Historical change of winter chill accumulation in some regions of Turkey

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RESUMEN

Los árboles frutales de hoja caduca deben estar expuestos a bajas temperaturas invernales durante un cierto período de tiempo para producir cosechas regulares. Además de los efectos del calentamiento global en muchas otras áreas, su efecto sobre la acumulación de frío también es preocupante. Como resultado de ello, se han realizado estudios en importantes áreas hortícolas del mundo sobre el impacto del cambio climático en la acumulación de frío. En este estudio, por primera vez, se examinaron los cambios históricos de la acumulación de frío calculados con cinco modelos en 12 lugares de Turquía. Se determinó que no hay una tendencia significativa en la acumulación de frío en algunas de las provincias estudiadas (Ankara, Bingöl, Diyarbakır, Malatya y Tunceli). En algunas ubicaciones, la importancia, magnitud y dirección de la tendencia de enfriamiento difirieron según el modelo utilizado. Según los cinco modelos utilizados en el estudio, en la localidad de Şanlıurfa, con inviernos relativamente suaves, se advirtieron disminuciones significativas en la acumulación de frío invernal. En Erzincan, que tiene inviernos relativamente fríos, se detectaron tendencias crecientes en la acumulación de frío calculada según los modelos de Utah, Utah modificado y Utah positivo. Los resultados han demostrado que pueden surgir graves consecuencias en términos de los requerimientos de frío de árboles de hoja caduca, especialmente en regiones con inviernos suaves.

ABSTRACT

Deciduous fruit trees need to be exposed to low winter temperatures for a certain period of time to produce regular crops. In addition to the effects of global warming in many other areas, its effect on cold accumulation is also a reason of concern. As a result, many studies have been carried out in important horticultural areas around the world on the impact of climate change on cold accumulation. In this study, historical changes of cold accumulation calculated using five models were examined in 12 locations in Turkey for the first time. Results show that there was no significant trend in cold accumulation in the provinces of Ankara, Bingöl, Diyarbakır, Malatya, and Tunceli. In some locations, the significance, magnitude, and direction of the chilling trend differed according to the model used. All five models used in the study indicated significant decreases in winter chill accumulation in Şanlıurfa, a site with relatively mild winters. In Erzincan, which has relatively cold winters, increasing trends were detected in cold accumulation calculated according to Utah, Modified Utah, and Positive Utah models. Results show that serious consequences may arise related to the chilling requirement of deciduous fruit trees, especially in regions with mild winters.

Keywords: climate change, dynamic model, Utah model, temperate fruit.

1. Introduction

Climate is the most important factor determining the successful production of deciduous fruit trees. Plants react to climate conditions by triggering different stages of development throughout the annual cycle. The most important one among them is the winter rest period. Deciduous fruit trees temporarily stop or slow their growth to survive under severe winter conditions and avoid cold damage. These trees must be exposed to cold winter temperatures for a certain period of time to break dormancy and resume normal growth in spring. The amount of cold needed, known as the chilling requirement, varies depending on the cultivars in a species. Insufficient exposure to chilling temperatures can cause erratic bud break, poor fruit development, small fruit, and uneven ripening.

In response to global climate change, temperatures have increased in many regions of the world and will continue to increase in the future (IPCC, 2007). As a result, it is predicted that the probability of inadequate chilling for deciduous species in several regions of the world will increase (Darbyshire et al., 2011). A decrease in chilling accumulation in 82 different regions of the world has been shown in some studies (Baldocchi and Wong, 2008; Luedeling et al., 2009a, b, c). Nicholls and Collins (2006) reported warming trends of 0.12 and 0.06 ºC/decade for minimum and maximum temperatures, respectively, observed from 1910 to 2004 across much of Australia. In contrast, Darbyshire et al. (2011) examined the historical change of the winter chilling of major fruit-growing regions of Australia and found that although the results changed depending on locations and chill model choice. The chilling accumulation generally remained stable or declined.

