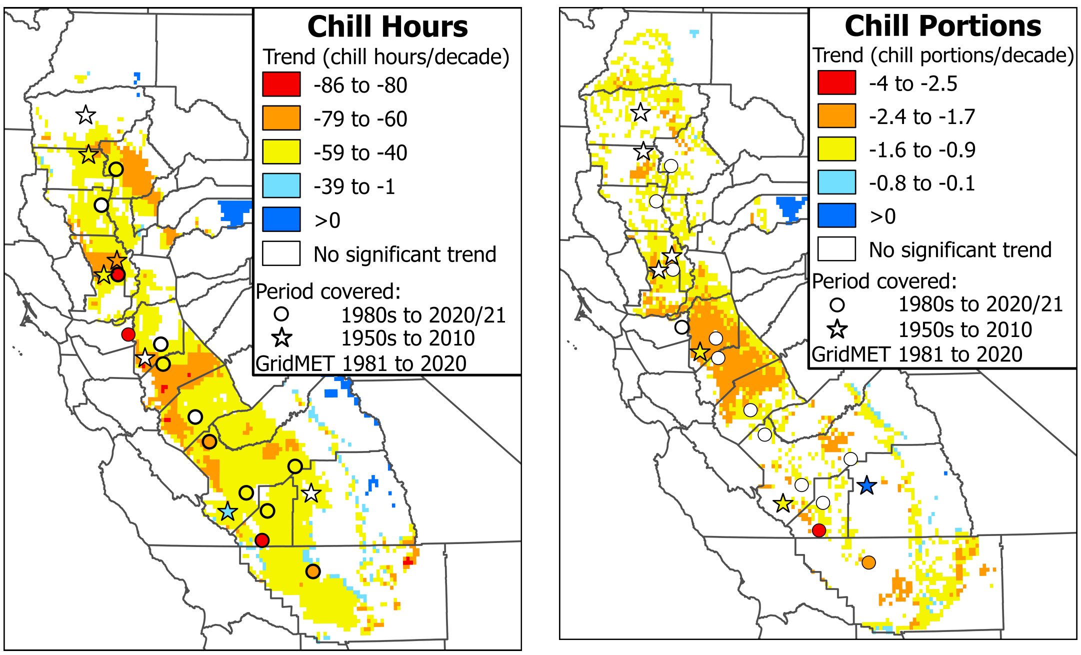
WINTER CHILL

Warming winter temperatures are reflected in declining trends in "winter chill," a measure of cold temperatures required for fruit and nut trees to produce flowers and fruits. Winter chill is tracked in two ways: "chill hours," a very sensitive and rudimentary metric used since the 1940s; and "chill portions," a biologically based metric that more closely approximates how California's agricultural trees experience winter chill. Both metrics show decreasing trends across the Central Valley over the past several decades.

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

A. Chill hours **B. Chill portions**



Source: GridMET analysis based on Zhang et al., 2021; weather station analysis based on UC Davis, 2021

A. Chill hours *represent the number of accumulated hours equal to or less than 45°F and above 32°F over the winter season.* ***B. Chill portions*** *accumulate most between 43° and 47°F, and progressively less at either side of this range, dropping to zero at 32°F and 54°F; periods of warm temperature can cancel this accumulation.*

Stars and circles represent trends at weather stations; coloring throughout the map represents trends derived from gridMET, a spatial data set, where white areas indicate non-significant trends ($p<0.05$). Trends for weather station sites use winter dates from November 1st to February 28th; gridMET-based trends use winter dates from November 1st to January 31st. (See Figure A-1 in the appendix for a map of weather station locations).

