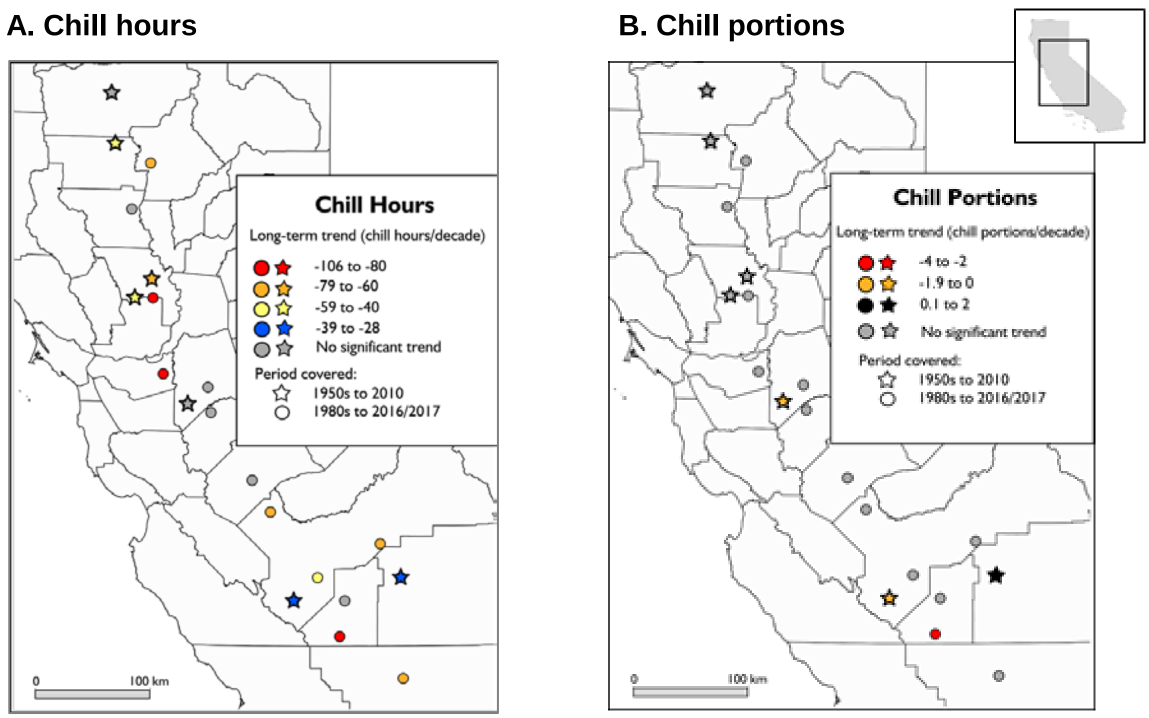
WINTER CHILL

Winter "chill hours," a very sensitive and rudimentary metric that has been used since the 1940s, have been declining in more than half of the sites studied in the state. However, "chill portions," a biologically based metric that more closely approximates how California's agricultural trees experience winter chill, have shown declines at far fewer sites. While warming winter temperatures in California's Central Valley are reflected in the "chill hours" metric, temperatures have not warmed enough to substantially impact the accumulation of "chill portions" in the region.

Figure 1. Long-term trends in winter chill in California's Central Valley



Source: UC Davis, 2017

Chill hours *(Fig 1A) represent the number of accumulated hours equal to or less than 45°F and above 32°F over the winter season (approximated as November 1st to February 28th).*
Chill portions *(Fig 1B) are accumulated based on different chill values assigned to different temperatures, including temperatures up to 54°F, where the accumulation can be reduced by periods of warm temperature. (See text for explanation and appendix for a map with location names.)*

What does the indicator show?

Winter chill is a period of cold temperatures above freezing required for deciduous fruit and nut trees to produce flowers and fruit. The amount of chill that is required is dependent on the type of tree, for example, whether they are almonds, apricots, cherries, grapes, peaches, pistachios or walnuts. As shown in Figure 1, winter chill in California's fruit- and nut-growing Central Valley has shown different trends over the past three to six decades, depending on how chill is calculated. Figure 1A presents chill hours, which have been declining in more than half of the sites studied (13 out of 20, $p<0.05$). However, chill portions, presented in Figure 1B, show significant negative trends at only a few sites.

Different models have been developed to approximate how trees respond to the passage of this cold period. Chill hours have been used to measure winter chill since the 1940s; however, recent research favors the use of a more biologically based metric, chill portions (Luedeling et al., 2009). Chill portion is a better suited measurement of winter chill than chill hours for California's Mediterranean climate and mild winters. The *Technical Considerations (Data Characteristics)* section below provides a description of the differences in how chill hours and chill portions are calculated.

