Temperature-related Variables Associated with Yield of ‘Kerman’ Pistachio in the San Joaquin Valley of California

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Abstract. Information on how annual pistachio yield is affected by air temperature (Ta) during the winter and growing season is lacking. Timely advance knowledge of the magnitude of the yield of the California pistachio harvest would be beneficial for the pistachio industry for efficient allocation of harvest and postharvest resources, such as personnel, harvesting machinery, trucks, processing facility capacity, crop storage facilities, and for making marketing decisions. The objective of this study was to identify parameters, especially Ta variables and time periods, calculated from Ta data during the previous fall, winter, spring, and summer, that were associated most closely with fall nut-crop yield. The premise of this study was that sequential, historical yield records could be regressed against a number of Ta-derived variables to identify Ta thresholds and accumulations that have value in explaining past and predicting subsequent nut yield. Of the 27 regression variables examined in this study, the following, which were all negatively correlated with subsequent yield, explained the greatest proportion of the variability present in predicting yield of ‘Kerman’ pistachio: yield of the previous-year harvest, hourly Ta accumulations above 26.7 or 29.4 °C from the time period between 20 Mar. and 25 Apr., hourly Ta accumulations below 7.2 °C from 15 Nov. to 15 Feb., and hourly Ta accumulations above 18.3 °C from 15 Nov. to 15 Feb.

About 85,000 ha of bearing pistachio (*Pistacia vera* L.) were in production in the San Joaquin Valley of California in 2015 (American Pistachio Growers, 2015), of which about 90% were the female cultivar Kerman and male pollinizer ‘Peters’. Bearing acreage in this area of California has more than doubled since 2005. Another 23,500 ha of pistachio have been planted but have not yet reached bearing age. Interest in planting new orchards remains high. In the foreseeable future, the yield of harvestable nuts associated with this rapid expansion of pistachio tree plantings will continue to challenge the existing crop harvesting and processing infrastructure. To further complicate the logistics of harvesting and marketing the crop, the ability of the pistachio industry to estimate the size of the crop in advance is limited (Klein, 2016). The alternate-bearing nature of

pistachio and years with what appears to be insufficient winter chilling complicate estimating annual crop production (Jackson et al., 2009; Pope et al., 2015). Basic physiological information on how annual yield is affected by winter Ta and Ta during the growing season is lacking (Pope et al., 2015). Timely advance knowledge of the magnitude of the yield of the next pistachio harvest would be beneficial for the pistachio industry for efficient allocation of harvest and postharvest resources, such as personnel, harvesting machinery, trucks, processing facility capacity, crop storage facilities, and for making marketing decisions.

For mature, bearing pistachio, nut development proceeds over the course of the season from pollination at bloom, initial fruit set, growth of the shell, and kernel filling through to maturation. For the female ‘Kerman’ in the San Joaquin Valley of California, these growth stages can be given approximate calendar dates. Obviously, these dates will show some variability from orchard to orchard and year to year. In ‘Kerman’ in the San Joaquin Valley, the bloom and early nut-set period occurs about from 20 Mar. to 25 Apr., initial fruit set and the growth of the shell from 26 Apr. to 14 June, and kernel filling from 15 June to 31 Aug. (Goldhamer and Beede, 2004; Lin et al., 1984). The initial breaking of dormancy through to nut maturity is encompassed by the time period from 16 Feb. to 15 Sept.

For adequate bloom in the spring, pistachio requires a substantial winter rest period (Crane and Iwakiri, 1981; Crane and Takeda, 1979; Lee and Sumner, 2016). Several models have been used to quantify the rest-period requirement of deciduous fruit and nut crops. The simplest model accumulates the number of hours, called “chill” or “chilling” hours, during a given fall and winter time period below a given critical Ta, commonly 7.2 °C (Aron, 1983; Crane and Takeda, 1979; Deschenes and Greenstone, 2007; Lee and Sumner, 2016), although other Ta bases or thresholds have been identified. Sparks (1993) identified 3.9 °C as an appropriate maximum and minimum threshold Ta for calculating the chill and heat requirement, respectively, for budbreak in pecan (*Carya illinoensis*). The minimum chill-hour accumulation for adequate rest in ‘Kerman’ pistachio has been estimated to be 800 to 1000 h below 7.2 °C as calculated from 1 Nov. to 28 Feb. (Beede et al., 2006; Crane and Takeda, 1979) with a higher requirement for its male pollinizer ‘Peters’. Hours at Ta below freezing do not contribute to chilling in some models (Richardson et al., 1974; Saure, 1985).