Figure 2. Location of weather stations analyzed for winter chill

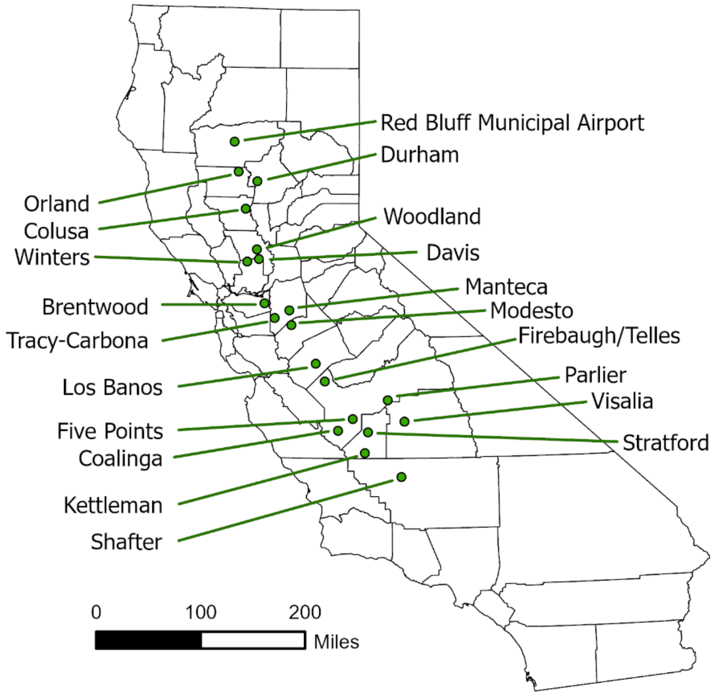


Table 1. Long-term decadal trends in winter chill at selected weather stations

Station	Years included	Chill hours trend (*p-value*)*	Chill portions trend (*p-value*)
Brentwood	1985-2019	-81.2 *(0.01)**	-2.4 *(0.17)*
Coalinga	1952-2010	-33.9 *(<0.01)**	-1.6 *(<0.01)**
Colusa	1983-2016	-70.7 (0.06)	0 (0.99)
Davis	1983-2021	-85.9 *(<0.01)**	-1.5 *(0.14)*
Durham	1983-2021	-46.8 *(0.03)**	-0.9 *(0.38)*
Firebaugh/Telles	1983-2020	-76.0 *(<0.01)**	-0.9 *(0.29)*
Five Points/WSFS USDA	1983-2020	-45.9 *(0.03)**	-0.8 *(0.38)*
Kettleman	1982-2016	-106.6 *(<0.01)**	-3.3 (0.02)*
Los Banos	1989-2020	-38.4 *(0.21)*	-1.5 *(0.23)*
Manteca	1988-2021	-30.1 *(0.29)*	-2.1 *(0.07)*
Modesto	1988-2021	-50.1 *(0.05)*	-2.0 *(0.05)*
Orland	1952-2010	-45.8 *(<0.01)**	-0.8 *(0.14)*
Parlier	1984-2021	-51.0 *(0.01)**	-1.1 *(0.32)*
Red Bluff Municipal Airport	1952-2010	-7.9 *(0.60)*	-0.1 *(0.84)*
Shafter/USDA	1983-2020	-69.6 *(<0.01)**	-1.9 *(0.03)**
Stratford	1983-2020	-43.6 *(0.04)**	-1.3 *(0.19)*
Tracy-Carbona	1952-2007	-19.7 *(0.23)*	-1.2 *(0.03)**
Visalia	1952-2010	-27.3 *(0.05)*	+1.2 *(0.02)**
Winters	1951-2010	-43.0 *(<0.01)**	-1.0 *(0.07)*
Woodland	1952-2010	-60.4 *(<0.01)**	-0.5 *(0.38)*

** Statistically significant trends (where p<0.05) are indicated with an asterisk.*

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 fruits. Two commonly used winter chill metrics are presented in Figure 1. The first metric, chill hours (Figure 1A), represents the number of accumulated hours equal to or less than 45 degrees Fahrenheit (°F) and above 32°F over the winter season. Chill hours have been used since the 1940s. However, recent research favors the use of a more biologically based metric, chill portions (Figure 1B). Chill portions accumulate in a two-step process: (1) exposure to cold temperatures accumulate as a "chill intermediate"; this accumulation is negated by exposure to temperatures above 54°F; (2) a certain quantity of these intermediates make up a "chill portion," which cannot be reversed by high temperatures (Luedeling et al., 2009).

Figure 1 presents trends for chill hours and chill portions based on two sources: temperature observations from weather stations (stars and circles, refer to Figure 2 for locations), and modeled high-spatial resolution surface temperatures (gridMET) (colored or white areas on the map). Weather station data show that chill hours have declined at more than half of the weather stations studied (12 out of 20, $p<0.05$; at two other stations, $p=0.05$) (Figure 1A, Table 1). Chill portions show statistically significant declining trends at just four weather stations – Kettleman, Coalinga, Shafter, and Tracy-Carbona (at one other station, $p=0.05$) – and an increasing trend (also significant) at one station (Visalia; Figure 1B, Table 1). Graphs for each weather station presenting data for chill hours and chill portions are in Figure A-1.

Winter chill trends were calculated using gridMET for 19 counties within the Central Valley: Butte, Colusa, Glenn, Fresno, Kern, Kings, Madera, Merced, Placer, San Joaquin, Sacramento, Shasta, Solano, Stanislaus, Sutter, Tehama, Tulare, Yolo, and Yuba. These estimates show declining chill hours in much of the Central Valley (Figure 1A); chill portions are also declining, although at a smaller spatial extent (Figure 1B). The latter suggests that although temperatures have warmed in certain areas, they may not have warmed enough across the region to affect the accumulation of biologically based chill portions, which account for hours at a higher temperature threshold (54°F) than chill hours (32°F - 45°F).

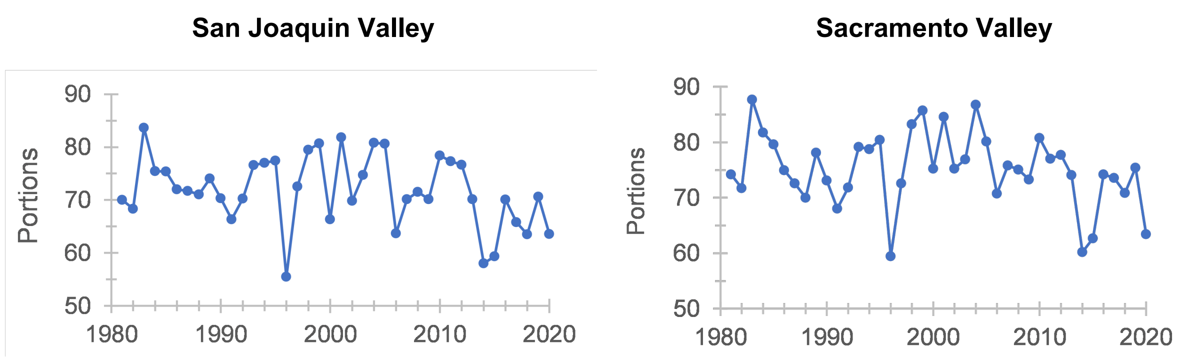
The influence of temperature on the biological processes underlying the breaking of dormancy — and the processes themselves — are poorly understood. It is known, however, that not all "chill" is effective. The chill portion metric considers this by incorporating a more biologically based theoretical framework: temperatures above 54ºF —common during the winter months in California — cancel the effect of previous chill accumulation (Luedeling et al., 2009). Chill hours, which count the number of winter hours when temperatures are between the freezing point and 45ºF, do not account for this canceling effect. For California's Mediterranean climate and mild winters in California's fruit and nut-growing regions, chill portions are better suited for tracking winter chill than chill hours. (See *Technical considerations* for how these metrics are calculated.) The amount of chill that is required is dependent on the type of tree; for example, almonds require 250 to 350 chill hours or 22 to 32 chill portions; apples, 1200 to 1500 chill hours or 50 chill portions; and Bing cherries, 1000 to 1300 chill hours or 65 chill portions (Erez, 2020 and Ryugo, 1988).