The increase in winter temperatures in the Central Valley is reflected in the decrease in chill hours at most of the sites. Given their lower temperature threshold (45°F), chill hours are more sensitive to warming temperatures. Unlike chill hours, chill portions show declining trends at just three sites – Coalinga, Kettleman, and Tracy-Carbona – and an increasing trend at one site (Visalia). At two additional sites – Orland and Winters, chill portions also appear to be declining ($0.1 \geq p \geq 0.05$; see Appendix for graphs). The fact that the increase in winter temperatures is not reflected in the chill portions metric indicates that temperatures have not warmed enough to affect the accumulation of biologically based chill portions, which are based on a higher temperature threshold (54°F).

Why is this indicator important?

An extended period of cold temperatures above freezing and below a threshold temperature is required for fruit and nut trees to become and remain dormant, and subsequently bear fruit. This chill requirement can vary widely from one fruit or nut to another, and even by variety of the same fruit (or nut). Fruit and nut trees need between 200 and 1,500 hours between 32 and 45°F during the winter (Baldocchi and Wong, 2006), or between 13 and 75 chill portions to produce flowers and fruit (Pope et al., 2014).

The importance of winter chill was demonstrated during the warm winter of 2013-2014. During this period, average chill portions dropped by 25 percent in the Central Valley. Orchards for many crops showed delayed and extended bloom, poor pollinizer overlap, and weak leaf-out. Low chill was likely responsible for much of the unusual tree behavior and low yields. Delayed bloom can extend later into spring, when conditions may be too warm for successful pollination. Extended bloom can result in changes in fruit or nut maturation timing, which could mean a more prolonged, costly harvest and increased risk of pests eating crops. Poor pollinizer overlap–-when the pollen-producing flowers and the fruit-producing flowers are not opening at the same time–-can result in decreased yield (Pope, 2014).

Current climate conditions provide the needed dormancy requirements partly as a result of prolonged periods of fog during the winter in the California Central Valley. In an analysis of weather data and satellite imagery for the Central Valley during the years 1981-2014, scientists found the number of winter fog events decreased 46 percent, on average, with much year-to-year variability (Baldocchi and Waller, 2014). If prolonged periods of winter fog disappear in the future, the Central Valley may experience larger diurnal swings in winter temperature and reduced hours below the critical temperature.

Future trend projections show that continued warming will reduce the accumulated winter chill for the Central Valley. By the middle to the end of the 21st century, it is projected that climatic conditions will no longer support current varieties of some of the main tree crops currently grown in California; chill hours are projected to show greater declines than chill portions. Current varieties of major tree crops may tolerate a 20 percent decline in winter chill. The tree crop industry will likely need to develop agricultural adaptation measures (e.g., the use of chill-compensating products, or by growing low-chill varieties) to cope with these projected changes. For some crops, production might no longer be possible (Luedeling et al., 2009). This would jeopardize the region's ability to sustain its production of high value nuts and fruits like almonds, cherries and apricots, resulting in serious economic, dietary and social consequences.

What factors influence this indicator?

The indicator is derived from temperature data, and as such, is influenced by the same factors that influence temperature. An additional consideration relates to the location where temperature measurements are taken, and whether they are close enough to the areas where fruits and nuts are grown to be representative of those air temperatures.

As discussed above, the choice of metric makes a difference in quantifying the magnitude of winter chill accumulation. The difference presented here between chill hours and chill portions is consistent with research that has modeled the potential impact of continued climate change. One study using weather data and several greenhouse gas emissions scenarios throughout California's Central Valley projected chill portions to decrease by 14 to 21 percent and chill hours to decrease by 29 to 39 percent between 1950 and 2050 (Luedeling et al., 2009). Projected impacts appear far more dramatic when seen through the lens of chill hours, although the chill hours model appears to be more sensitive to change than the trees themselves.

The influence of temperature on the biological processes underlying the breaking of dormancy — and the processes themselves — are poorly understood. It is known, however, that not all "chill" is effective. Temperatures above 45°F — which is common during the winter months in California — can cancel the effect of previous chill accumulation. Chill hours, which simply count the number of winter hours when temperatures are between the freezing point and 45°F, do not account for this cancelling effect. Chill portions, on the other hand, reflect a more biologically based theoretical framework, incorporating temperature fluctuations (see Luedeling et al., 2009 for details).

Technical Considerations

Data Characteristics

The indicator presents a metric for chill hours and the more mathematically complex metric for chill portions. The primary differences in the calculations for these two metrics are:

- Chill hours equally count any hour when temperatures are between 32-45°F. Chill portions give different chill values for temperatures, with those between 43-47°F having the most value. Chill values on either side of the range are lower.
- Chill hours only count up to 45°F. Chill portions count up to 54°F, which better approximates effective chilling for trees grown in fairly mild climates.
- Chill hours are a sum of hours between the temperatures described above, without accounting for warm hours. With chill portions, the running total of chill accumulation is reduced when warm hours closely follow cold periods.

