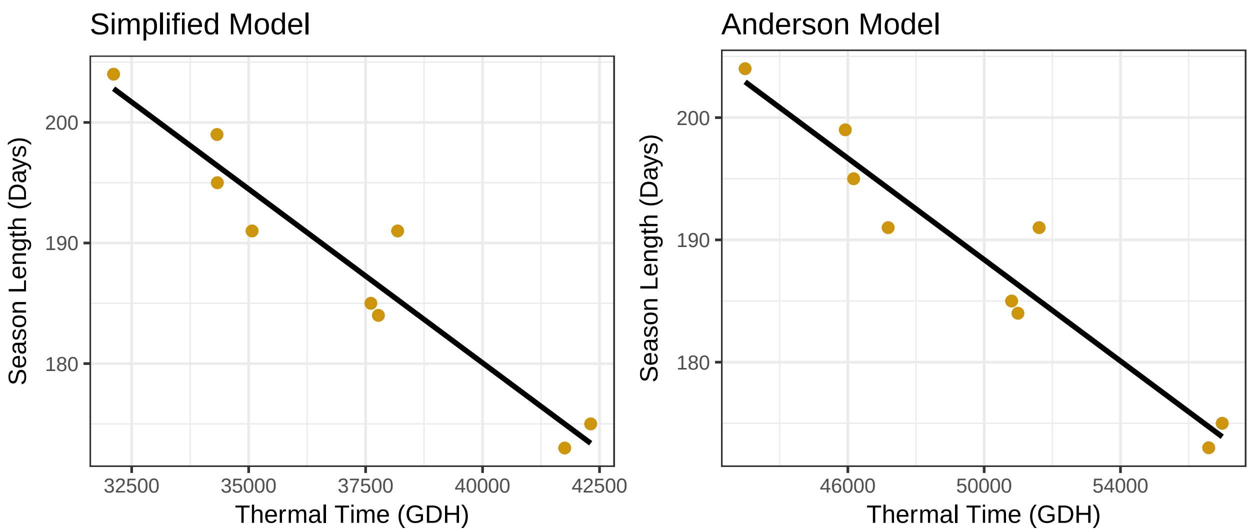

Figure 15: Figure 31. Season length vs. thermal accumulation for Mission almonds in Chico, CA.

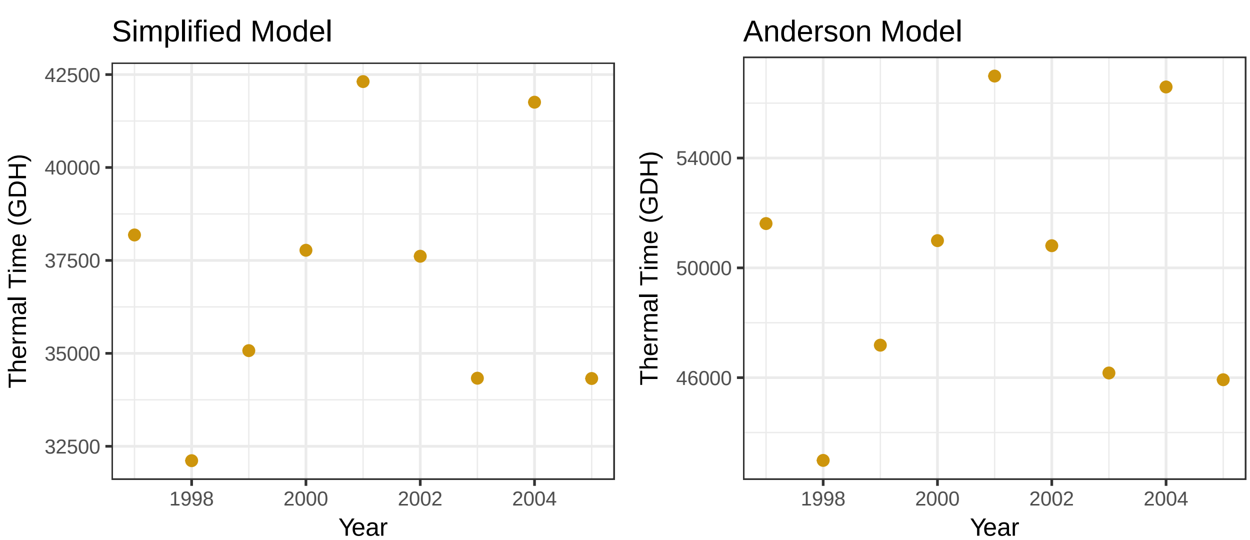

Figure 16: Figure 32. Thermal accumulation for Mission almonds in Chico, CA.

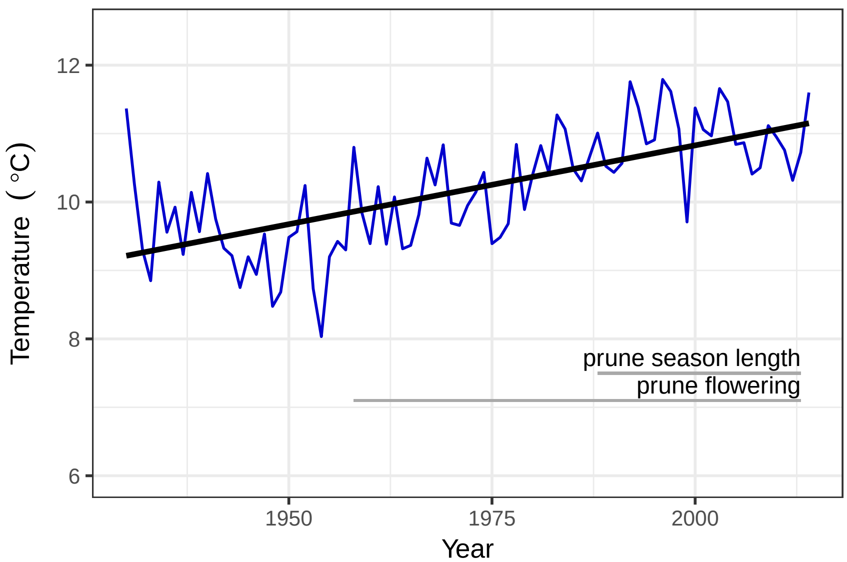

Figure 17: Figure 33. Mean annual minimum temperatures from 1931 to 2014 in Parlier, CA, duration of phenology record shown with grey lines.

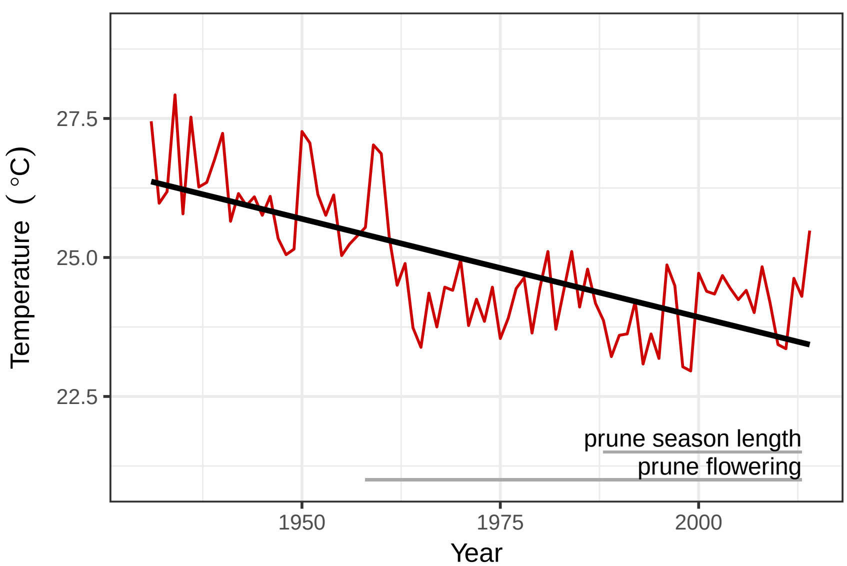

Figure 18: Figure 34. Mean annual maximum temperatures from 1931 to 2014 in Parlier, CA, duration of phenology record shown with grey lines.