When a grower decides to choose a cultivar, it is important to consider whether its chilling requirement is appropriate for the location. Additionally, due to the longevity of most fruit trees, chilling accumulation at a given location must be suitable for them over a long period, usually more than 25 years. This situation has increased the interest in studies on how global warming would affect chilling accumulation. To select appropriate cultivars in terms of the chilling requirement, it is necessary to correctly measure the chill accumulation of the region and the chilling requirement of cultivars. There are many chill models developed for this purpose. The earliest one, which

farmers are most familiar with, is the 0-7.2 ºC model (Weinberger, 1950). This model has been used to determine the chill requirement for many years. The understanding of the negative effects of warm temperatures and differential weighting of temperature ranges on chill accumulation led to Utah model (Richardson et al., 1974). Then, several modifications were made to the Utah model to enhance its results with species other than peach and areas with climatic conditions different from those in Utah. Fishman et al. (1987) developed the dynamic model, which has a different fundamental structure. Based on the assumption that cold accumulation occurs in two steps, it is considered to be a milestone in dormancy modeling. The first step is the accumulation of an intermediate product promoted by low temperatures. However, once a certain amount of the intermediate product has accumulated, it converts to a chill portion which is permanent and cannot be reversed by warm temperatures.

According to Luedeling et al. (2009d), models differ greatly in their sensitivity to climate change. In this study, historical winter chill accumulations of some temperate regions of horticultural importance in Turkey have been studied using the 0-7.2 ºC, Utah, Positive Utah (PU) (Linsley-Noakes et al., 1994), Modified Utah (MU) (Linvill, 1990), and Dynamic (Fishman et al., 1987) chill models. It has been reported that the Mediterranean basin, which includes Turkey, is one of the most fragile regions against climate change (Giorgi, 2006). Temperatures in Turkey, according to the values observed between 1970 and 2011, have increased significantly (Şen et al., 2013). Until the end of the century, the average annual temperature in Turkey is expected to increase by 1.5-5 degrees (Demircan et al., 2017). It is not known whether climate change has affected or not winter chilling accumulation in Turkey. This is the first study examining the historical changes in winter chilling in Turkey.

2. Materials and methods

2.1. Study data

Twelve important production sites of temperate trees were selected from Turkey for determining the historical chilling (Fig. 1). Hourly temperature values from 1971 to 2020 for 12 studied sites were taken from the Turkish State Meteorological Service.

TURKEY

Legend

■ Working locations

Fig. 1. Provinces where the study was conducted.

Using five different models (0-7.2 ℃, Utah, MU, PU and Dynamic) the cold accumulation between 1971 and 2020 for 50 years was calculated.

2.2. Methods

The equations for each model are given below. In these equations, T_t represents temperature (℃) at a given hour t, st and en represent the start and end time of the chilling period to estimate total chill, respectively. The 0-7.2 ℃ model sums the number of hours with temperatures between 0 and 7.2 ℃. Utah models transfer temperate chill units.

2.2.1 0-7.2 ℃ model

$$CH_{tot} = \sum_{t=st}^{en} CH \begin{cases} T_t < 0\ ℃ & CH_t = 0 \\ 0\ ℃ \leq T_t \leq 7.2\ ℃ & CH_t = 1 \\ T_t > 7.2\ ℃ & CH_t = 0 \end{cases} \quad (1)$$

2.2.2 MU model

$$MCU_{tot} =$$

$$\sum_{t=st}^{en} MCU \begin{cases} T_t \leq 0\ ℃ & MCU_t = 0 \\ 0\ ℃ < T_t \leq 21\ ℃ & MCU_t = sin\left(\frac{2\pi T}{28}\right) \\ T_t > 21\ ℃ & MCU_t = -1 \end{cases} \quad (2)$$

2.2.3 Utah model

$$CU_{tot} =$$

$$\sum_{t=st}^{en} CU \begin{cases} T_t \leq 1.1\ ℃ & CU_t = 0 \\ 1.1\ ℃ < T_t \leq 2.2\ ℃ & CU_t = 0.5 \\ 2.2\ ℃ < T_t \leq 8.8\ ℃ & CU_t = 1 \\ 8.8\ ℃ < T_t \leq 10.5\ ℃ & CU_t = 0.5 \\ 10.5\ ℃ < T_t \leq 15.5\ ℃ & CU_t = 0 \\ 15.5\ ℃ < T_t \leq 18.3\ ℃ & CU_t = -0.5 \\ 18.3\ ℃ < T_t & CU_t = -1 \end{cases} \quad (3)$$