Chill hours and chill portions were calculated using “chillR," a statistical model for phenology analysis (Leudeling, 2017). The model is an extension to a commonly used statistics software, R. It includes a library that provides a number of utilities for phenology analysis in fruit trees, including automated retrieval of climate data from weather station databases including the University of California Statewide Integrated Pest Management Program (UCIPM) archive for California, modeling of hourly temperatures from daily minimum and maximum temperatures, and computation of three different horticultural chill metrics (Chilling Hours, Chill Units, and Chill Portions) and one heat metric. Climate data for Central Valley locations listed in Baldocchi and Wong (2008) were retrieved through the chillR downloading interface. Climate stations for which data were not retrievable from the UCIPM archive were omitted from the analysis.

The UCIPM archive includes data from the California Irrigation Management Information System (CIMIS) and the National Weather Service Cooperative Network (NWS COOP). Hourly temperature records, which are needed to calculate chill accumulation, are available from CIMIS. However, these stations only have data back to 1982; some stations were established even more recently. NWS COOP has records that date back decades earlier (the earliest records used in this indicator start in 1951), but only for daily maximum and minimum temperature; hourly temperatures were estimated using an algorithm based on diurnal temperature trends and reported maximum and minimum temperature (chillR, Leudeling, 2017).

NWS COOP station winter records were analyzed for trends from 1953 to 2010. CIMIS station winter records were analyzed from the beginning of the record, which was in the early-to-mid 1980s, depending on the station, until 2017.

Strengths and Limitations of the Data

Summary statistics that are commonly used to track temperature (such as average, minimum and maximum) generally do not provide the resolution necessary to examine temperature trends relevant to agriculture. Deriving winter chill accumulation from temperature data for the winter months yields a more meaningful measure for tracking a change in climate that would be more predictive of fruit production. Winter chill accumulation provides an indication of whether specific fruit and nut trees are experiencing sufficient periods of dormancy.

The hourly data from CIMIS provide direct inputs into the calculation of winter chill degree hours, unlike daily minimum and maximum temperature data from NWS, which require the use of an algorithm. CIMIS weather stations are designed to monitor agricultural climate conditions. Thus, they are almost exclusively in agricultural areas, with the monitoring equipment located in a well-irrigated pasture. NWS COOP weather stations are designed with a broader use in mind. As such, they are generally located in developed, paved areas – in towns and cities, or at airports. As a result, temperatures at the NWS COOP stations in the winter are likely higher than they would be in an open field a few miles away. While this means that the chill accumulation at each NWS COOP weather station may not be precisely representative of what an orchard in that area would experience, any trends of increased or decreased chill accumulation of years and decades would likely be similar.

Historic temperature records are rarely complete. Many different approaches are used to fill in gaps in temperature records to analyze long term trends. In this study, hourly or daily temperatures were interpolated following Luedeling (2017). If more than 50 percent of the winter record required interpolation, that winter was not included in the analysis.

The chill portions model has become increasingly popular for climates with Mediterranean or otherwise mild winters. Multiple studies have found the chill portions model to count winter chill accumulation does as well as or better than the chill hours model.

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Modeling and data analysis provided by Allan Hollander, UC Davis Information Center for the Environment.

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Baldocchi D and Waller E (2014). Winter fog is decreasing in the fruit growing region of the Central Valley of California. *Geophysical Research Letters.* **41**(9).

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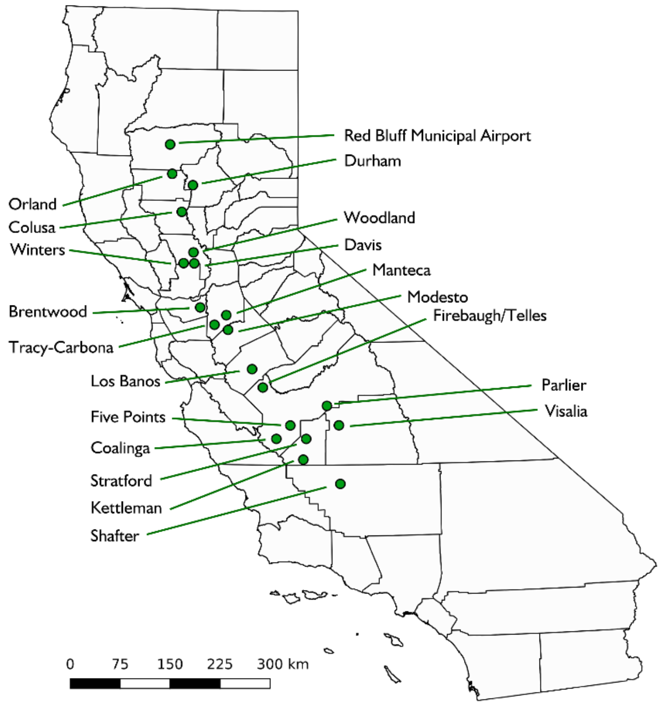
UC Davis (2017). Chill hours and chill portions at selected Central Valley sites, estimated using chillR (Luedeling 2017), using data from UC IPM (Weather, Models, and Degree Days. University of California Statewide Integrated Pest Management System). November, 2017.