The dynamic model (Erez and Fishman, 1988; Fishman and Couvillon, 1987) is another commonly used model for estimating the effectiveness of the rest period. The dynamic model calculates “chill portions” (CPs) from Ta data collected throughout the year, generally, with net accumulations beginning in the fall and continuing into early spring. As part of this model, a CP accumulates in a two-step process that can be interrupted by warm Ta during the rest period. Warm Ta occurring during the rest period of temperate fruit and nut trees may delay or prevent the development of adequate rest (Erez et al., 1979; Richardson et al., 1974; Saure, 1985). The dynamic model appears to be gaining support for use in estimating the effectiveness of the rest period (Elloumi et al., 2013; Guo et al., 2013; Pope et al., 2015; Zhang and Taylor, 2011). Zhang and Taylor (2011) determined that a CP accumulation of 59 was sufficient to achieve normal bloom for ‘Sirora’ pistachio in Australia, whereas Elloumi et al. (2013) proposed a CP accumulation of 36 as the threshold for ‘Mateur’ in Tunisia. In the Central Valley of California, winter fog is associated with cooler daytime temperatures and has long been associated with improved chilling for deciduous fruit and nut crops (Chandler et al., 1937). However, nut-crop yield has not correlated well with existing model thresholds established to predict adequate budbreak, bloom, and pollination (Pope et al., 2015).

Pistachio, in addition to requiring a relatively long winter rest period, requires substantial heat during the growing season to produce high yields of well-split nuts (Ferguson and Kallsen, 2016; Küden et al., 1995). Growing degree hours (GDHs) or growing degree days (GDDs) are commonly calculated from Ta data to characterize heat accumulations for given periods of time

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throughout the growing season. For most models, GDH or GDD accumulations are bounded by a base threshold T_a above which GDHs or GDDs begin to accumulate and a maximum T_a above which no further GDHs or GDDs are accrued (Gholipour, 2007; Küden et al., 1995; Lee and Sumner, 2016). A base T_a of 4.5 °C with no maximum cut-off T_a has been used in the calculation of GDDs and GDHs (Gholipour et al., 2007; Zhang and Taylor, 2011). Zhang and Taylor (2011) used a minimum base T_a of 4.4 °C for calculating GDDs for ‘Sirora’ pistachio in Australia. Lee and Sumner (2016) and Deschenes and Greenstone (2007) used a base T_a of 8 °C and a maximum of 32 °C for calculation of GDDs. More complex models assume that heat accumulates when hourly temperatures range between a base T_a and a maximum cut-off T_a , but with maximum heat accumulation occurring at an optimum T_a (Guo et al., 2013). In Anderson et al. (1986) and Guo et al. (2013), the base, optimum, and cut-off T_a for fruit trees were set at 4, 25, and 36 °C, respectively. Zhang et al. (2015) used similar equations to model heat accumulation in ‘Sirora’ pistachio. These authors found that a base, optimum, and cut-off T_a of -1, 26, and 26 °C for bloom timing and a base T_a of 14 °C and maximum T_a of 32 °C for harvest timing minimized the covariance in the modeled data.

The use of T_a -related variables to predict current season yield is more complicated in alternate-bearing fruit and nut crops as opposed to annual crop plants. Alternate-year nut bearing (i.e., a higher-yielding year followed by a lower-yielding year) is a prominent characteristic of ‘Kerman’ pistachio (Crane and Iwakiri, 1981; Crane and Nelson, 1971; Kallsen et al., 2007; Monselise and Goldschmidt, 1982). Whereas alternate bearing may be mitigated in pistachio, some evidence suggests that cumulative yield over a multiyear period remains similar (Ferguson et al., 1995). In an alternate-bearing crop, subsequent season yield is inversely proportional to previous-season yield and so this, almost by definition, will be a useful variable in predicting subsequent season yield. The underlying physiological mechanism in alternate bearing is not well understood for pistachio. Some authors have suggested that alternate bearing is an ecological adaptation referred to as masting (Silvertown, 1980; Stevenson and Shackel, 1998). Evidence suggests that alternate bearing is, at least in part, related to carbohydrate storage and partitioning (Nzima et al., 1997, 1999). However, this does not imply a simple relationship between T_a , carbohydrate fixation, and subsequent yield. In alternate-bearing perennial species, carbohydrate fixed and stored in the tree during the previous year in response to T_a at that time may not be mobilized and metabolized into nut yield until the subsequent year (Monselise and Goldschmidt, 1982). This subsequent mobilization and metabolization of previously stored carbohydrates into tree growth and yield would occur under a different T_a regime from when it was

originally fixed in photosynthesis. The purpose of examining related variables in this study was to provide initial information on how the T_a environment might modify the expression of subsequent yield within the limitations of the alternate-bearing cycle. Hourly T_a or GDD accumulations would be expected to impact yield differently depending on the status of the tree in the alternate-bearing cycle. Unlike what occurs in annual plants, yield potential is depressed in the “off” year of an alternate crop such as pistachio. A limitation on yield potential, such as occurs in an “off”-bearing year, likely alters the response of the tree to T_a experienced during the dormant season and current season no matter how potentially favorable to tree growth and yield. For an alternate-bearing tree species, discussing the effect of T_a on yield is probably futile, without some reference to the present status of the tree in its alternate-bearing cycle. For the purposes of this study, the yield of the previous season serves this purpose. As a model variable, previous-season yield may assist in accounting for some of the variability in tree reaction to T_a as possibly modified by the stage of the orchard in the cycle of alternate bearing. In examining T_a variables in this way, the objective is to identify variables that improve yield prediction above that of simply making simple correlations with previous-season yield. Obviously, crop yield is a function of many other variables in addition to T_a or previous yield, and inputs such as irrigation water quantity, quality, and scheduling; fertilization; pest control; and pruning.