2.2.4 PU model

$$PCU_{tot} =$$

$$\sum_{t=st}^{en} PCU \begin{cases} T_t \leq 1.4\ ℃ & PCU_t = 0 \\ 1.4\ ℃ < T_t \leq 2.4\ ℃ & PCU_t = 0.5 \\ 2.4\ ℃ < T_t \leq 9.1\ ℃ & PCU_t = 1 \\ 9.1\ ℃ < T_t \leq 12.4\ ℃ & PCU_t = 0.5 \\ T_t > 12.4\ ℃ & PCU_t = 0 \end{cases} \quad (4)$$

The dynamic model calculates chilling accumulation differently from the other models, considering the interactions between temperatures. Firstly, an

intermediate product promoted by cold temperatures is created. This intermediate product can then be destroyed by subsequent warmer temperatures. When this product reaches a certain amount, it becomes a stable form that cannot be destroyed regardless of subsequent temperatures. This irreversible product is expressed as a chill portion (CP):

$$x_t = \frac{e^{slp.\,tetmlt.(T_t - tetmlt)/T_t}}{1 + e^{slp.\,tetmlt.(T_t - tetmlt)/T_t}} \tag{5}$$

$$y_t = \frac{a_0}{a_1}\, e^{(e_1 - e_0)/T_t}$$

$$ak_t = a_1 . e^{(-e_1/T_t)}$$

$$Inter_{Et} = y_t - \left(y_t - Inter_{St}\right) . e^{-ak_1}$$

$$Inter_{St} =$$
$$\begin{cases} t = 1, & 0 \\ if\, t > 1 \wedge Inter_{Et-1} < 1, & Inter_{Et-1} \\ t > 1 \wedge Inter_{Et-1} \geq 1, & Inter_{Et-1} . (1 - x_{t-1}) \end{cases}$$

$$delt_t = \begin{cases} t = 1, & 0 \\ if\, t > 1 \wedge Inter_{Et-1} < 1, & 0 \\ t > 1 \wedge Inter_{Et-1} \geq 1, & Inter_{Et} . x_t \end{cases}$$

$$CP_t = \begin{cases} if & t = 1, & delt_t \\ & t > 1, & delt_t + P_{t-1} \end{cases}$$

$$CP_{tot} = \sum_{t=st}^{en} CP_t$$

In the model, the constants referred to as a_0, a_1, e_0, e_1, *slp* and *tetml* were set to 1.395×10^5, 2.567×10^{18}, 4153.5, 12 888.8, 1.6 and 277, respectively. Although the developers of the model suggested that constants should be adjusted for each cultivar, this is not often considered in practice. Therefore, the extensively preferred values in literature were used in this study (Erez et al., 1990; Darbyshire et al., 2011; Luedeling and Brown, 2011).

The monotonic trend in the outputs from the five chill models was investigated for each studied site to assess the possible impact of global climate change on chill accumulation.

Although the parametric or non-parametric approaches to test whether the climate-based time series have the existence of the upward or downward trends are prominent in the literature, the Mann-Kendall (MK) technique has been widely used in detecting monotonic trends associated with a hydro-meteo-rological data set. The reason for this choice is that while applying this method, there is no obligation for existing data to fit a certain frequency distribution and the presence of its low sensitivity to abrupt breaks. Additionally, the approach has a higher success power than other widely used approaches in revealing the change in the data (Hess et al., 2001; Jaagus, 2006; Sunley et al., 2006).The null hypothesis (H_o) related to the MK test points out that the relevant time series are independent and identically distributed, whereas the alternative hypothesis (H_1) emphasizes that the data set has a monotonic trend. This approach is conducted on the S statistic whose relation is given below:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{6}$$

In Eq. (6), where n is the number of observations, x_j and x_i are the jth and i^{th} observations, respectively. The sgn($\cdot$) is the sign function that takes the following values:

$$sgn\left(x_j - x_i\right) = \begin{cases} +1 & if\left(x_j - x_i\right) > 0 \\ 0 & if\left(x_j - x_i\right) = 0 \\ -1 & if\left(x_j - x_i\right) < 0 \end{cases} \tag{7}$$

In Eq. (7), a positive S value designates an upward trend in the data set, whereas a negative S value corresponds to a downward trend. The statistic S is assumed to be approximately normally distributed with the mean zero and one standard deviation. In the case where the sample size (n) is bigger than 10, the relevant variance is obtained by:

$$\sigma_s^2 = 18^{-1}$$
$$\left[n(n-1)(2n+5) - \sum_{i=1}^{m} t_1(t_1 - 1)(2t_1 + 5) \right] \tag{8}$$