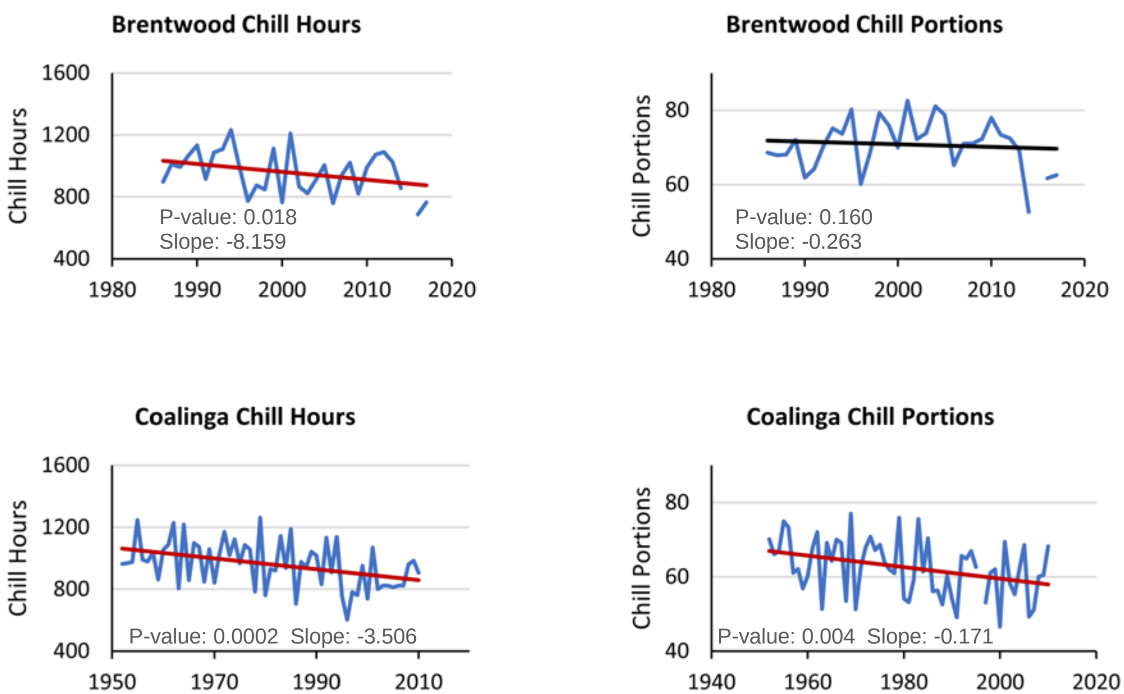
APPENDIX

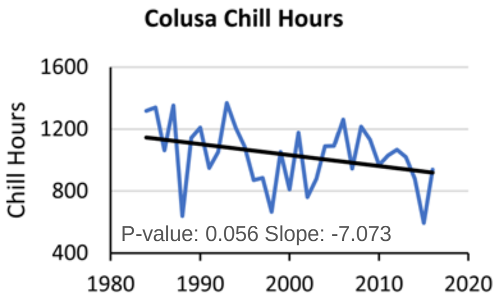
Figure A1. Map of winter chill sites in California