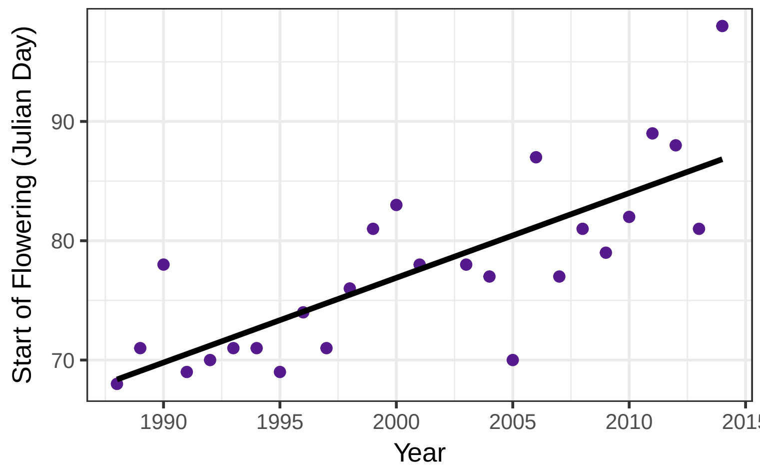

Figure 19: Figure 35. Improved French prune flowering dates in Parlier, CA.

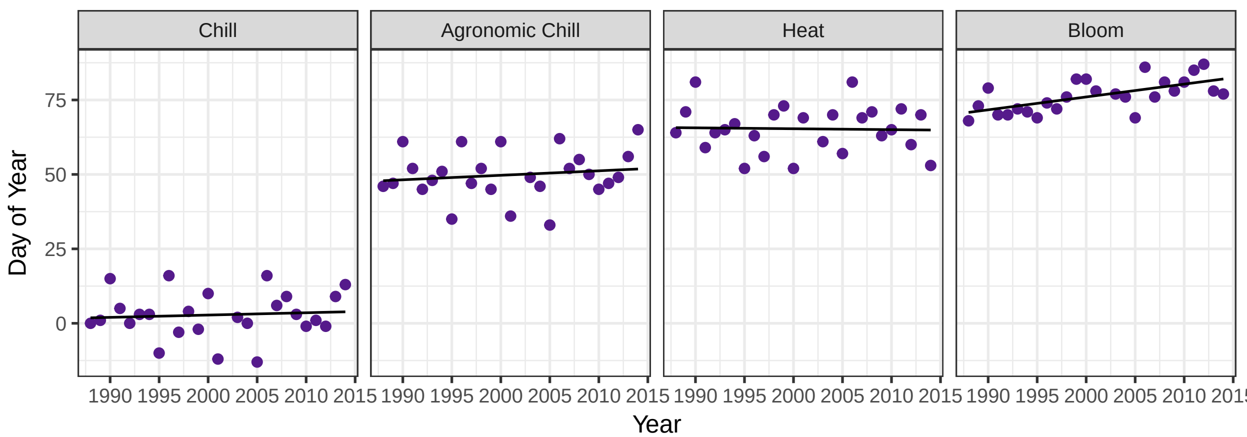

Figure 20: Figure 40. Timing of prune chill and heat requirements met in Parlier, CA

Table 11: Table 13. Summary of linear models comparing almond flowering dates to monthly temperatures.

Response	Adj. R^2	Predictor	Coefficient	p-value
Flowering Date	0.112	January_tavg	1.680	0.012
		February_tavg	-1.495	0.049
Season Length	0.388	May_tmax	-2.448	0.002

When bloom timing was compared with monthly average temperatures, Improved French prune flowering dates in Parlier correlated with January and February monthly temperatures, but in opposite directions (Figure 36, Table 13). While there are some slight trends in Parlier monthly temperature, none of them are strong enough, or in the right direction, to produce the trend in Figure 35.

Changes in Timing of Chill and Heat Requirements Being Met

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.

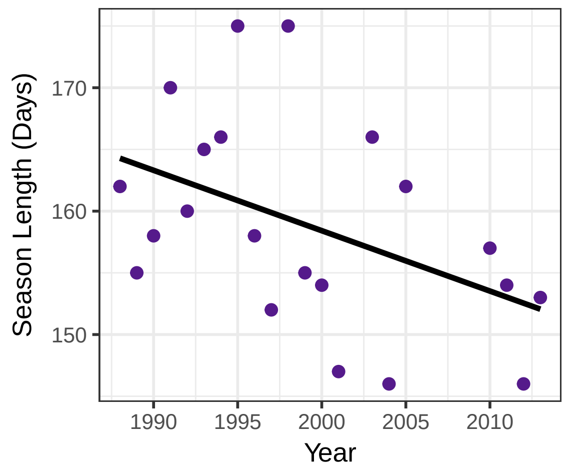

Figure 21: Figure 41. 'Improved French' prune season length in Parlier, CA.

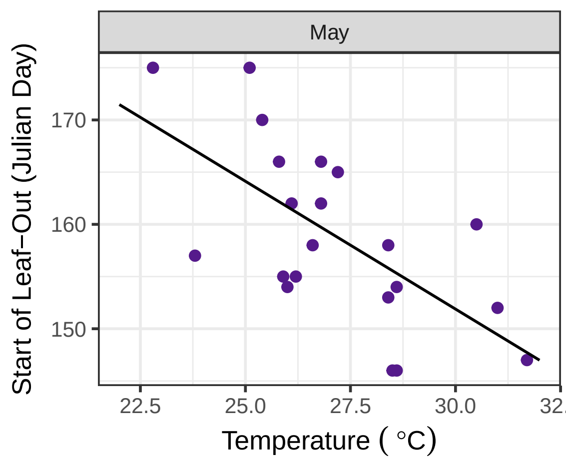

Figure 22: Figure 42. 'Improved French' prune season length response to average maximum May temperatures in Parlier, CA.

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.

Table 12: Table 15. Summary of linear models comparing prune season length to thermal time accumulated (GDH) for Anderson and simplified models in Parlier, CA.

Response	Predictor	Coefficient	p-value	Adj. R^2
Season Length	Year	-0.489	0.041	0.160
Season Length	Anderson	-0.005	0.000	0.818
Season Length	Simplified	-0.012	0.000	0.794

Response	Predictor	Coefficient	p-value	Adj. R^2
Anderson	Year	81.379	0.080	0.108
Simplified	Year	36.677	0.048	0.147

Walnuts

Temperature Context: Davis

Annual minimum temperatures have risen an average of 0.21°C per decade over the past 80 years in Davis based on an autoregressive linear analysis (Figure 45). Annual maximum temperatures, however, have stayed fairly constant (Figure 46).

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 16).