From Eq. (8), t_i indicates the number of ties of extent i, and m is the number of tied groups. The MK test statistics, symbolized by Z_{MK} is achieved as:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{\sigma_S^2}} & if \ \ S > 0 \\ 0 & if \ \ S = 0 \\ \dfrac{S+1}{\sqrt{\sigma_S^2}} & if \ \ S < 0 \end{cases} \qquad (9)$$

The Z_{MK} test statistic obtained from Eq. (9) conforms to the standard normal distribution. The Z_{MK} value is compared to the value of $Z_{1-\alpha/2}$ from the two-tailed Z table at a certain significant level. The null hypothesis expressed as no trend is rejected if the calculated Z_{MK} value is greater than the critical table value at the significance level. A positive Z_{MK} value indicates an increasing trend; a negative Z_{MK} value indicates a decreasing trend.

Theil-Sen's estimator (Theil, 1950; Sen, 1968) has been widely used to measuringe the slope of the trend line of hydro-meteorological time series. This non-parametric statistical method has the ability to robustly estimate the magnitude of the trend. The brief descriptions of this method are as follows:

1. The slope estimates (Q_k) of N pairs of time series are first computed after sorting data in ascending order:

$$Q_k = \frac{x_j - x_i}{j - i} \, for \, k = 1,\dots, N \qquad (10)$$

where x_j and x_i are the data values at times j and i ($j > i$), respectively.

2. According to condition that N is odd or even, the median concerning with total N values of Q_k is calculated by:

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & if \ N \ is \ odd \\ 2^{-1}\left\{Q_{[N/2]} + Q_{[(N+2)/2]}\right\} & if \ N \ is \ even \end{cases} \qquad (11)$$

3. Results and discussion

Mean chill accumulation and *coefficient of variation (CV)* for the period 1971-2020 in the studied location are shown in Table I. The dynamic model had a lower CV than other models for all locations. This result showed that this model was least affected by the annual climate difference. Several authors have claimed that the dynamic model is the most plausible among the common models due to its homogenous rate of chill accumulation (Erez et al., 1990; Pérez et al., 2008; Alburquerque et al. 2008; Luedeling et al., 2009a; Darbyshire et al., 2011; Luedeling and Brown, 2011). In some previous studies examining the change of chill requirement of individual cultivars according to site and year, it was reported that the dynamic model had the lowest *coefficient of variation (*Ruiz et al., 2007; Viti et al., 2010; Campoy et al., 2012). For the Utah, MU and 0-7.2

Table I. Mean cold accumulation and coefficients of variation of the studied locations.

Locations	0-7.2 °C		Utah		MU		PU		Dynamic	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Adıyaman	1615	18.0	1669	23.1	1802	20.5	2325	13.9	107	8.8
Ankara	1914	13.9	1774	18.9	1724	18.4	2128	15.2	122	8.6
Bingöl	1906	17.5	1602	22.8	1592	21.9	1816	21.8	115	9.2
Diyarbakır	1794	12.9	1646	20.5	1740	18.7	2195	16.2	108	8.6
Elazığ	1967	15.4	1756	20.5	1799	19.5	2117	17.6	116	8.8
Erzincan	1793	16.7	1585	21.8	1590	20.7	1867	19.2	120	9.7
Gaziantep	1915	13.0	1894	18.3	2013	16.3	2494	10.3	114	7.9
Malatya	1987	13.5	1749	21.5	1797	20.0	2129	17.3	115	8.5
Siirt	1865	15.4	1813	20.6	1940	19.2	2335	12.0	112	8.1
Şanlıurfa	1356	23.3	1348	31.9	1621	24.9	2253	10.6	97	9.2
Tokat	1806	13.0	1615	20.3	1702	19.5	2063	16.8	116	8.6
Tunceli	1948	16.0	1664	21.2	1634	19.6	1916	17.9	113	9.1

CV: coefficient of variation.

models, the greatest variability was observed in chill accumulation at Şanlıurfa. On the other hand, the PU model had one of its lowest coefficients of variation at the same location. This province has warmer winter conditions than others. This support the finding of Linsley-Noakes et al. (1994) regarding the fact that PU model was shown to perform better in mild winter conditions.