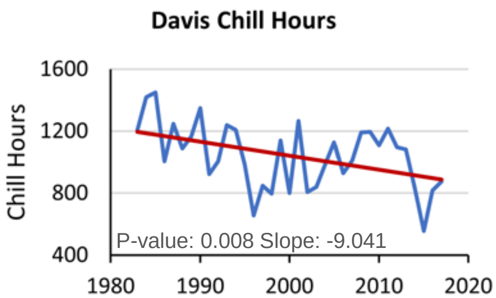


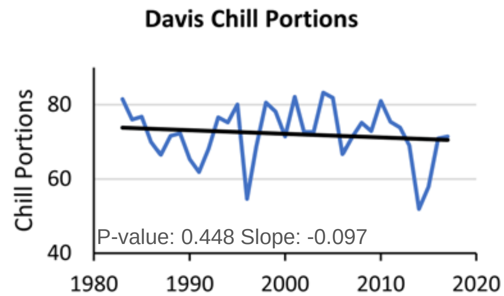
Source: UC Davis, 2017

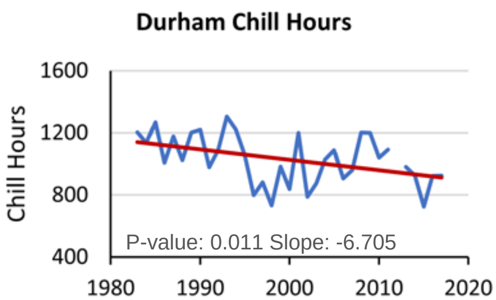
Figure A2. Long-term trends in chill hours and chill portions, by location
Statistically significant trends ($p<0.05$) are shown as red lines; non-significant trends, as gray lines.

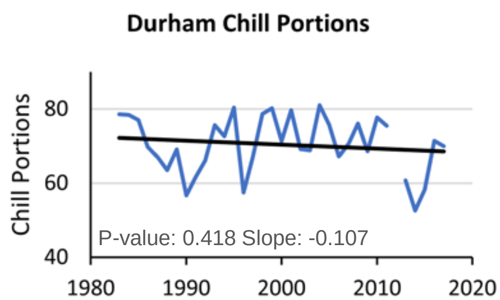


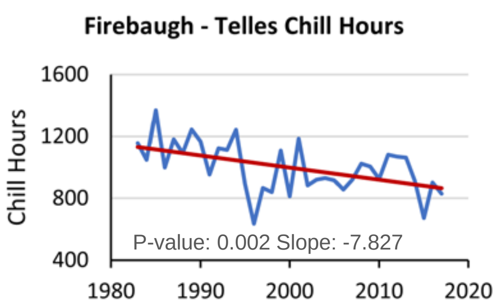

Colusa Chill Hours
Chill Hours
1600
1200
800
400
P-value: 0.056 Slope: -7.073
1980
1990
2000
2010
2020

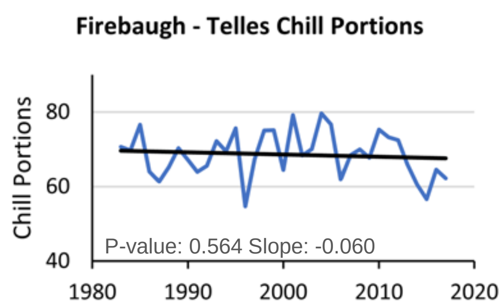

Davis Chill Hours
Chill Hours
1600
1200
800
400
P-value: 0.008 Slope: -9.041
1980
1990
2000
2010
2020

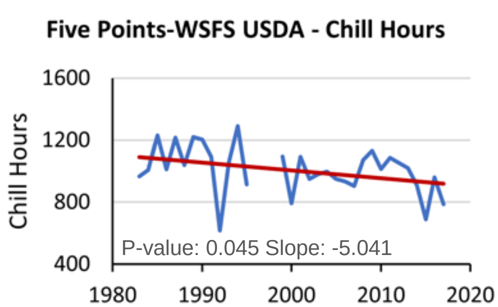

Davis Chill Portions
Chill Portions
80
60
40
P-value: 0.448 Slope: -0.097
1980
1990
2000
2010
2020

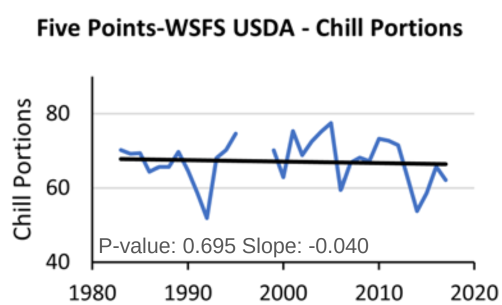

Durham Chill Hours
Chill Hours
1600
1200
800
400
P-value: 0.011 Slope: -6.705
1980
1990
2000
2010
2020

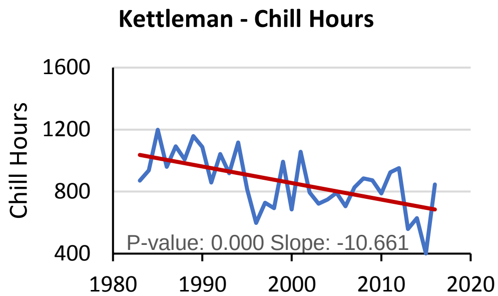

Durham Chill Portions
Chill Portions
80
60
40
P-value: 0.418 Slope: -0.107
1980
1990
2000
2010
2020