Table 13: 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	0.13	0.16	0.17	0.055	**0.16**	**0.021**
February	0.14	0.079	0.12	0.064	**0.13**	**0.021**
March	**0.26**	**8.8e-05**	0.12	0.22	**0.19**	**5.1e-03**
April	**0.18**	**1.4e-03**	-0.033	0.75	0.098	0.17
May	**0.27**	**2.8e-05**	0.078	0.42	**0.18**	**0.014**
June	**0.25**	**5.2e-06**	0.056	0.46	**0.14**	**0.012**
July	**0.22**	**1.8e-05**	**-0.14**	**0.035**	0.022	0.65
August	**0.24**	**8.5e-06**	-0.071	0.29	0.087	0.054
September	**0.16**	**4.7e-03**	0.0095	0.9	0.093	0.082
October	**0.2**	**5.6e-04**	0.049	0.57	**0.14**	**0.016**
November	**0.23**	**2.2e-03**	-0.086	0.36	0.074	0.2
December	0.09	0.33	0.024	0.77	0.053	0.43
Annual	**0.15**	**5.9e-05**	0.018	0.61	**0.073**	**6.8e-03**

Spring Phenology

Leaf-out dates

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

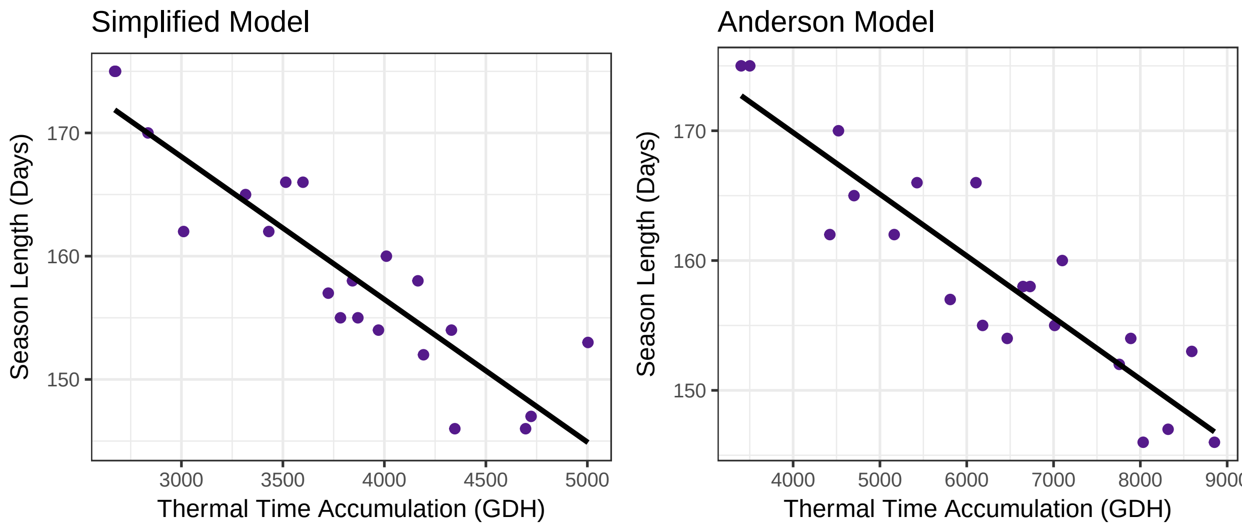

Figure 23: Figure 43. 'Improved French' prune season length Response to thermal time accumulation in Parlier, CA.

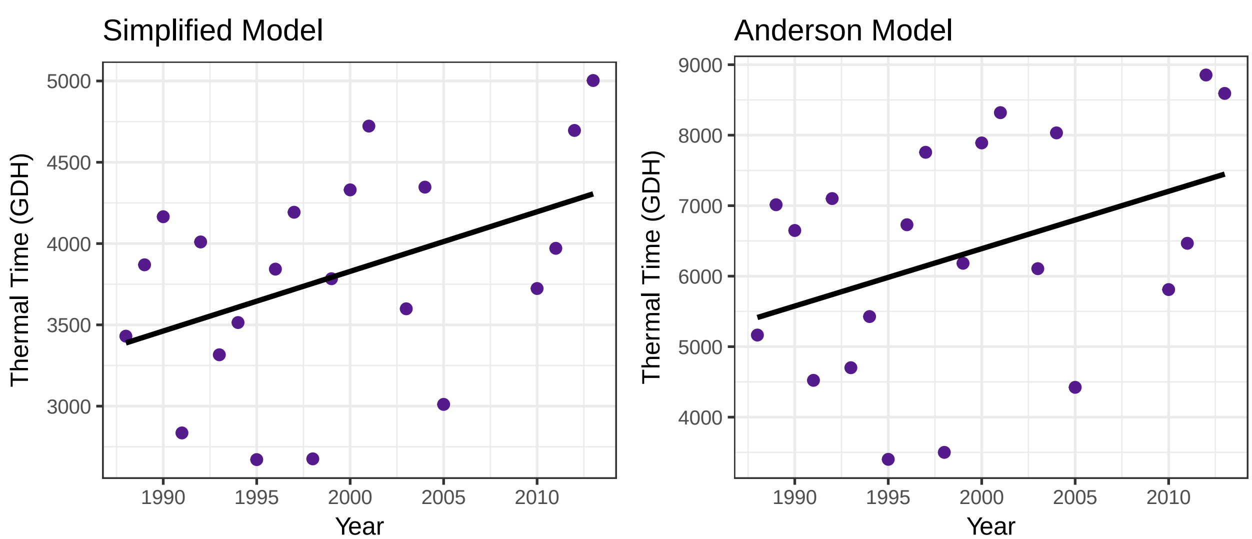

Figure 24: Figure 44. Thermal accumulation for French prunes in Parlier, CA.

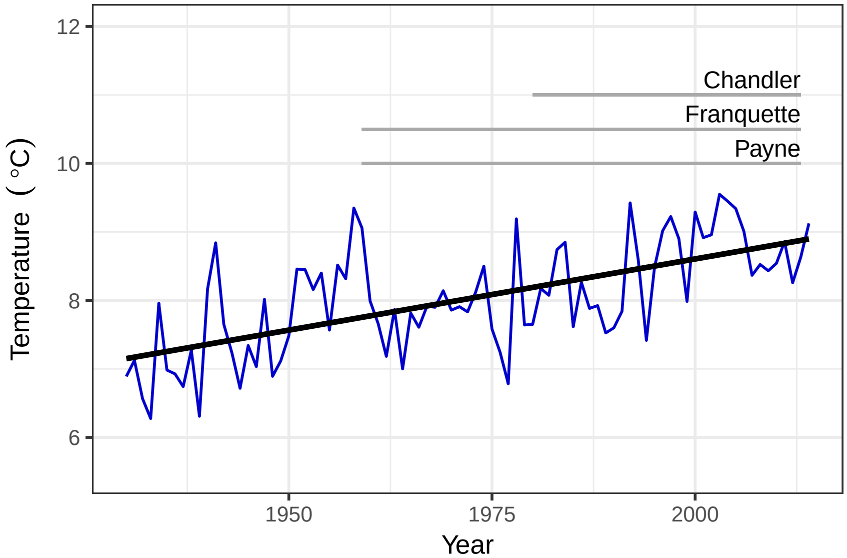

Figure 25: Figure 45. Mean annual minimum temperatures from 1931 to 2014 in Davis, CA, duration of phenology record shown with grey lines.