The objective of this study was to identify T_a thresholds and time periods, calculated from temperature data during the previous winter, spring, and summer that could be used in association with previous-season yield to more accurately predict fall nut-crop yield in ‘Kerman’ pistachio in the San Joaquin Valley.

Materials and Methods

Experimental design. The premise of this study was that sequential yield records could be regressed against a number of variables to identify T_a thresholds and accumulations that have value in explaining past and predicting future (i.e., subsequent) nut yield. The yield records used in this study were produced over a time span of 20 to 31 years by a private commercial farming company from three large orchards. Using these yield records, four separate forward stepwise multiple regression models were developed. One regression model was developed for each orchard and the fourth for the combined data from the three orchards. If similar independent parameters were identified in the models as explaining variations in subsequent yield, these might be candidates for further study and possible inclusion in models to predict fall crop yield earlier in the production season.

Selection of variables for the multiple regression. Air temperature-related variables were chosen for calculation based on current understanding of general physiological responses of pistachio, or deciduous crop plants in general, to T_a in relation to the developmental stage of the fruit. Growth stages for the developing nuts were defined on a calendar basis since the actual dates of bloom, nut fill, and other growth stages of the individual growing seasons were not available. Variables were defined by both their calendar periods and the threshold air temperatures used for calculation of T_a -related values. In addition to the T_a -related variables, previous yield (the nut yield harvested the year before the predicted) was included in the three respective multiple regression analyses for the three orchards and for the combined regression as an additional independent variable. Subsequent yield, for the three individual orchards and for the combined model, was the only dependent variable. The complete list of variables includes descriptions, calendar periods, average values, and units (Table 1). Variables 28, 29, and 30 were dependent variables for yield against which the T_a -related values and previous-yield variables (nos. 25, 26, and 27) from the three separate orchards and the combined values from these three orchards were regressed.

Statistical analysis. Data were analyzed using multiple regression statistical packages in Statistica software (StatSoft, Inc., Tulsa, OK). Forward stepwise regression analysis was used to evaluate the relationship between yield (the dependent variable) and the independent variables which included previous-year yield and a number of T_a -related variables. A high degree of multicollinearity was present in the original set of independent variables. This multicollinearity was expected and unavoidable in attempting to separate and identify variables with similar calendar periods and closely spaced T_a thresholds that would best account for the variability in yield. Multicollinearity among independent variables in the final models was reduced by applying stringent F-to-enter and F-to-remove thresholds for entering or removing a variable from the forward stepwise multiple regression model. The threshold values of F to enter and retain a variable in the stepwise regression were chosen and applied to all of the data sets on a trial-and-error basis designed to retain only the most significant three or four independent variables in the final model. An F value of 7.0 or higher to enter and an F of <5.0 to remove met this requirement. Plots of residuals against predicted values were prepared for each regression to ensure that no gross violations of the assumption of linear relationships among the variables in the equation and a normal distribution of residuals occurred. Based on these plots, no observations were considered outlying, and no observations were removed from the analyses. Interaction and squares of all variables were included in the multiple regressions as separate variables to test for interaction and curvilinear effects.

Table 1. List of independent variables [(i.e., previous-yield and temperature-related variables used in the regression analysis (Variable nos. 1–27)] and dependent variables (Variables nos. 28–30).