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 then bear fruit. As noted above, this chill requirement can vary widely from one fruit or nut to another and even across varieties of the same fruit or nut. Fruit and nut trees need 200 to 1,500 hours of temperature between 32°F and 45°F during the winter (Baldocchi and Wong, 2006), or between 13 and 75 chill portions to produce flowers and fruits (Pope et al., 2014).

The warm winter of 1998 and 2013-2014 demonstrated the importance of winter chill (Figure 3). Above-normal temperatures in January and February of 1998 meant many fruit and nut trees did not receive sufficient chilling time necessary for dormancy; revenues from almonds and cherries dropped by about 40 and 50 percent, respectively, compared to the two prior years (USDA, 2022). During 2013-2014, the Central Valley's average chill portions dropped by 25 percent. As a result, orchards for many crops showed delayed and extended bloom, poor pollinizer overlap (when the pollen-producing flowers and the fruit-producing flowers do not open simultaneously), and weak leaf-out (when fewer leaves emerge). The 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 an increased risk of pests eating crops (Pope, 2014).

Figure 3. Chill portions from 1981-2020



Source: Parker et al., 2022

Annual chill portions within two regions of the Central Valley (San Joaquin Valley and Sacramento Valley)

Prolonged periods of fog during the winter in the California Central Valley provide favorable conditions to meet dormancy requirements. 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 by 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 sun hitting buds in the Central Valley will increase the internal temperature in the buds, thus reducing the number of hours below the critical temperature. Agronomists are finding methods to adapt to this, such as by applying kaolin clay to reflect sunlight or calcium carbonate to modify incoming light (Beede, 2016).

Future trend projections show that continued warming will reduce the accumulated winter chill in the Central Valley (Luedeling et al., 2009). By the middle to the end of the 21st century, projections suggest 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, and current varieties of major tree crops may tolerate a 20 percent decline in the winter chill. This decline 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. The tree crop industry will likely need to develop agricultural adaptation measures (e.g., using chill-compensating products or growing low-chill varieties) to cope with these projected changes.

What factors influence this indicator?

The indicator is derived from temperature data. As such, it is influenced by the same factors that influence air temperature; the increase in winter temperatures in the Central Valley (see *Air temperature* indicator) is reflected in the decrease in chill hours at most of the weather stations and throughout the region. In addition to regional influences such as topography and proximity to the ocean, local factors such as degree of urbanization and land use can affect temperature. Furthermore, "microclimates" exist within the same orchard, so temperature differences could occur at smaller spatial scales.

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. For example, 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 changes in temperature than the trees themselves.

While both metrics quantify chill accumulation, factors such as proximity of the weather station or, as noted above, the presence of microclimates introduce uncertainties in whether the temperature measurements used in deriving them are representative of what trees are experiencing.

Technical considerations

Data characteristics

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

- Chill hours equally count any hour when temperatures are between 32°F and 45°F. Chill portions accumulate when temperatures are between 32°F and 54°F, with the most accumulation occurring between 43°F and 47°F.
- 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. Chill portions accumulate in a two-step process first reaching a "chill intermediate" that can be negated by exposure to high temperatures (above 54°F); a certain quantity of chill intermediates make up a "chill portion," which cannot be reversed by high temperatures (Leudeling et al., 2009).

Weather station-based 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. Weather station data for Central Valley locations listed in Baldocchi and Wong (2008) were retrieved through the chillR downloading interface. Stations for which data were not retrievable from the University of California Statewide Integrated Pest Management Program (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. 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 (Leudeling, 2017).

To estimate chill hours and chill portions using gridMET, daily temperature time series were downscaled to hourly and fed into chillR (Zhang et al., 2021). GridMET trends were calculated for the 19 counties within the Central Valley: Butte, Colusa, Glenn, Fresno, Kern, Kings, Madera, Merced, Placer, San Joaquin, Sacramento, Shasta, Solano, Stanislaus, Sutter, Tehama, Tulare, Yolo and Yuba.

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 climate trends relevant to agriculture. Deriving 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.

Historical temperature records are rarely complete. Many different approaches are used to fill in gaps in temperature records to analyze long-term trends. In this report, hourly or daily station 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.

GridMET provides a daily temperature product at a 4-km spatial resolution within the USA from 1979 to the present. This allows for analyses across the entire landscape, unlike weather station data which only shows weather at one location. Since gridMET is modeled product, it may not be as accurate as station-based data. However, like weather station data, the direction of the gridMET trends is accurate.