The Z_{MK} test statistics has shown that there were no significant trends in the chill accumulations calculated by using five different models for Ankara, Bingöl, Diyarbakır, Malatya, and Tunceli. On the other hand, according to all five models used in the study, significant decreases (P < 0.001 for Utah and MU, and P < 0.01 for other models) were observed for Şanlıurfa in winter chill accumulation from 1971 to 2020 (Table II). Decreases in cold accumulation for Şanlıurfa over the years are further illustrated by the line in Figure 2. The decreasing trend observed in Şanlıurfa (which is located in southern Turkey and has warmer winter) is in agreement with review assessments by Luedeling (2012), who reported that chill losses are more severe in regions with warmer winters.

Considering other locations, significance, magnitude, and direction of the chilling trend differed according to location and the model used. For example, Z_{MK} test statistics indicated that there was a significant decreasing trend according to the Utah, dynamic, and 0-7.2 models while no significant trends were observed

according to PU and MU models in chill accumulation of Adiyaman. The chill accumulation data set of Gaziantep showed a statistically significant decreasing trend at 0.01 and 0.001 levels for dynamic and 0-7.2 models, respectively. No significant trend was detected in the chill accumulations of this province calculated according to other models. In Siirt, while Utah and 0-7.2 models showed significant decreasing trends at a 0.05 significant level, it was found that there was no statistically significant change in the data sets from other models. Similar to the findings in this study, Darbyshire et al., (2011) also reported that the magnitude and direction of chilling trends differed between the chill models and the sites.

A different situation has been identified in the chill accumulation of Erzincan, which has relatively cold winters compared to other provinces. In this province, the data sequences belonging to the Utah, MU, and PU models indicated an upward trend in chill accumulation. These increasing trends are further illustrated by the line in Figure 3. These results are in agreement with the findings of Luedeling et al. (2011), who reported that while the warm region had major chilling losses (and will continue to have them in the future), the cold region experienced little change, or even increases in winter chill, as a greater numbers of days become frost-free. Similarly, as a result of their investigations in different regions of Germany, Luedeling et al. (2009e) documented that warming might lead to more winter

Table II. Mann-Kendal test statistics and slopes for each location.

Locations	0–7.2 ºC		Utah		MU		PU		Dynamic	
	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}	Q	Z_{MK}
Adıyaman	−6.5	−2.49[*]	−11.9	−3.01[**]	−6.3	−1.41	6.0	1.85	−0.3	−2.83[**]
Ankara	0.3	0.12	0.9	0.13	3.0	0,66	4.8	1.57	−0.2	−1.51
Bingöl	3.1	0.73	2.4	0.51	2.1	0.59	7.1	1.80	0.0	0.03
Diyarbakır	−3.1	−1.22	−3.0	−0.70	−3.2	−0.99	4.3	1.33	0.0	−0.38
Elazığ	3.2	0.92	1.1	0.47	5.2	1.30	9.5	2.11[*]	−0.0	−0.28
Erzincan	6.9	1.89	7.5	2.16[*]	7.8	2.21[*]	11.3	2.88[**]	0.1	0.75
Gaziantep	−7.6	−3.41[***]	−6.8	−1.92	−3.9	−1.1	1.1	0.50	−0.3	−3.16[**]
Malatya	1.3	0.50	−1.3	−0.3	−0.1	−0.05	8.2	1.93	−0.1	−0.97
Siirt	−7.1	−2.51[*]	−8.0	−2.06[*]	−6.9	−1.79	−0.7	−0.27	−0.2	−1.94
Şanlıurfa	−9.6	−3.13[**]	−16.1	−3.86[***]	−14.4	−3.33[***]	−6.5	−2.64[**]	−0.3	−2.87[**]
Tokat	0.7	0.23	−1.2	−0.38	1.9	0.45	7.0	2.00[*]	−0.1	−1.22
Tunceli	3.1	0.74	2.2	0.42	1.2	0.28	4.8	1.27	0.1	0.37