Variable no.	Variable description and time interval	Orchard A Mean ^z	Orchard B Mean ^z	Orchard C Mean ^z	units
1	No. of CPs by dynamic model ^y , 1 Sept.–28 Feb.	70.5	65.2	64.0	CP
2	No. of CPs with a maximum accumulation of 65 CPs ^y , 1 Sept.–28 Feb.	63.8	62.0	60.6	CP
3	No. of CPs with a maximum accumulation of 70 CPs ^y , 1 Sept.–28 Feb.	67.9	64.1	62.6	CP
4	GDD base 7.2 °C, 16 Feb.–15 Sept.	2,813.6	3,148.0	3,182.9	GDD
5	GDD base 7.2 °C, 26 April–14 June	649.0	739.1	751.1	GDD
6	GDD base 7.2 °C, 15 June–31 Aug.	1,450.0	1,596.2	1,621.4	GDD
7	GDD base 12.8 °C, 15 Feb.–15 Sept.	1,757.9	2,058.2	2,098.6	GDD
8	GDD base 12.8 °C, 26 April–14 June	387.2	468.2	479.5	GDD
9	GDD base 12.8 °C, 15 June–31 Aug.	1,015.6	966.7	1,188.1	GDD
10	No. of hours > 23.9 °C, 20 Mar.–25 Apr.	74.6	102.1	99.0	h
11	No. of hours > 26.7 °C, 20 Mar.–25 Apr.	32.6	44.8	43.3	h
12	No. of hours > 29.4 °C, 20 Mar.–25 Apr.	10.0	16.0	15.6	h
13	No. of hours > 12.8 °C, 15 Dec.–31 Jan.	166.2	185.5	222.0	h
14	No. of hours > 15.6 °C, 15 Dec.–31 Jan.	61.3	65.0	77.8	h
15	No. of hours > 18.3 °C, 15 Dec.–31 Jan.	15.0	18.9	24.2	h
16	No. of hours > 12.8 °C, 15 Nov.–15 Feb.	464.1	519.0	608.0	h
17	No. of hours > 15.6 °C, 15 Nov.–15 Feb.	208.6	230.3	272.0	h
18	No. of hours > 18.3 °C, 15 Nov.–15 Feb.	66.9	79.1	97.1	h
19	No. of hours < 7.2 °C, 15 Nov.–15 Feb.	935.0	760.4	618.5	h
20	No. of hours < 0.0 °C, 15 Nov.–15 Feb.	153.1	47.2	27.9	h
21	No. of hours ≥ 0.0 and < 7.2 °C 15 Nov.–15 Feb.	781.9	713.2	590.6	h
22	(No. of hours < 7.2 °C) minus (no. of hours > 15.6 °C, 15 Nov.–15 Feb.	726.4	546.2	371.4	h
23	No. of hours < 7.2 °C with a maximum accumulation set at 800, 15 Nov.–15 Feb.	773.5	652.8	591.9	h
24	(No. of hours < 7.2 °C with an 800 max. accumulation) minus (no. of hours > 15.6 °C), 15 Nov.–15 Feb.	564.9	438.6	344.8	h
25	Previous-year annual yield ^x from Orchard A	4,177.3			kg·ha ⁻¹
26	Previous-year annual yield ^x from Orchard B		3,785.5		kg·ha ⁻¹
27	Previous-year annual yield ^x from Orchard C			3,913	kg·ha ⁻¹
28	Annual yield from Orchard A ^x	4,051.2			kg·ha ⁻¹
29	Annual yield from Orchard B ^x		3,602.1		kg·ha ⁻¹
30	Annual yield From Orchard C ^x			3,701.0	kg·ha ⁻¹

CP = chilled portion; GDD = growing degree day.

^zOrchard A, Blackwell CIMIS Stn. 1987–2015; Orchard B, Kettleman CIMIS Stn. 1985–2015; and Orchard C, Kettleman CIMIS Stn. 1996–2015.

^yFishman and Couvillon (1987).

^xCalculated as ACP-assessed weight (Administrative Committee for Pistachios, 2014).

Hourly accumulations and calculation of GDD and CPs. Temperature-related variables were categorized in three ways. Those in the first category were CP-related, as calculated by the dynamic model and included Variables 1–3. Variable 1 was the actual number of CPs accumulated, whereas Variables 2 and 3 were limited to a maximum allowable value of 65 and 70, respectively, assuming that once sufficient chilling is achieved, any additional CP would not further account for variation in yield. In the second category were GDD accumulations for a number of calendar periods and included Variables 4–9. The assumption made in calculating these variables was that GDD accumulation may be more important during certain stages of crop development (herein estimated by calendar dates) than at other times. Growing degree days were calculated from 24 discreet hourly Ta measurements made per day as follows: $GDH = \sum (T_m - \text{base temperature in } ^\circ\text{C})$ (Shaltout and Unrath, 1983; Zhang and Taylor, 2011), where T_m is one of the 24 hourly temperatures recorded per day. If T_m was equal to or below the base temperature, the GDH was given a value of 0. Each hourly