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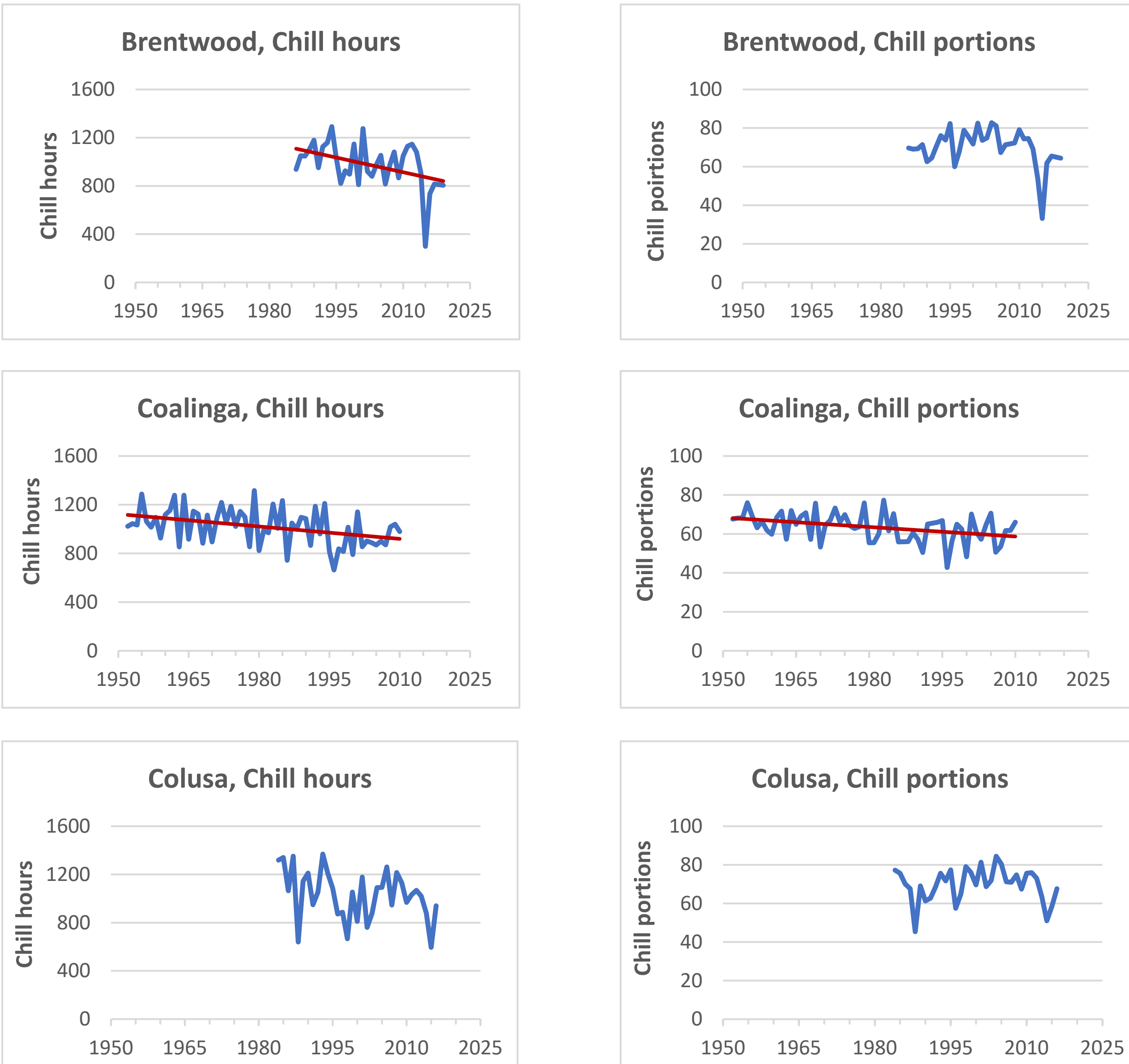
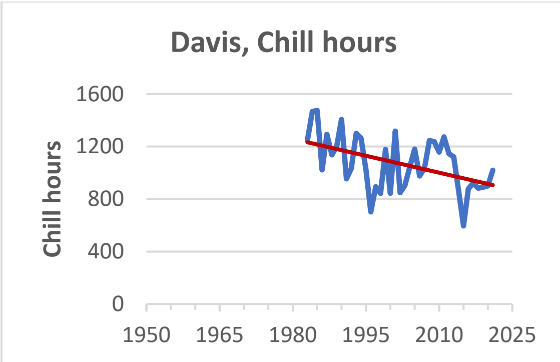
Appendix

Figure A-1. Long-term trends in chill hours and chill portions, by location.

Statistically significant trends ($p<0.05$) are shown as red lines; no trend line is shown for non-significant trends.