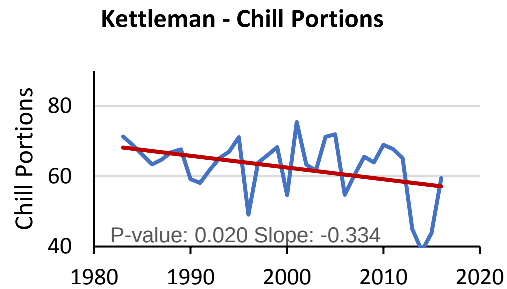

Firebaugh - Telles Chill Hours
Chill Hours
1600
1200
800
400
P-value: 0.002 Slope: -7.827
1980
1990
2000
2010
2020

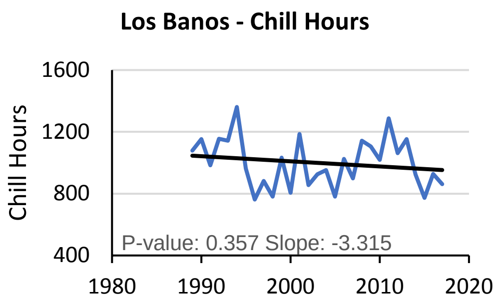

Firebaugh - Telles Chill Portions
Chill Portions
80
60
40
P-value: 0.564 Slope: -0.060
1980
1990
2000
2010
2020

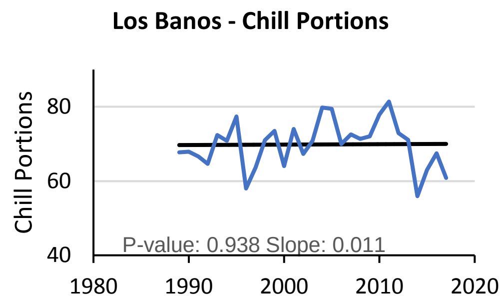

Five Points-WSFS USDA - Chill Hours
Chill Hours
1600
1200
800
400
P-value: 0.045 Slope: -5.041
1980
1990
2000
2010
2020

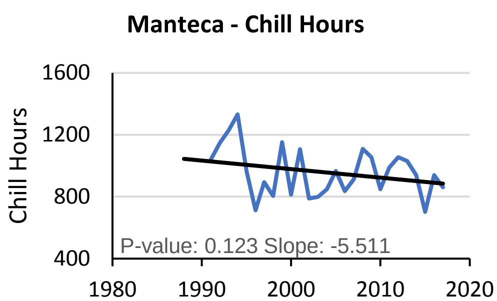

Five Points-WSFS USDA - Chill Portions
Chill Portions
80
60
40
P-value: 0.695 Slope: -0.040
1980
1990
2000
2010
2020

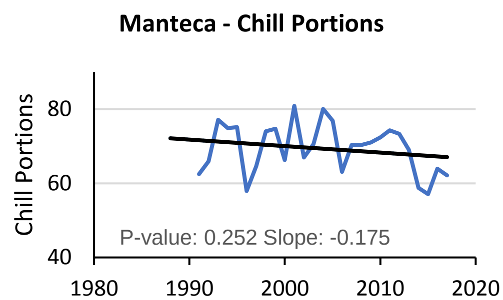

Kettleman - Chill Hours
Chill Hours
1600
1200
800
400
1980
1990
2000
2010
2020
P-value: 0.000 Slope: -10.661

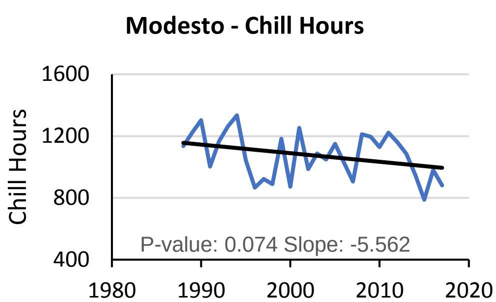

Kettleman - Chill Portions
Chill Portions
80
60
40
1980
1990
2000
2010
2020
P-value: 0.020 Slope: -0.334

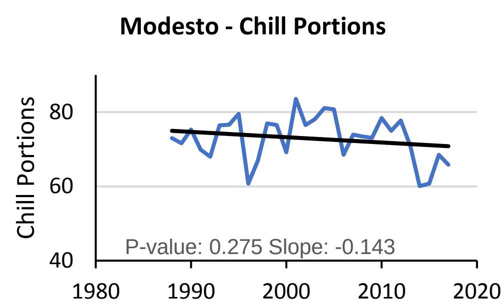

Los Banos - Chill Hours
Chill Hours
1600
1200
800
400
1980
1990
2000
2010
2020
P-value: 0.357 Slope: -3.315