GDH value was divided by 24, and the resulting 24 values obtained each day were summed to give a daily GDD value. No maximum cut-off Ta threshold was used in the calculation of GDD. GDD units were calculated using base Ta of 7.2 or 12.8 °C. For the purpose of this study, the temperature 7.2 °C was chosen as a base for calculating GDD, partly because values less than this were used as a threshold value to calculate hourly chill accumulation. The base value of 12.8 °C was chosen as an alternative for the calculation of GDD, to determine if higher Ta might be required for pistachio growth and yield because it is one of the last fruit and nut crops to bloom in the San Joaquin Valley. This 12.8 °C threshold is similar to the 14.0 °C found by Zhang et al. (2015) to predict harvest timing for ‘Sirora’ pistachio in Australia. The third category of variables (Variables 10–24) was hourly Ta accumulations above or below a threshold value for a number of calendar periods. Robust bloom and early nut set is an important requirement for high yields. Variables 10–12 were designed to test the hypothesis that hourly accumulations above a threshold value might reduce pollination and fruit set. Variables 13–18 were designed

to test whether Ta above a threshold value from 15 Nov. to 15 Feb. might negatively impact the effectiveness of the rest period. Variables 19–23 were related to hourly chill accumulation during the dormant period preceding the growing season and that season’s harvest. Variable 19 was calculated as the number of hours below 7.2 °C from 15 Nov. to 15 Feb. Variable 19 was further divided into two components. Variable 20 was calculated as the chill-hour accumulation below 0.0 °C, and Variable 21 was the number of hours equal to or greater than 0.0 °C and <7.2 °C, both from the calendar period 15 Nov. to 15 Feb. Variable 22 was calculated as Variable 19 minus Variable 14 (“the number of hours <7.2 °C” minus “the number of hours >15.6 °C” for the same time period). Variable 23 was calculated as the chill-hour accumulation below 7.2 °C from 15 Nov. to 15 Feb., but any hourly accumulation above 800 was limited to 800 assuming that once sufficient chilling is achieved for optimal rest and yield, additional chill-hour accumulations would not further account for variation in yield. Variable 24 was calculated as Variable 23 minus the number of hours >15.6 °C for the same period. For Variables 23 and 24, any

negative values arising from subtraction were given a value of 0 h.

Variables 25–27 were the respective nut yield, for Orchards A, B, and C, for the year previous to subsequent year yields. Variables 28–30 were the respective nut yields for the year after the previous-year yields and were the dependent variable in each of the individual stepwise regression models for the three orchards.

Source temperature data. Hourly T_a data for the regression analyses were retrieved from Station 54 (Blackwell) and Station 21 (Kettleman) of the California Irrigation Management Information System (CIMIS) network (<http://www.cimis.water.ca.gov/>). Station 54 is located at lat. 35.64981 long. -119.9593 which is ≈ 9.0 km northwest of the town of Blackwell, CA. This weather station is positioned at the center of a large grass field surrounded by an almond (*Prunus dulcis*) orchard at an elevation of 215 m above sea level. The location of CIMIS Station 21 is lat. 35.867750 long. -119.8949 which is ≈ 16.5 km south, south-east of Kettleman City, CA. This weather station is positioned within an open field at an elevation of 104 m.

Subsequent yield data from three orchards were regressed against T_a data from CIMIS stations 21 and 54. Selection of the CIMIS station that would provide T_a data for a given orchard was based on the proximity and similar elevation of the orchard to the CIMIS station site. Missing hourly T_a data were replaced following the procedure of Pope et al. (2015).

Source yield data and orchard descriptions. Historical yield data were supplied by a private, commercial farming company for three orchards. These orchards were chosen for this study based on the age and health of the trees, orchard uniformity, available yield records, and proximity to their respective CIMIS weather stations. These orchards were located on the west side of the San Joaquin Valley on deep, well-drained, clay-loam soils, fertilized and irrigated to meet the near optimal nutritional and evapotranspiration requirement of the crop. The high yields for these orchards indicate that care was taken in managing insect and disease control, and pruning. In some years, beginning in the early 2000s, horticultural oil sprays were used in these orchards in an attempt to overcome what was perceived to be insufficient chill. However, no peer-reviewed scientific research appears to be extant to support the efficacy of horticultural oil treatments used to overcome insufficient winter chilling to increase subsequent yield in pistachio. No horticultural oil in the United States is registered on the label for use for this purpose. Data in a published report demonstrated negligible effects on average subsequent yield (Beede et al., 2003). Over a 6-year period, winter foliar oil treatments in January or February increased assessed yield by only $14.3 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ in ‘Kerman’ orchards in the San Joaquin Valley, assuming that these reported average differences were significant (Beede et al., 2002).

Owing to the dry climate of the west side of the San Joaquin Valley, foliar fungal diseases, such as those caused by *Botryosphaeria* and *Alternaria* sp., seldom reduce crop yields.

The three orchards were identified in this study as Orchards A, B, and C. Orchard A was 333.6 ha in area with 333.5 trees/ha. ‘Kerman’ scions were grafted to *P. atlantica* Desf. rootstock in 1973. This orchard was located 5.0 km south of the Blackwell CIMIS station and 252 m above sea level. Orchard B was 121 ha in area with 373.1 trees/ha. ‘Kerman’ scions were grafted to *P. atlantica* rootstock in 1971. The center of the orchard was 2.0 km southeast of the Kettleman CIMIS station and 87 m above sea level. Orchard C was 328.8 ha in area with 373.1 trees/ha. ‘Kerman’ scions were grafted on *P. integerrima* rootstock in 1982. This orchard was 9.0 km southeast of the Kettleman CIMIS station and 85 m above sea level.