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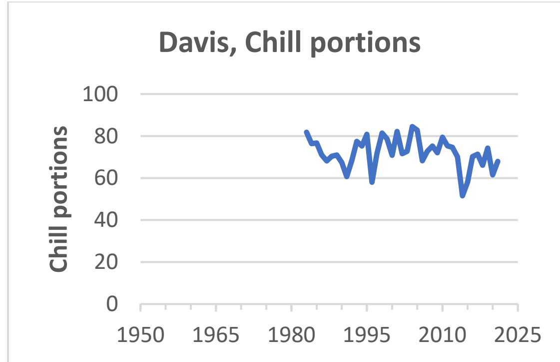
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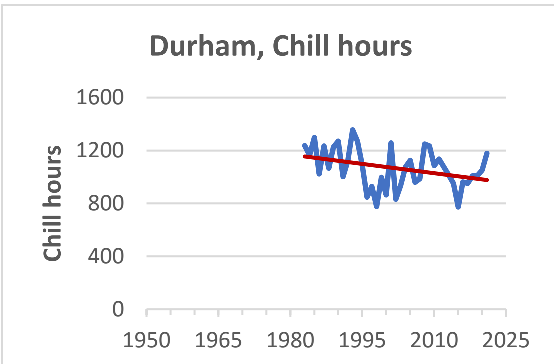
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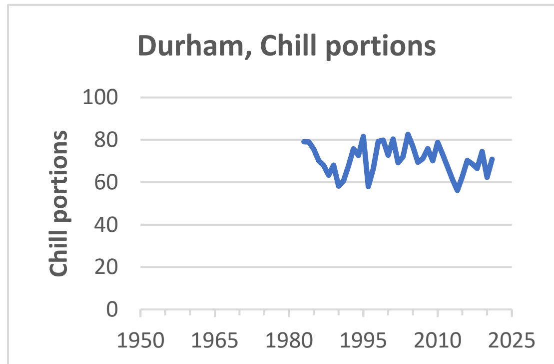
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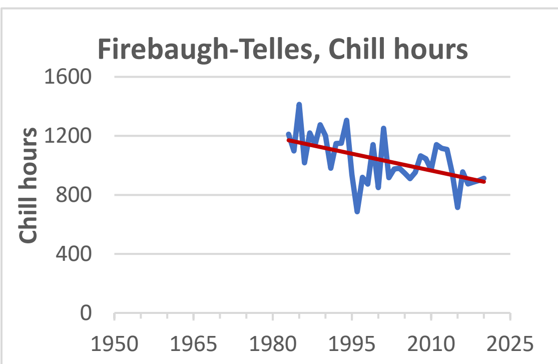
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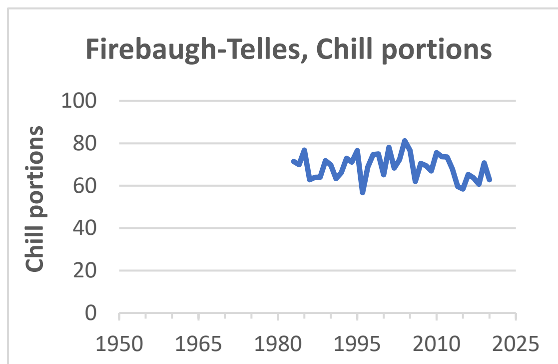
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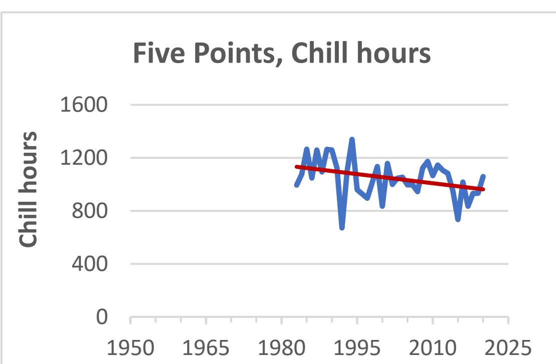
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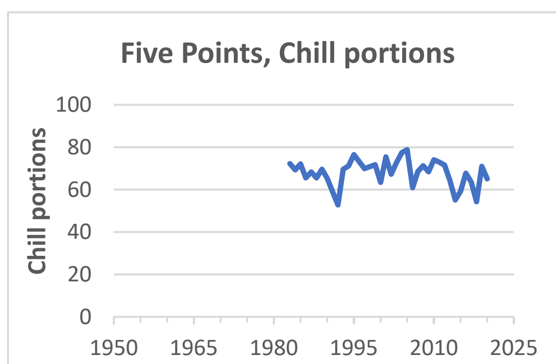
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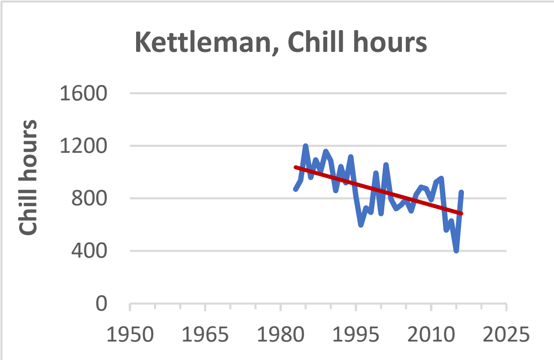
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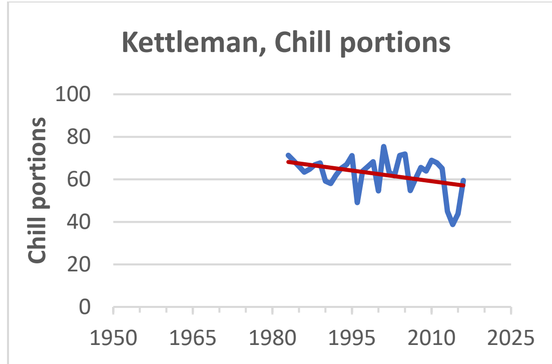
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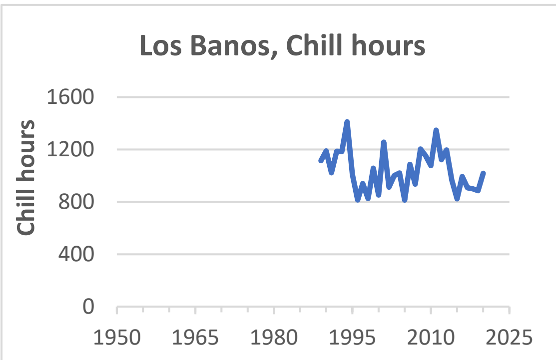
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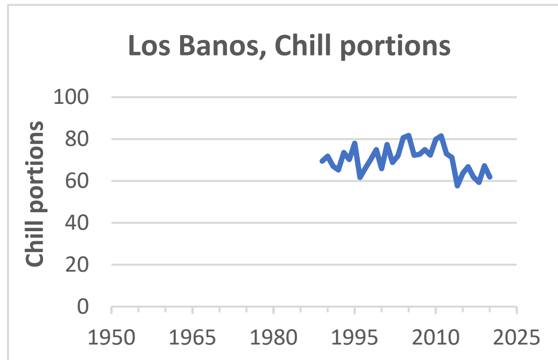