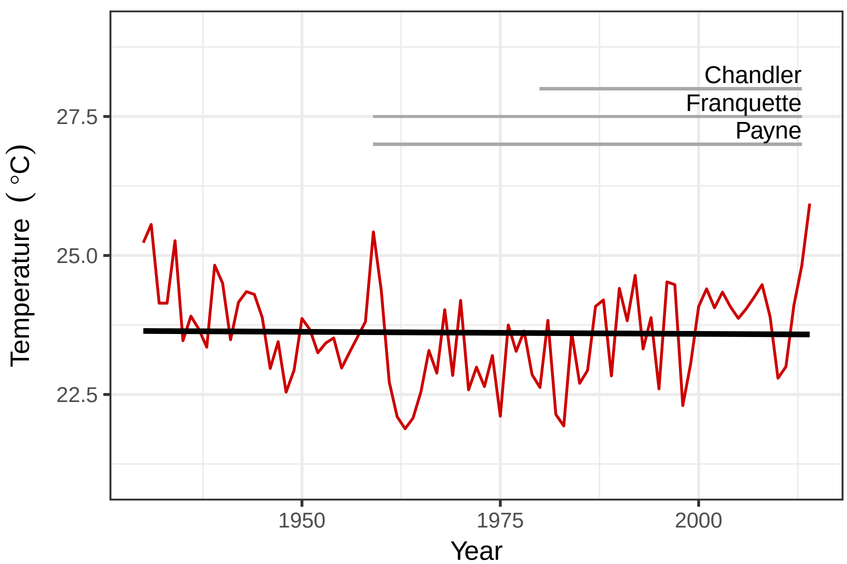

Figure 26: Figure 46. Mean annual maximum temperatures from 1931 to 2014 in Davis, CA, duration of phenology record shown with grey lines.

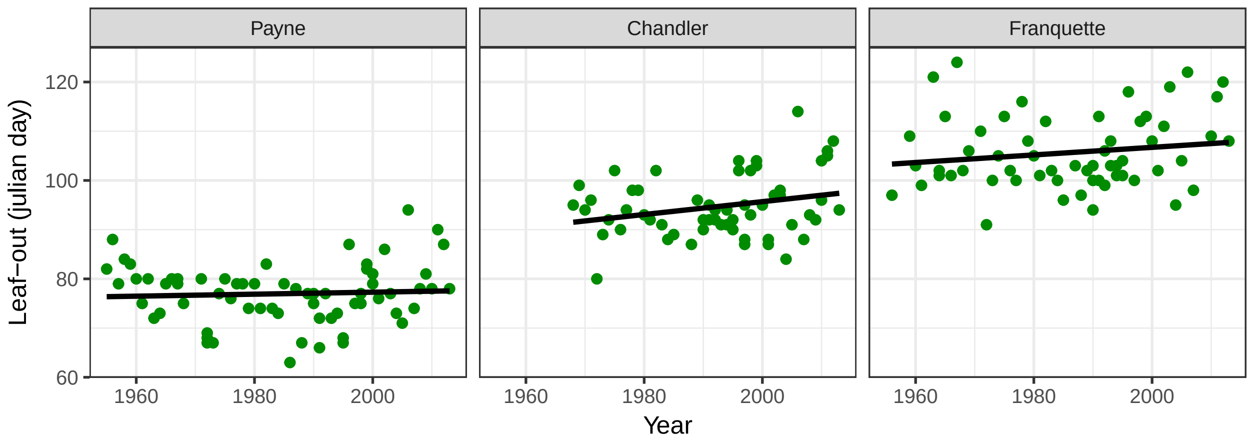

Figure 27: Figure 47. Walnut leaf-out dates by cultivar in Davis, CA.,

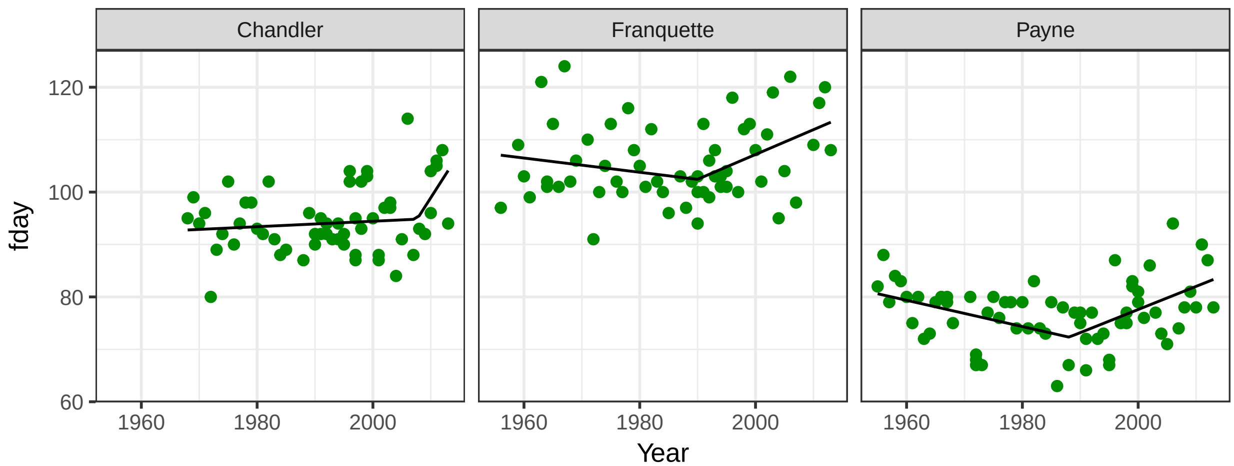

Figure 28: Figure 48. Walnut leaf out day by cultivar over time, segmented regression analysis.

(R^2=0.17), showing leaf-out coming later by 0.47 days/year.

Table 14: Table 17. Walnut leaf-out day change over time.

cultivar	lm p-value	seg.lm p-value	change point	1st slope	2nd slope	p-value since 1988
Chandler	0.049	0.507	2008	0.052	1.675	0.2508
Franquette	0.233	0.342	1990	-0.136	0.609	0.0123
Payne	0.655	0.011	1988	-0.250	0.692	0.0001

Leaf-out dates and monthly temperature

Earlier leaf-out for Payne and Chandler walnuts correlate positively with warmer temperatures in November and December, and negatively with warmer temperatures in March (Figure 49-50, Table 18). In other words, warmer February temperature correlate with earlier Payne leaf-out. Consequently, is likely that Payne and Chandler walnuts accumulate a large part of their required chill in November and December. Thus, earlier leaf-out results from earlier heat accumulation. However, this does not explain the later leaf-out found in the phenology record.

March average temperatures, on the other hand, appear to be increasing, pointing to earlier leaf out for both cultivars. This is not reflected in the current leaf out trends though. The conflictiong signs on the correlations between leaf-out and monthly temperatures for Payne and Chandler walnuts, mean it is not possible to tell what the effect of future climate change will be.

Table 15: Table 18. Summary of linear models comparing walnut flowering dates and season lengths to monthly temperatures in Davis, CA.