Nuts were harvested in the fall using commercial self-propelled mechanized shakers and catching frames. Immediately after harvest, harvested nuts were collected in trailers and transported to commercial processing facilities for weighing and processing. A representative sample was taken from each trailer and used to evaluate nut quality and yield. Yields were expressed as “Administrative Committee for Pistachio (ACP)-assessed yield” (Administrative Committee for Pistachio, 2014; California Pistachio Commission, 1990). ACP-assessed yield is adjusted to 5% moisture and includes the weight of edible kernels and their shells. Culled nuts (nuts with damaged kernels such as from insects), nuts without kernels (referred to as “blank” nuts within the industry), and small nuts do not contribute to ACP-assessed yield.

Hourly T_a data were available from the Kettleman CIMIS station beginning in 1985 and for the Blackwell CIMIS station in 1987, and the regression analysis begins in these orchards on these dates and continues through the 2015 harvest. Yield data for Orchard C were only available from 1995 onward, and the regression analysis for this orchard is for harvest data from 1996 through 2015. Historical yield data for Orchards A and B, which predated the years for which the first hourly T_a data were available from the CIMIS stations, were not used for the statistical analysis.

Results

By controlling the statistical significance of the variables entered and removed from the forward stepwise regressions, a yield-prediction model was developed for each of the three orchards, and the combined data from the three orchards, that contained the most significant variables (Table 2) of those listed in Table 1. Generally, the inclusion of squared variables and interaction terms did little to improve the amount of variation explained by the multiple regression models (data not shown). The notable exception was the square of previous yield (Variable 25

and 27) and the variable of previous yield in the combined multiple regression analysis. Previous yield (Variable 26) or the square of previous yield (Variables 25 and 27) were the most significant independent variables in each individual orchard model and in the combined model and accounted for most of the variation explained by these models (Table 2). Previous yield, or the square of previous yield, accounted for 31%, 63%, and 42% of the unadjusted variation in annual yield in Orchards A, B, and C, respectively, and 43% of the variation in yield in the combined regression (Table 2). The negative sign of the regression coefficients (B) for the square of this variable indicates that as previous yield increased, subsequent yield declined linearly or quadratically (Table 2).

In this study, these three orchards demonstrated alternate bearing (Fig. 1). The data in Fig. 1 demonstrate that maximum yields in the 1980s and 1990s were similar to those from 2000 to 2015, suggesting that crop production practices such as pest control, irrigation and fertilization, canopy density, and health did not change much over the 30-year history of these orchards.

For reasons that remain unclear, “on” and “off” years tend to become synchronized across the entire San Joaquin Valley over time, regardless of the year of planting (American Pistachio Growers, 2015). The alternate-bearing index, as developed by Hoblyn et al. (1926), reviewed by Pearce and Dobersek-Urbanc (1967), and used by others (Kallsen et al., 2007), ranges from 0 (no alternate bearing) to 1 (complete alternate bearing) and can be used to quantify the degree of alternate bearing for the three orchards examined in this study. The alternate-bearing indices were similar for Orchards A, B, and C and were, respectively, 0.402, 0.429, and 0.415, indicating that alternate bearing is prominent in these orchards. For a crop that consistently demonstrates a high degree of alternate bearing, previous-year yield should be a meaningful predictor of the subsequent-year yield. If previous year’s yield is high, the expectation for next year’s yield is low and vice versa.

The T_a -related variables that were most significantly associated with subsequent yield were similar among the three individual orchards and the combined model. Variables 11 or 12, the number of hours >26.7 and 29.4°C , respectively, during the bloom and early nut-set period from 20 Mar. through 25 Apr., were highly significant (Table 2) and inversely related to subsequent yield, in the models for Orchards A, B, and the combined model (Table 2). The signs of the partial regression coefficient (b) for these variables were negative, suggesting that T_a above the thresholds set in these variables during bloom was associated with decreased yield at harvest. The value of b for Variable 11 estimates for each hour above 26.7°C in the time period from 20 Mar. to 25 Apr. that subsequent yield is reduced by $15.5 \text{ kg}\cdot\text{ha}^{-1}$ (Table 2). Variable 18, the number of

Table 2. Regression summaries for Orchards A, B, C, and combined data from three orchards in the southwestern San Joaquin Valley of California (1985–2015).