[*], [**] and [***] indicate significant monotonic trend at the 0.05, 0.01 and 0.001 levels, respectively.
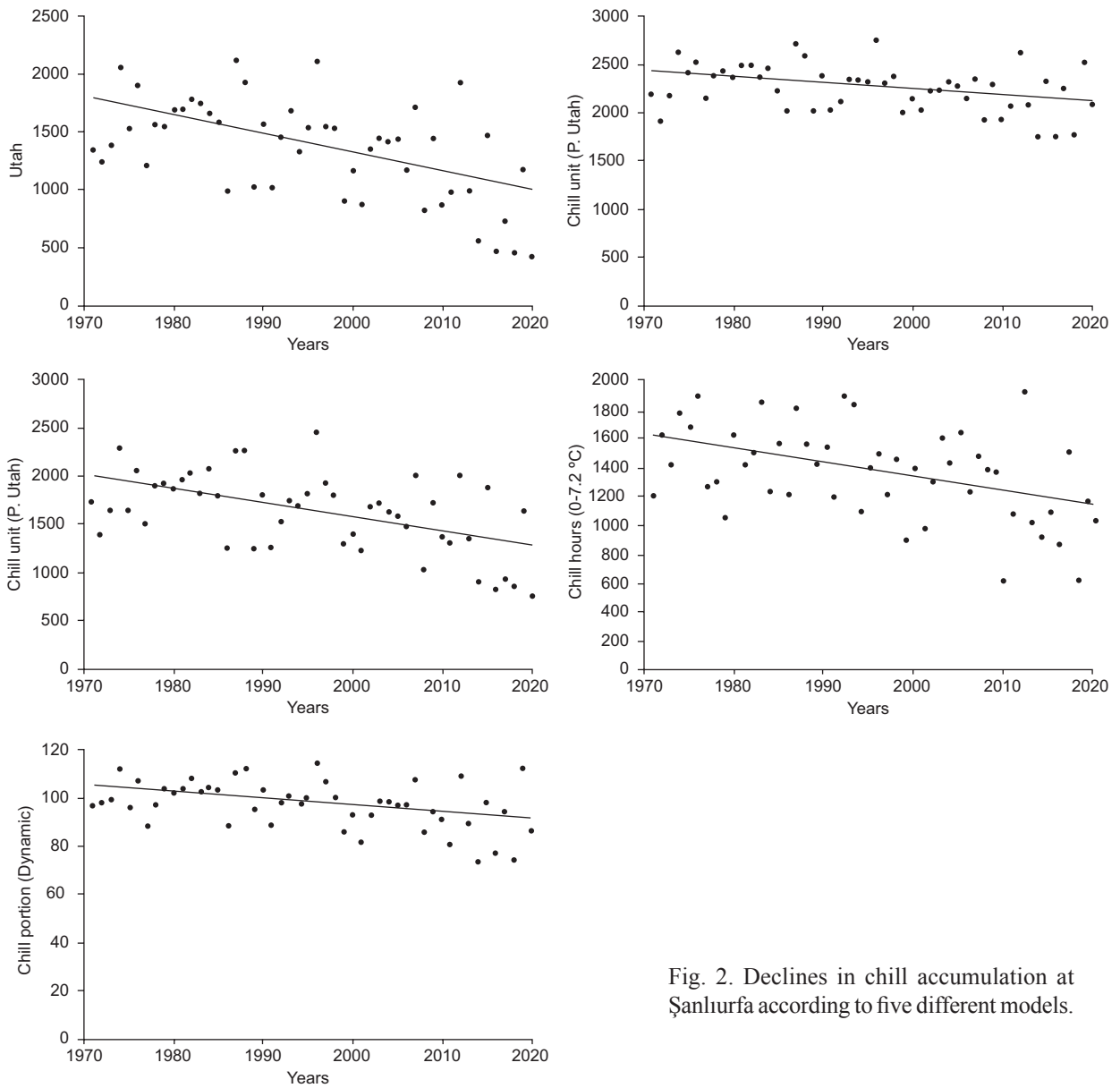
Fig. 2. Declines in chill accumulation at Şanlıurfa according to five different models.

chill accumulation if frost hours become non-freezing or lead to less chill accumulation if cold hours become too warm to be effective.

Unlike other models, the PU model showed positive trends in the chill accumulation of Elazığ and Tokat, as well as Erzincan. This positive trend probably stems from the mathematical structure of this model, which does not negate previous chilling due to the influence of high temperatures.