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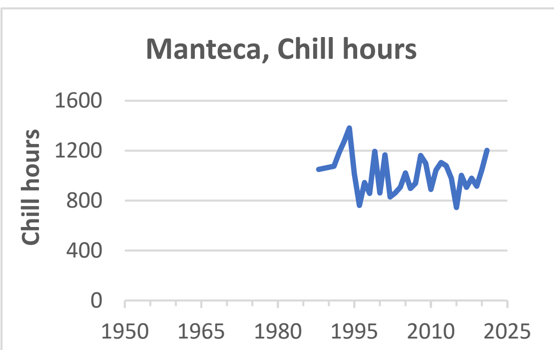
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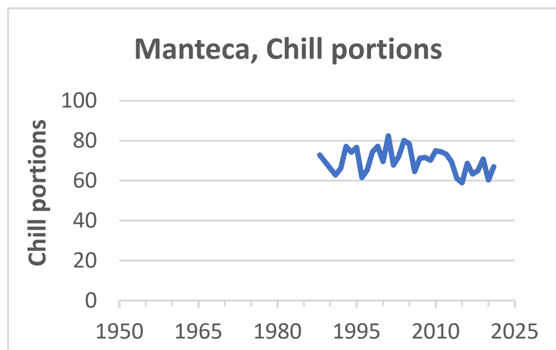
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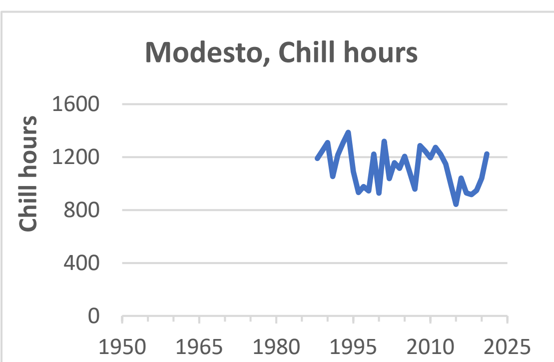
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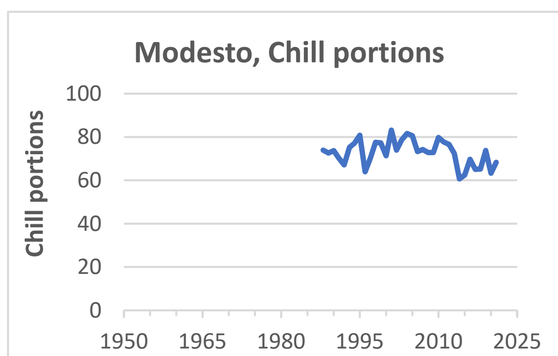
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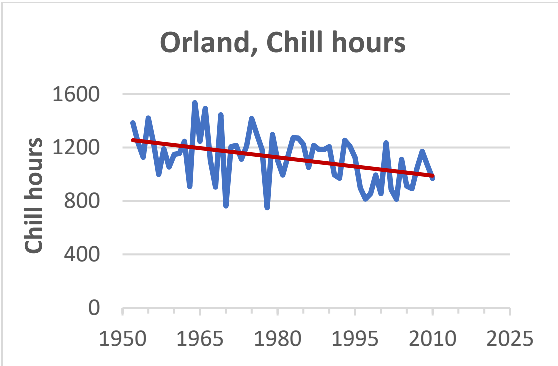
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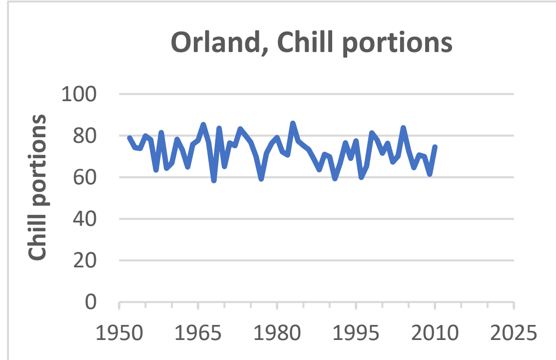
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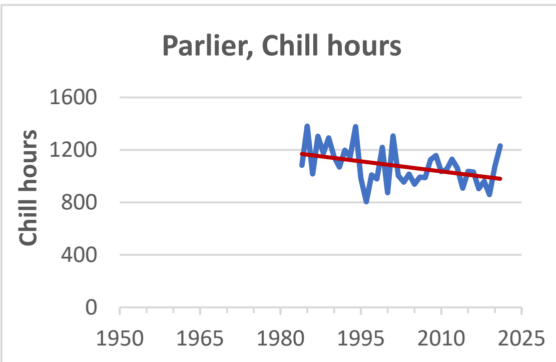
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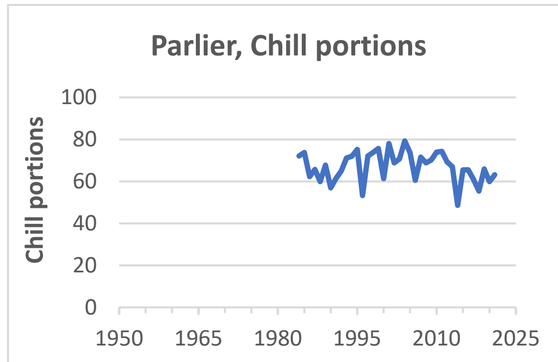
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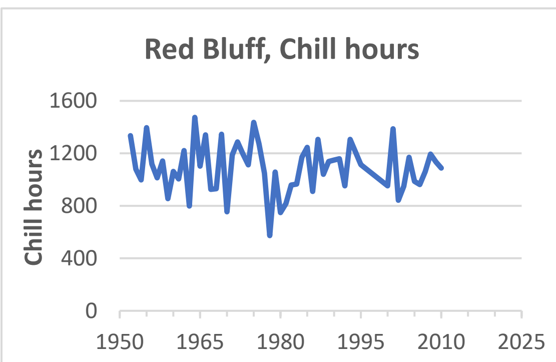
Red Bluff, Chill hours
Chill hours
1600
1200
800
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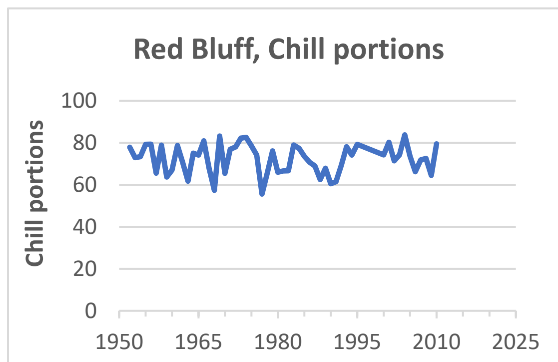
1950
1965
1980
1995
2010
2025