Data set	Intercept or variable no. ²	Standardized partial regression coefficients (Beta)	SE of Beta	Intercept or partial regression coefficient (b)	SE of b	t test of variable	P-level of variable	Variable contribution to unadjusted R ² of model	Adjusted R ² of model
Orchard A	Intercept			8.42×10^3	7.92×10^2	10.6	9.09×10^{-11}		0.61
	25 ^{squared}	-0.87	0.14	-1.23×10^{-4}	1.93×10^{-5}	-6.39	1.08×10^{-6}	0.31	
	18	-0.48	0.13	-21.8	6.06	-3.59	1.39×10^{-3}	0.20	
	11	-0.38	0.12	-33.7	10.8	-3.16	4.57×10^{-3}	0.14	
Orchard B	Intercept			8.51×10^3	5.80×10^2	14.7	1.11×10^{-14}		0.70
	26	-0.85	0.10	-0.90	0.11	-8.32	4.69×10^{-9}	0.63	
	12	-0.31	0.10	-44.2	14.4	-3.06	4.84×10^{-3}	0.09	
Orchard C	Intercept			6.90×10^3	6.24×10^2	11.07	3.44×10^{-9}		0.63
	27 ^{squared}	-0.74	0.14	-1.0×10^{-4}	1.92×10^{-5}	-5.20	7.16×10^{-5}	0.42	
	18	-0.50	0.14	-13.0	3.67	-3.55	2.45×10^{-3}	0.25	
Combined A, B, and C	Intercept			9.95×10^3	7.02×10^2	14.2	6.33×10^{-23}		0.65
	Previous yield ^{squared}	-0.79	0.07	-1.08×10^{-4}	9.43×10^{-6}	-11.4	5.81×10^{-18}	0.43	
	11	-0.21	0.07	-15.5	5.33	-2.91	4.82×10^{-3}	0.10	
	18	-0.47	0.09	-14.7	2.69	-5.47	5.47×10^{-7}	0.06	
	19	-0.36	0.08	-2.85	0.64	-4.47	2.75×10^{-5}	0.09	

Orchards A, B, and C have 29, 31, and 20 years of annual observations, respectively.

²Variable numbers are described in Table 1. The word “squared” next to a variable number indicates that the listed variable is the square of that variable number.

Fig. 1. Annual nut yield for ‘Kerman’ pistachio in three orchards in the San Joaquin Valley of California during the period 1985–2015.

accumulated hours $>18.3^{\circ}\text{C}$ during late fall and winter, from 15 Nov. to 15 Feb., was highly significant in Orchard A, Orchard C, and in the model for the combined data. Again, the sign of b for this variable was negative in all models when significant (Table 2), suggesting that warm temperatures during the dormancy period for mid-November through mid-February were associated with reduced yield at harvest. This association is important and one of the key findings from this study. In the combined model, b for Variable 18 estimates for each hour in excess of 18.3°C (15 Nov.–15 Feb) that subsequent yield was reduced by

$14.7\text{ kg}\cdot\text{ha}^{-1}$. Variable 19, the accumulation of hours below 7.2°C (15 Nov.–15 Feb.), was the only significant chill-related variable to appear in a model. Variable 19 appeared only in the combined model and, unexpectedly, was inversely related to yield, suggesting that greater chill-hour accumulation during the late fall and winter was associated with lesser yield at harvest (Table 2). The value of b for Variable 19 estimates that for each hour below 7.2°C in the time period from 15 Nov. to 15 Feb., a reduction in yield of $2.8\text{ kg}\cdot\text{ha}^{-1}$ may be expected. Chilling portions (Variable 1) was correlated with chill-hour accumulation below 7.2°C (Variable 19)

with an r value of 0.53 (data not shown), but Variable 19 explained a greater proportion of the variability in subsequent yield, and the CP variable (Variable 1) was removed from the model during the forward stepwise regression procedure.

Discussion

The use of historical long-term crop production data for investigating associations among weather variables and previous yields is not new for perennial fruit crops. For example, Jones and Cree (1965) found that yearly variations in navel orange yield were inversely related to the crop load from the previous year and with the single-day maximum T_a between 10 May and 30 June, the period after bloom, when they examined a 38-year yield history from trials conducted in Riverside County, CA.

Average yields, calculated from “on” and “off” years, averaged 4051.2 , 3602.1 , and $3701.0\text{ kg}\cdot\text{ha}^{-1}$ for Orchards A, B, and C over the time periods evaluated in this study. The high yields achieved in these commercial orchards must, in part, be the result of successful production practices. These yields were in excess of average county yields in Kern County for mature trees which have been closer to $3136\text{ kg}\cdot\text{ha}^{-1}$, the typical average yield for pistachio in the San Joaquin Valley (Brar et al., 2015). Whereas irrigation, fertilization, pruning, and pest control can greatly affect yield and were not directly accounted for in the regression models in this study, the relatively higher yields achieved in the orchards studied here suggest production practices were near optimal, and differences in yield among years, generally, reflect the influence of the previous crop and weather conditions.

The models in this study would be expected to have the highest predictive value for pistachio production located on the west side of the southern San Joaquin Valley at elevations between 80 and 250 m above sea level.