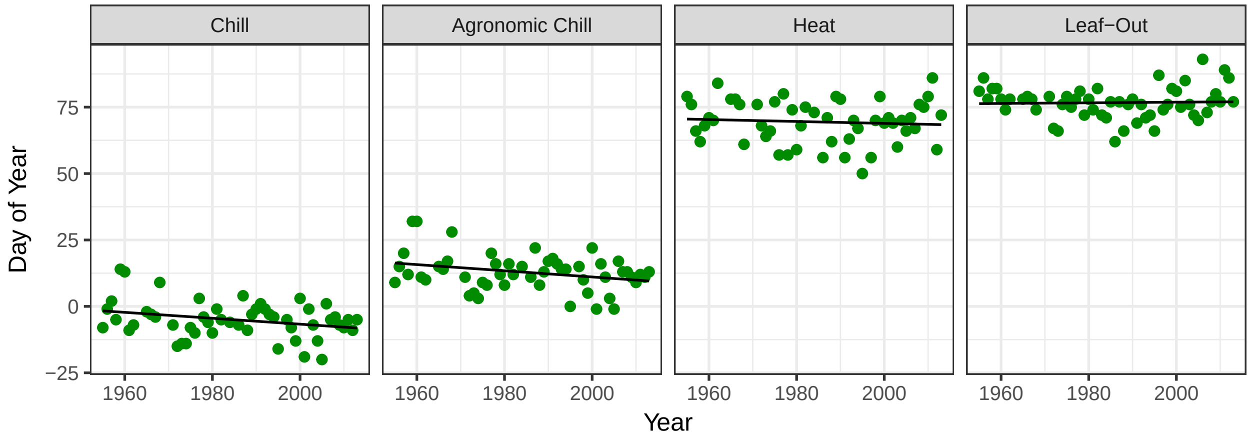

Figure 29: Figure 55. Timing of requirements met in Payne walnuts, Davis, CA

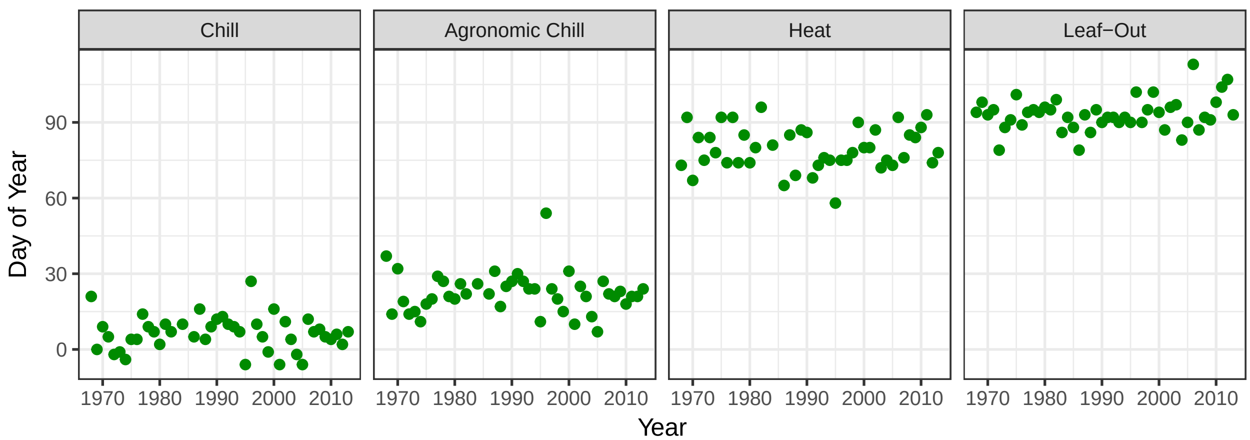

Figure 30: Figure 56. Timing of chill and heat requirements met in Chandler walnuts, Davis, CA

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

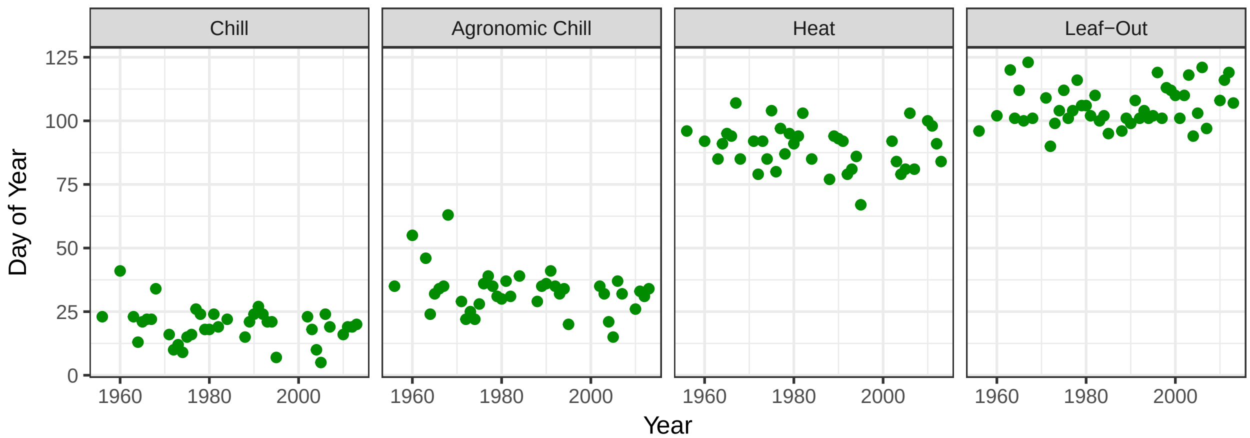

Figure 31: Figure 57. Timing of chill and heat requirements met in Franquette walnuts, Davis, CA

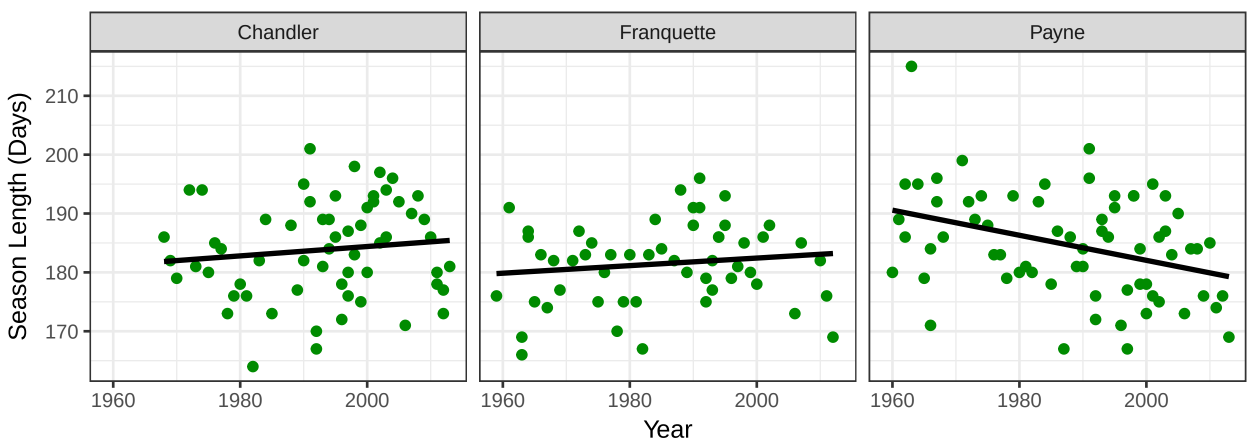

Figure 32: Figure 58. Walnut season length by cultivar in Davis; Chandler NS, Franquette NS, Payne p=0.0010

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 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.