The Q values indicating magnitude of chilling trends differed depending on the sites and the chill models. Calculated Q values showed that the highest decreases in chill accumulation using the 0-7.2 ºC (average 9.6 CB year^{-1}), Utah (average 16.1 CU year^{-1}), or MU (average 14.1 MCU year^{-1}) models were found in Şanlıurfa. When Q values determined for the PU model are evaluated, it is seen that the cold accumulation in Erzincan increased by an average of 11.3 PCU year^{-1}. The q values of the dynamic model indicated that chill accumulations in Adıyaman, Gaziantep and Şanlıurfa decreased by an average around of 0.3 CP p year^{-1} (Table II).
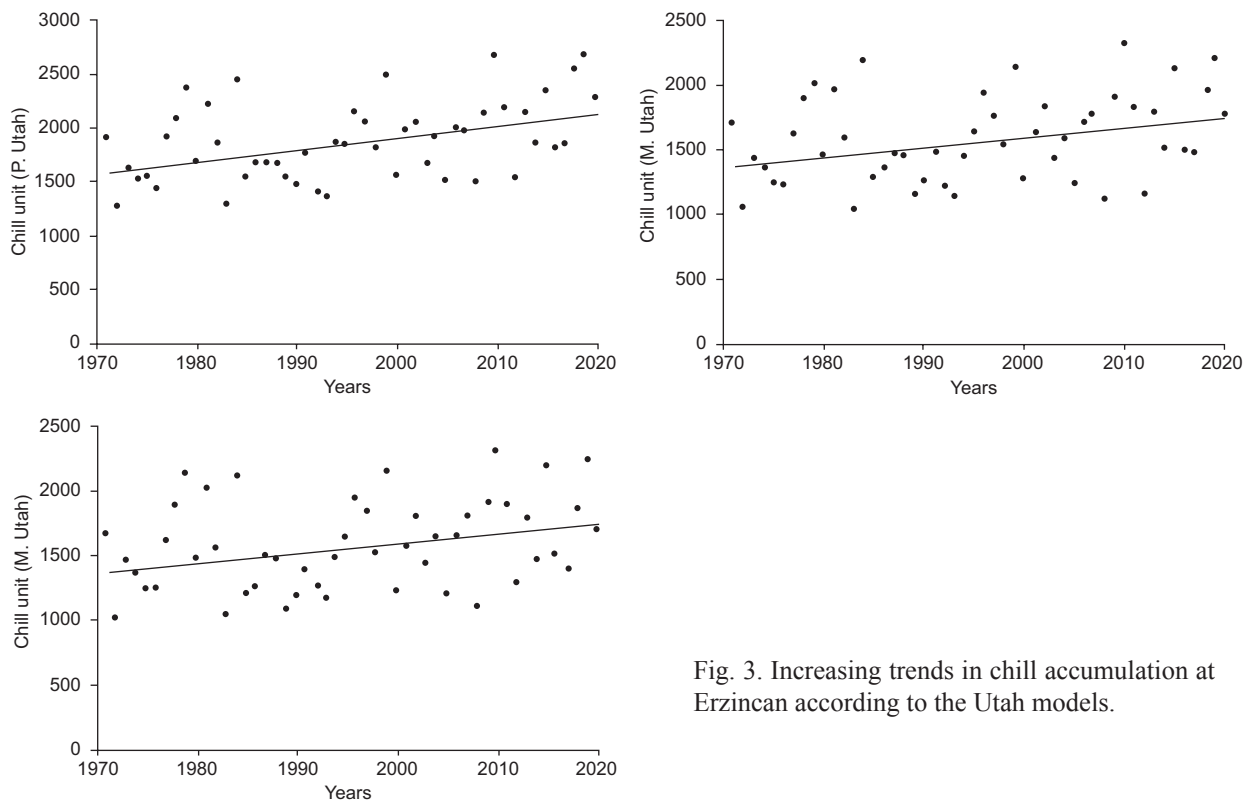
Fig. 3. Increasing trends in chill accumulation at Erzincan according to the Utah models.

4. Conclusions

In the context of possible impacts of global climate change, historical trend analyses for winter chilling of some temperate fruit growing regions of Turkey were carried out using a statistical approach and different chilling accumulation models. It was determined that the magnitude and direction of the monotonic trend changed in relation to locations and the model used. For this reason, in order to determine the presence of an increasing or decreasing trend for winter chill accumulation series in the studied sites, the most suitable model for the relevant site should be correctly determined first. The results of the study indicat that while cold regions might experience non-significant changes in winter chill accumulation or even positive ones, regions with mild winters such as Şanlıurfa might experience serious chilling losses. If the growers are aware of this fact when planning their orchards, the risks of serious losses will be reduced, and they may offer healthy and good quality fruits to the consumers.

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