Red Bluff, Chill portions
Chill portions
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2010
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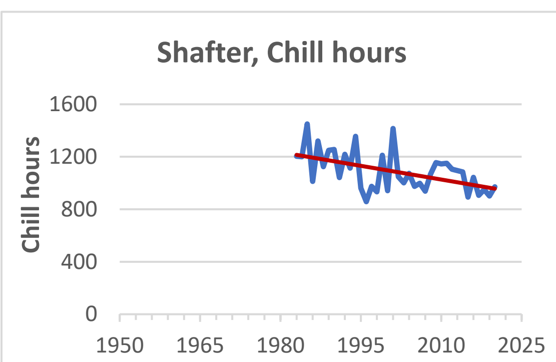
Shafter, Chill hours
Chill hours
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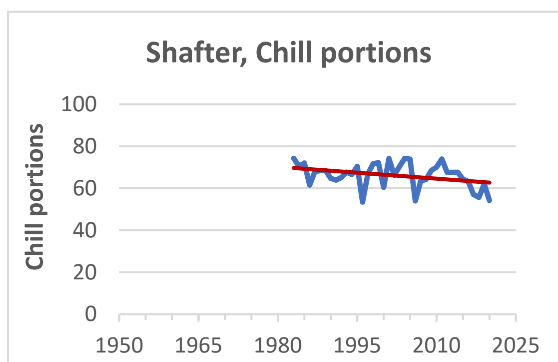
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Chill portions
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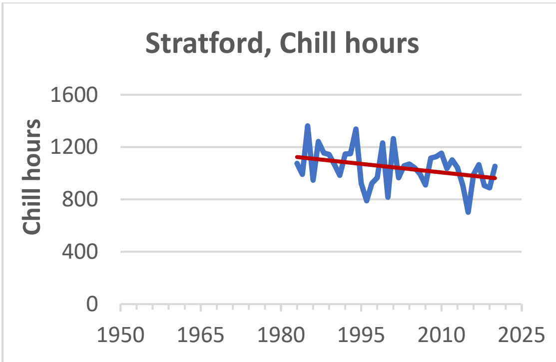
Stratford, Chill hours
Chill hours
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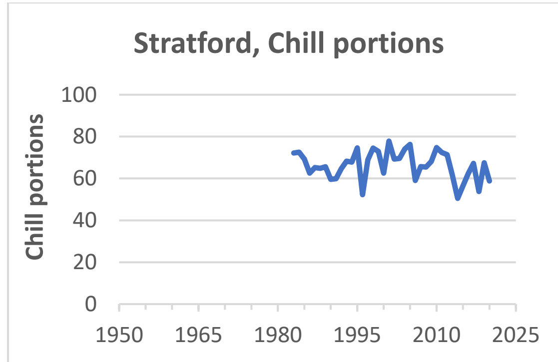
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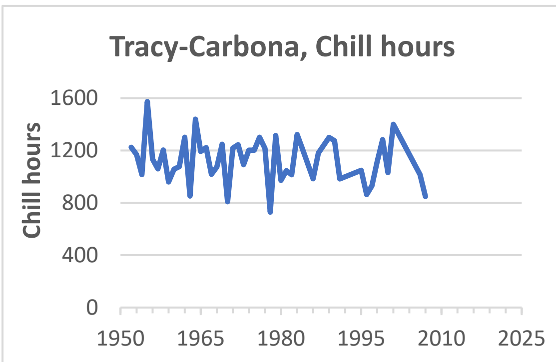
Tracy-Carbona, Chill hours
Chill hours
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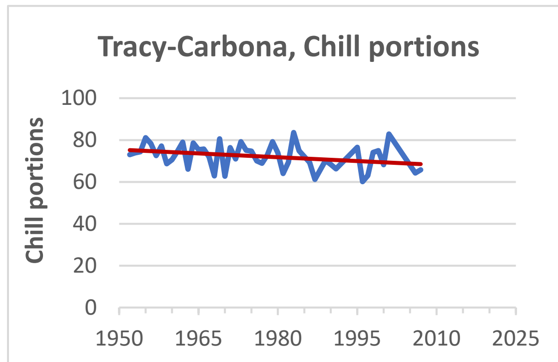
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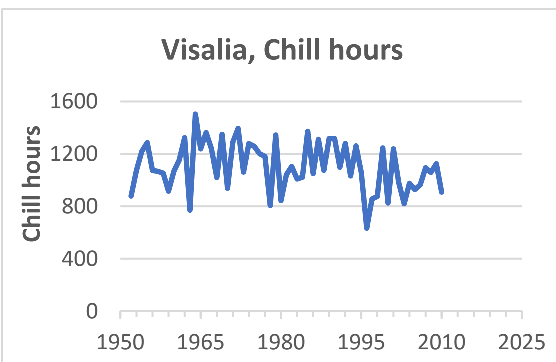
Visalia, Chill hours
Chill hours
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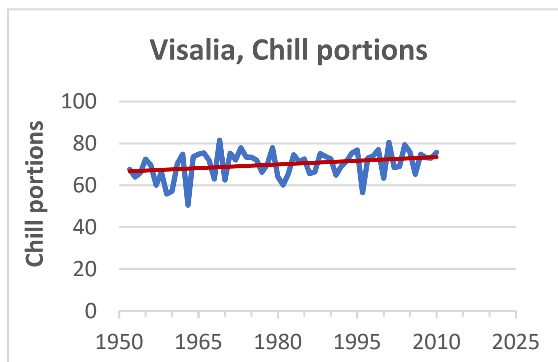
Visalia, Chill portions
Chill portions
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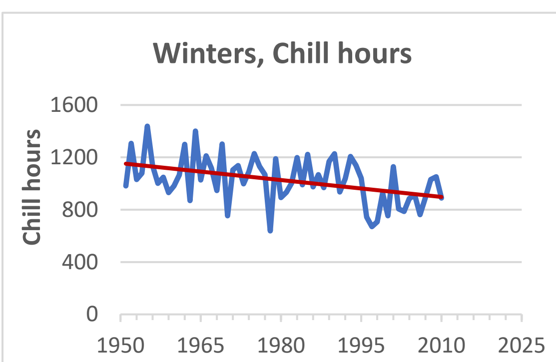
Winters, Chill hours
Chill hours
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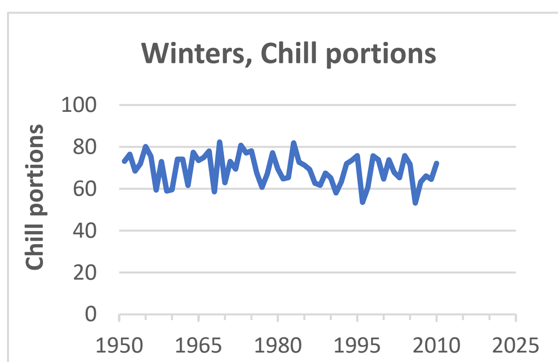
2025