Fall Phenology

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

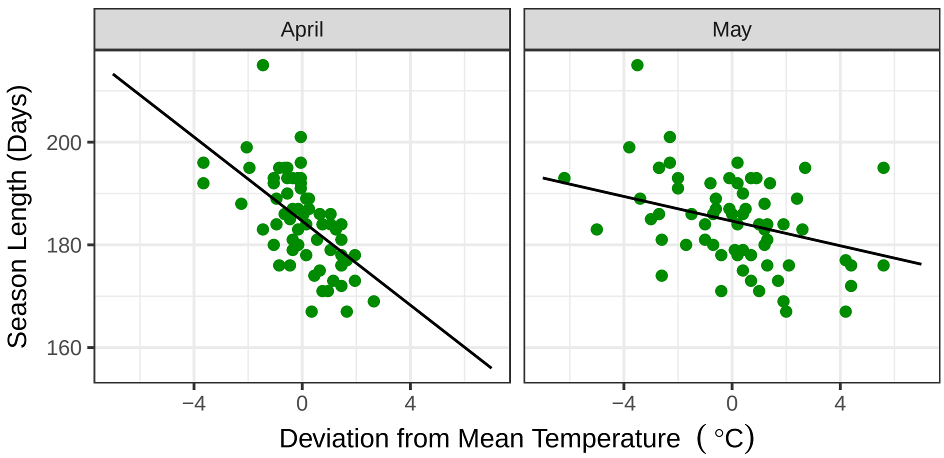

Figure 33: Figure 59. 'Payne' walnut season length response to monthly temperatures in Davis, CA.

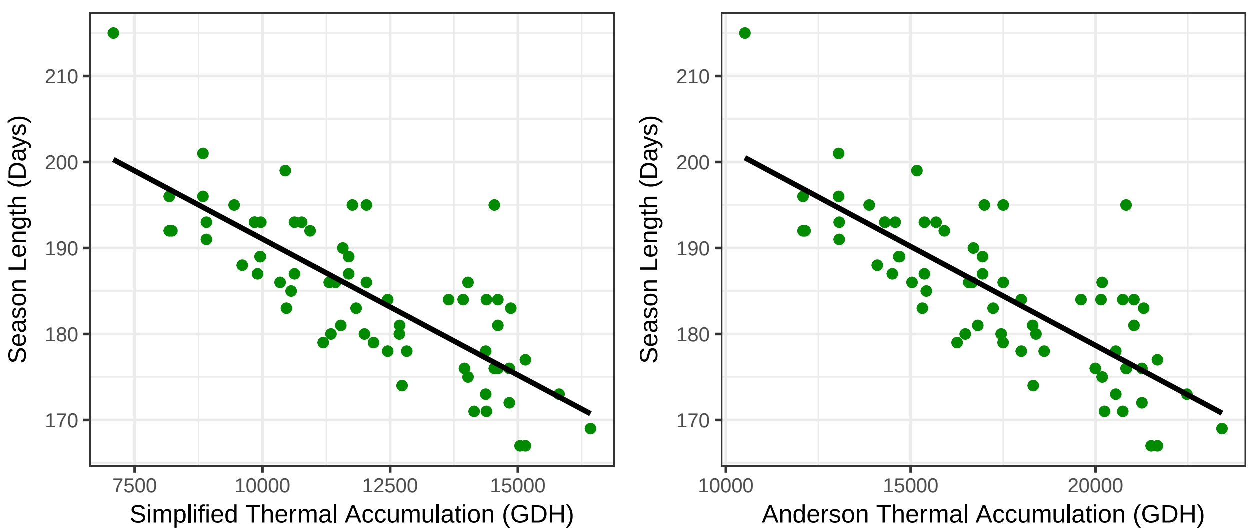

Figure 34: Figure 60. 'Payne' walnut season length response to thermal time accumulation in Davis, CA.

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 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

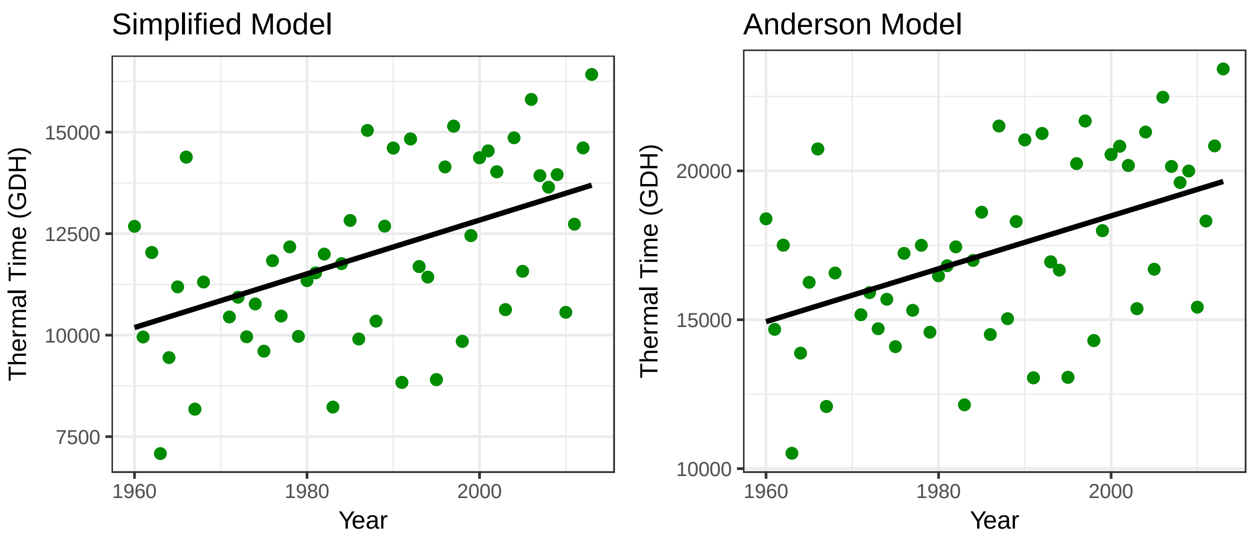

Figure 35: Figure 61. Thermal accumulation for Payne walnuts in Davis, CA.

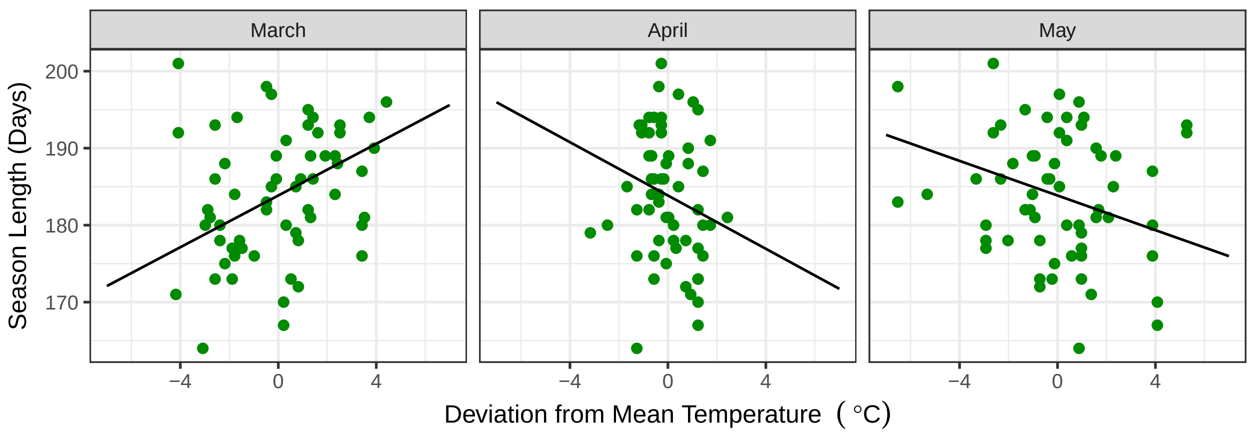

Figure 36: Figure 62. 'Chandler' walnut season length response to monthly temperatures in Davis, CA.