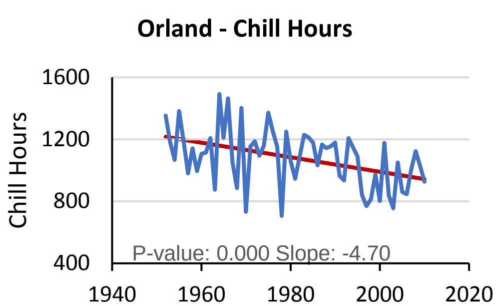

Los Banos - Chill Portions
Chill Portions
80
60
40
1980
1990
2000
2010
2020
P-value: 0.938 Slope: 0.011

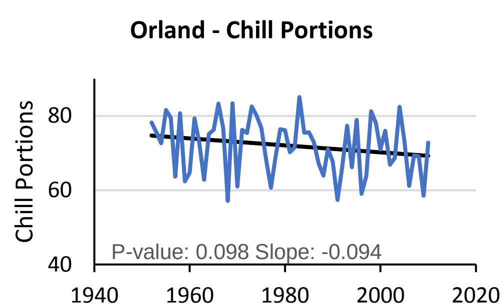

Manteca - Chill Hours
Chill Hours
1600
1200
800
400
1980
1990
2000
2010
2020
P-value: 0.123 Slope: -5.511


Manteca - Chill Portions
Chill Portions
80
60
40
1980
1990
2000
2010
2020
P-value: 0.252 Slope: -0.175

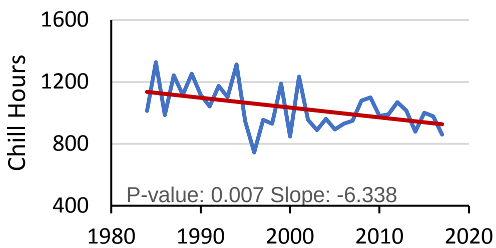

Modesto - Chill Hours
Chill Hours
1600
1200
800
400
1980
1990
2000
2010
2020
P-value: 0.074 Slope: -5.562


Modesto - Chill Portions
Chill Portions
80
60
40
1980
1990
2000
2010
2020
P-value: 0.275 Slope: -0.143

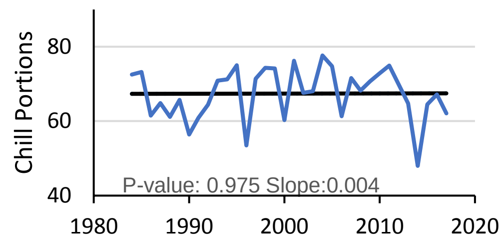

Orland - Chill Hours
Chill Hours
1600
1200
800
400
1940
1960
1980
2000
2020
P-value: 0.000 Slope: -4.70


Orland - Chill Portions
Chill Portions
80
60
40
1940
1960
1980
2000
2020
P-value: 0.098 Slope: -0.094

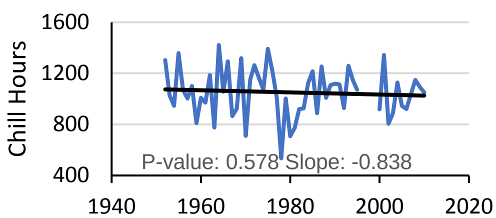
Parlier - Chill Hours



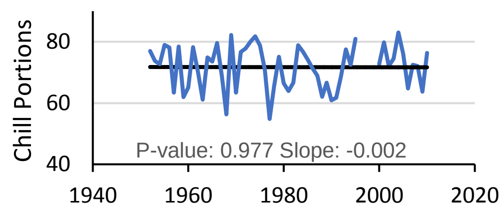
Parlier - Chill Portions



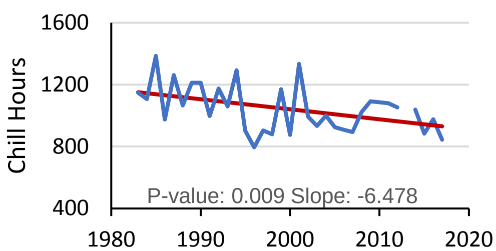
Red Bluff Municipal Airport - Chill Hours



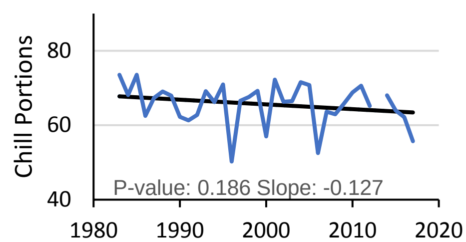
Red Bluff Municipal Airport - Chill Portions