Winters, Chill portions
Chill portions
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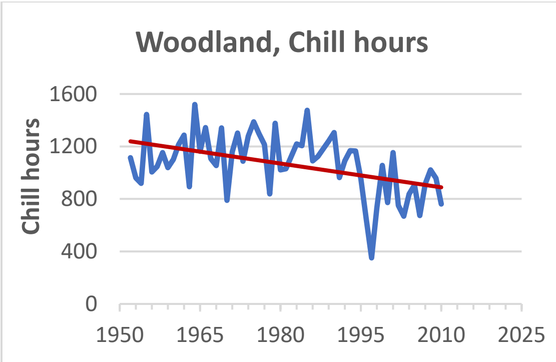
Woodland, Chill hours
Chill hours
1600
1200
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400
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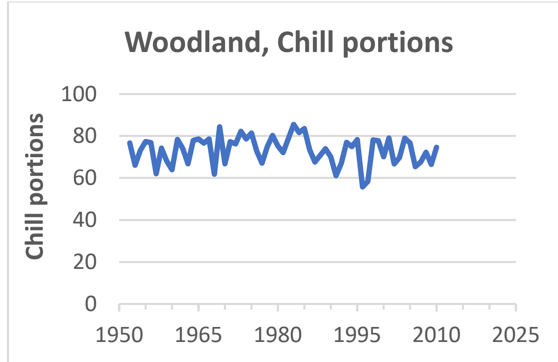
1950
1965
1980
1995
2010
2025


Woodland, Chill portions
Chill portions
100
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1980
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2010
2025