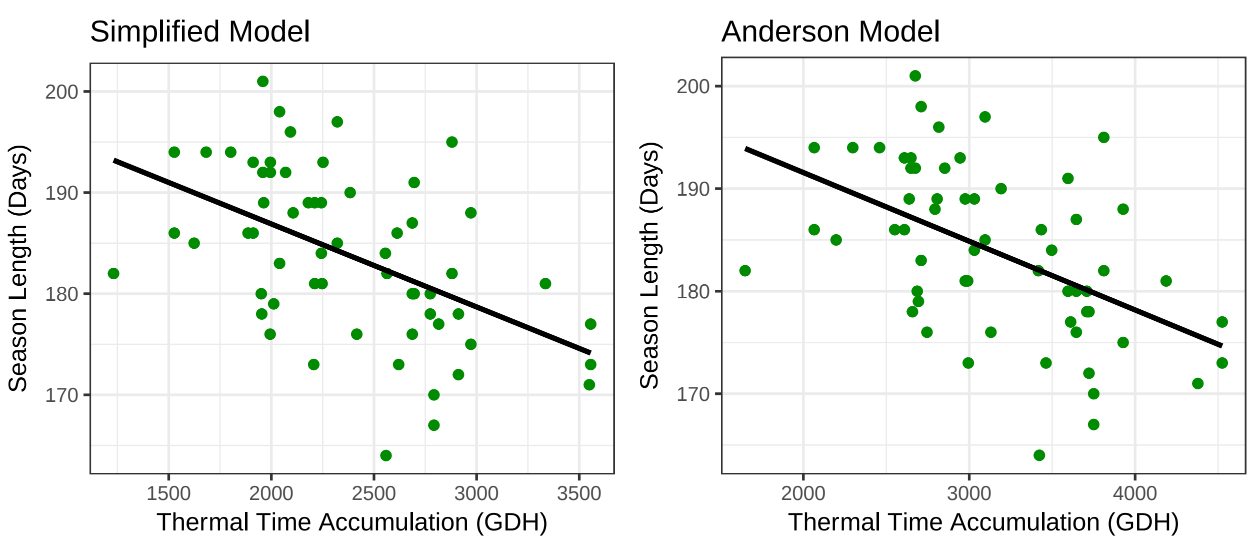

Figure 37: Figure 63. 'Chandler' walnut season length response to thermal time accumulation in Davis, CA.

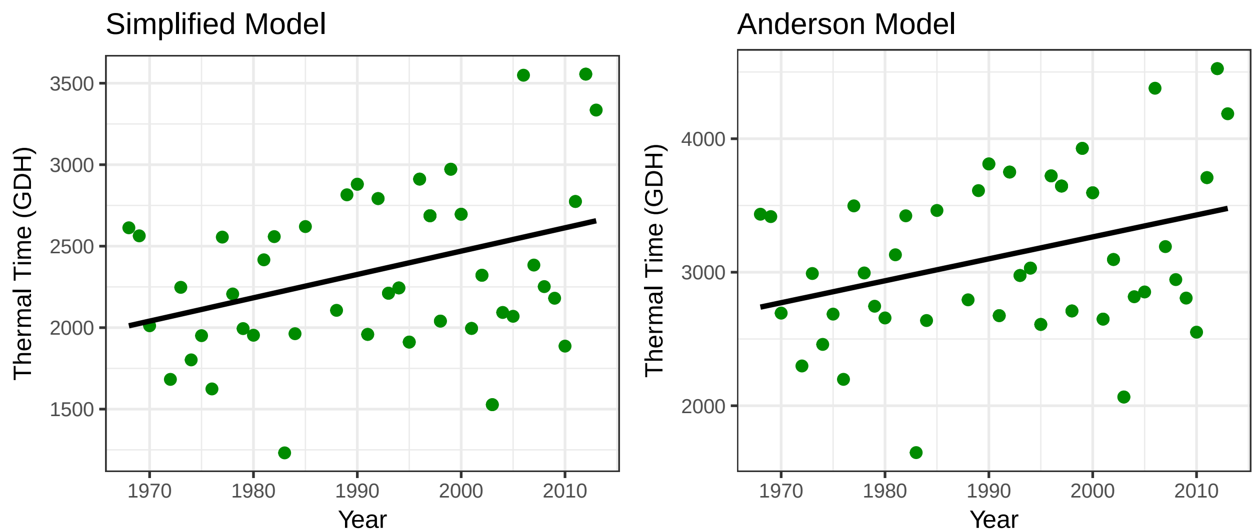

Figure 38: Figure 64. Thermal accumulation over time for Chandler walnuts in Davis, Simplified model p=0.0069; Anderson model p=0.012

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.

Table 16: Table 19. Summary of linear models comparing walnut season length to thermal time accumulated (GDH) for Anderson and simplified models in Davis, CA.

Cultivar	Response	Predictor	Coefficient	p-value	Adj. R^2
Payne	Season Length	Year	-0.213	0.003	0.116
	Season Length	Anderson	-0.002	0.000	0.615
	Season Length	Simplified	-0.003	0.000	0.615
	Anderson	Year	88.832	0.000	0.179
	Simplified	Year	66.168	0.000	0.189
Chandler	Season Length	Year	0.080	0.369	-0.003
	Season Length	Anderson	-0.007	0.000	0.241
	Season Length	Simplified	-0.008	0.000	0.241
	Anderson	Year	16.435	0.012	0.090
	Simplified	Year	14.318	0.007	0.104
Franquette	Season Length	Year	0.064	0.341	-0.001
	Season Length	Anderson	-0.006	0.000	0.347
	Season Length	Simplified	-0.010	0.000	0.325
	Anderson	Year	8.979	0.157	0.020
	Simplified	Year	7.876	0.045	0.058

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

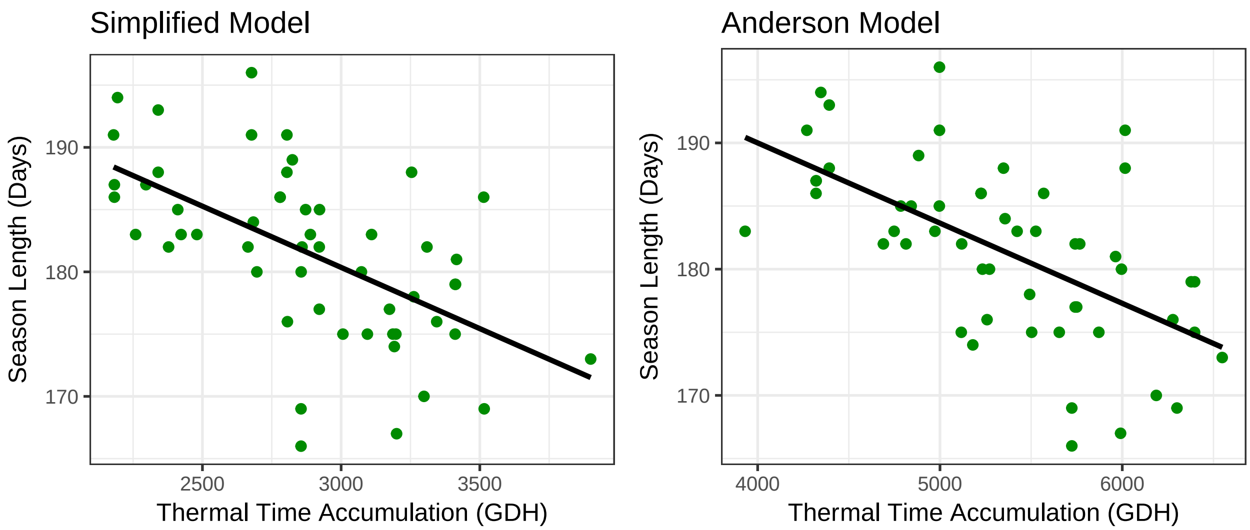

Figure 39: Figure 65. ‘Franquette’ walnut season length response to thermal time accumulation; Simplified model R^2= 0.325 and p=5.0 * 10^{-6}, Anderson model R^2= 0.347 and p=2.1 * 10^{-6}