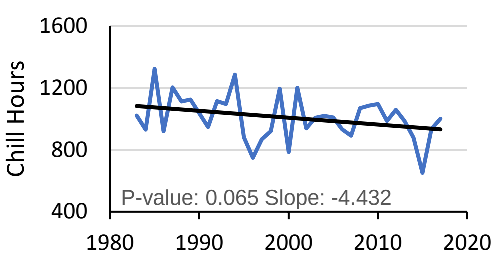
Shafter USDA - Chill Hours



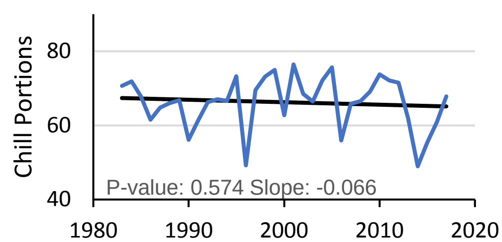
Shafter USDA - Chill Portions



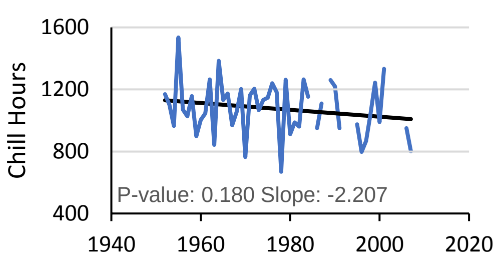
Stratford - Chill Hours



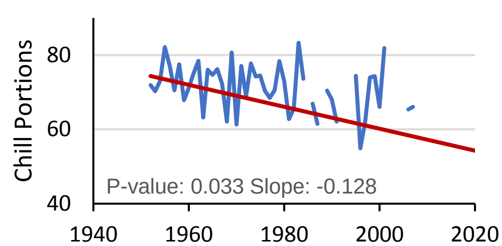
Stratford - Chill Portions

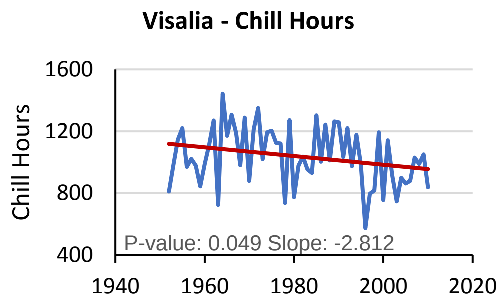


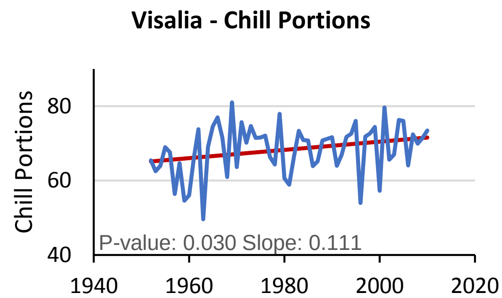
Tracy-Carbona - Chill Hours

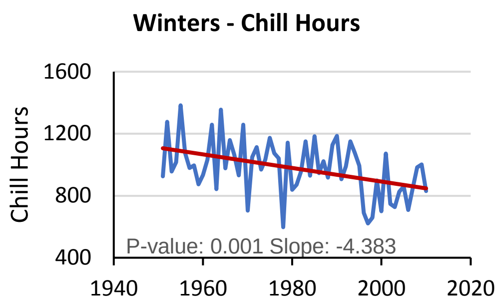


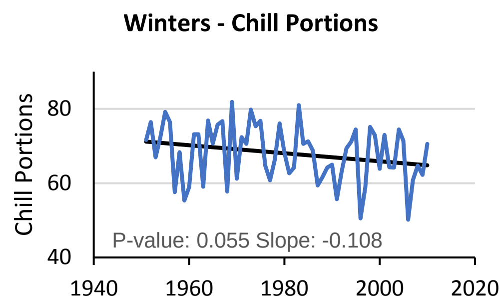
Tracy-Carbona - Chill Portions

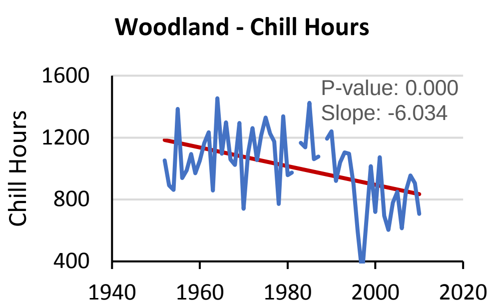


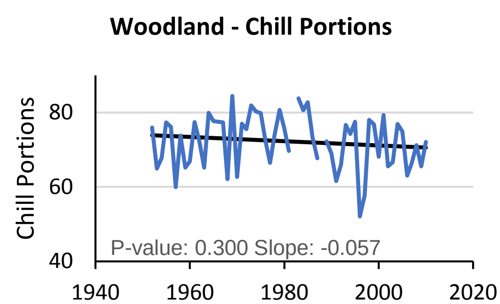












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