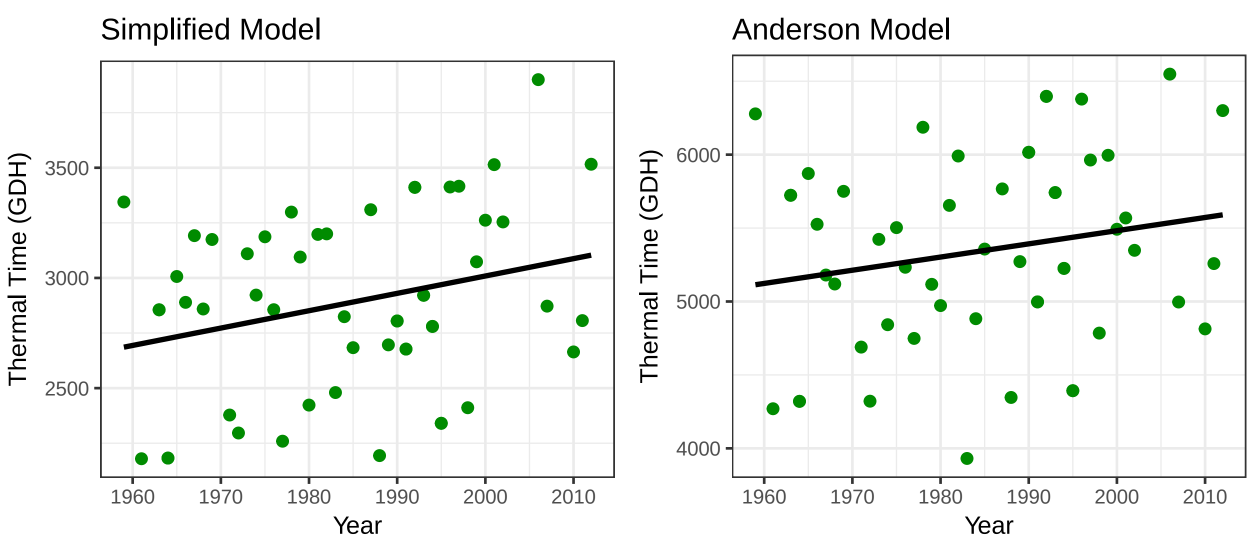

Figure 40: Figure 66. Thermal accumulation for Franquette walnuts in Davis; Simplified model p=0.045, Anderson model p=0.157

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).

Appendix: Maps

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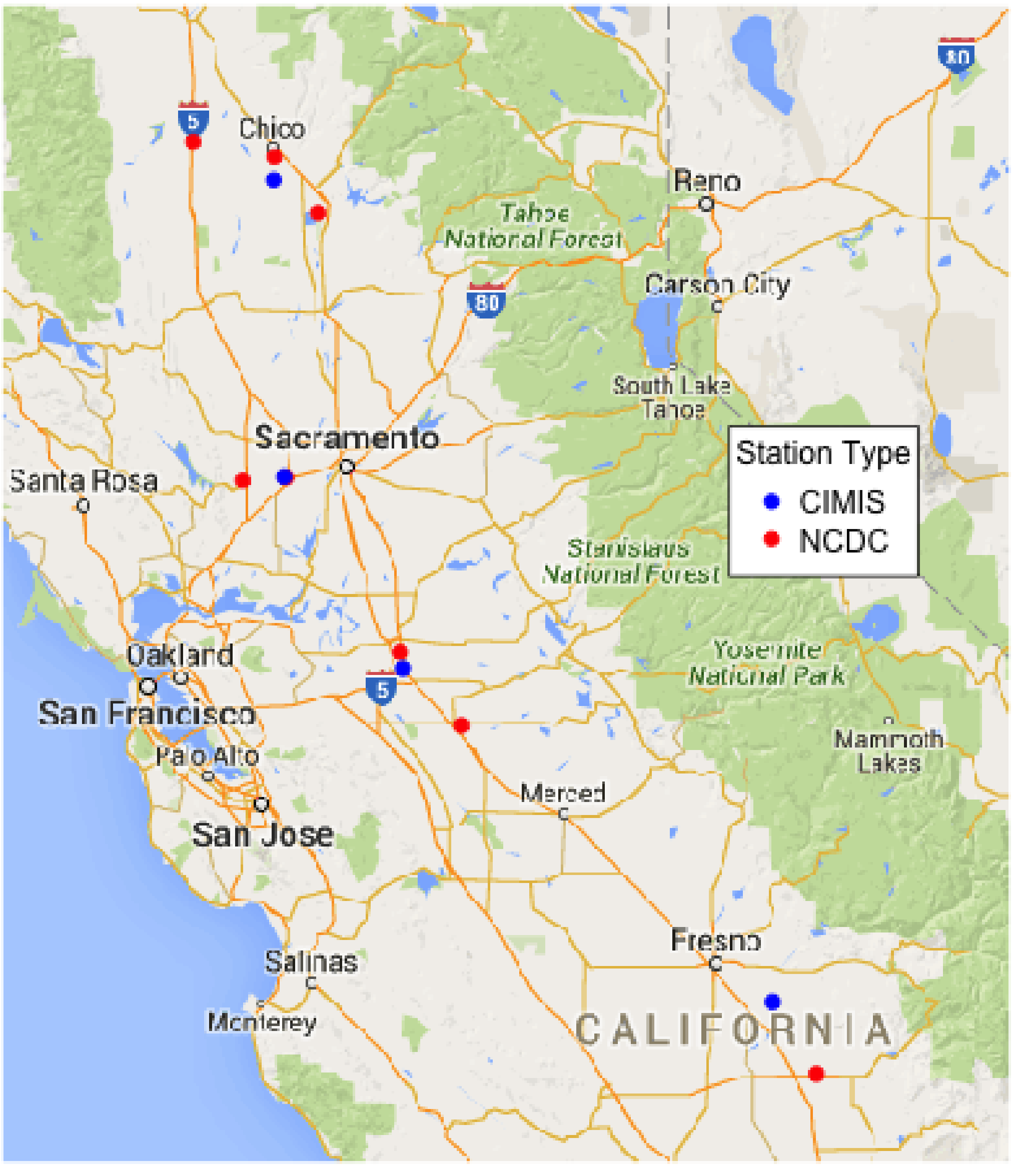

Figure 41: Climate Stations by Station Type

Figure 42: Orchards by Crop

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