In the initial reviews of this article, concern was expressed that the excess production of nuts that are full size but do not contain kernels (referred to as blank nuts) which occurs after low-chill winters would invalidate comparisons of Ta variables with yield. Reasons for the observed increase in blanking and early nut abortion in pistachio as a result of insufficient chilling, and its contribution to poor yields (Crane and Takeda, 1979) are not well understood. Blanking, and associated lower yields, appears, at least in part, to be due to parthenocarp, which is the production of fruit with the stimulus of pollen but with ovules that remain unfertilized (Polito, 1999), and to postfertilization nut abortion (Crane, 1986; Shuraki and Sedgley, 1996). ‘Kerman’ has been described as a cultivar that typically produces an excessive amount of blank nuts compared with many other cultivars (Crane, 1986). More recent cultivar-evaluation trials have supported this description as ‘Kerman’ has exhibited higher production of blank nuts than other commercial cultivars even in years with adequate chilling (Kallsen and Parfitt, 2017). However, whether the cause for blanking is as simple as the desynchronization of the male and female bloom periods resulting in inadequate pollen for ‘Kerman’, physiological processes or degeneration of male and female floral parts as a result of inadequate rest-breaking, or other causes, Ta during the previous fall and winter or during bloom, would be expected to be implicated in any of these scenarios. If Ta was too high during the rest-breaking period or too high during bloom, this negative effect of Ta on yield should be discernable in a regression model; more so if these conditions existed before the onset of an “on” year.

The absence of significance with respect to a given variable in these regressions does not imply that that variable is not important in determining the yield of pistachio, in general. Lack of significance may only imply that a given variable was not useful in explaining the differences in subsequent yield of the ‘Kerman’ female and ‘Peters’ male cultivar combination in the San Joaquin Valley. For example, if accumulated chill hours greatly exceed the minimum number required for maximum yield at a given location, chill accumulation will not be a good predictor of variations in yield at that location. Pope et al. (2015) suggested that the CP requirement for adequate chill in pistachio, based on California data, may be <57 CP, whereas Zhang and Taylor (2011) estimated that 59 was sufficient for ‘Sirora’ in Australia. Average CP for Orchards A, B, and C were 70.5, 65.2, and 64.0 CP, respectively, which were above these values. In this study, during the time period from 1985 to 2015, CP accumulations were <57 (1 Sept.–28 Feb.), only three

years at the Blackwell CIMIS station (1996, 2013, and 2014) and five years at the Kettleman CIMIS station (1996, 2006, and 2013–15). The possibility also exists that existing models do not adequately estimate or reflect that actual winter rest or chilling requirement of pistachio. The observation by Elloumi et al. (2013) found that a CP threshold of 36 was adequate for rest-breaking in ‘Mateur’ pistachio in contrast to the 57 or 59 proposed by Pope et al. (2015) or Zang and Taylor (2011), respectively, suggests that either wide variations are present in the chill requirements among pistachio cultivars or the dynamic model for predicting rest breaking in fruit and nut crops is not readily transferable among different fruit and nut species or geographical locations.

The apparent lack of an association between methods of quantifying winter chilling and subsequent yield in the San Joaquin Valley individually in these three orchards suggests that accumulating hours below a threshold value or calculating CPs had limited utility for predicting subsequent yield. In two of the individual orchards in this study, hours of heat above a threshold value of 18.3 °C during the period from 15 Nov. to 15 Feb. (Variable 18) explained more of the total variation in yield than did methods for estimating chilling, perhaps because these warm temperatures have a negative or interruptive effect on chilling hour accumulation. Similarly, Variable 18 explained more of the total variation in subsequent yield than did using a lower threshold value for accumulation of heat hours in the calendar period of 15 Nov.–15 Feb. (i.e., Variables 16 and 17) or using the shorter calendar period of 15 Dec.–31 Jan. in Variables 13–15. Variable 18 explained 20%, 25%, and 9% of the total variation in yield in Orchards A, C, and the combined regression model, respectively. Variable 18 was not significant in Orchard B where previous yield, Variable 26, explained 63% of the unadjusted variation in subsequent yield. These results suggest that in the San Joaquin Valley, calculating and accumulating hours above a given temperature threshold during the “rest” or “dormant” period would be more useful in predicting subsequent yield than calculating CP or chilling hours below a given threshold. Similarly, these data suggest that strategies to maintain subsequent yield, perhaps by applying heat-reflective materials to the tree canopy, such as kaolin clay or calcium carbonate, to lower orchard temperatures below 18.3 °C from 15 Nov. to 15 Feb. might be economically feasible, whereas attempting to increase chill hours by lowering temperatures below 7.2 °C would not. Lower yields associated with higher winter heat-hour accumulations are a concern because winter temperatures have been rising as chill accumulations have been decreasing at the two CIMIS stations used in this study (Fig. 2). This phenomenon was not limited to these two stations but has been noted previously across California (Baldocchi and Waller, 2014; Luedeling,

Fig. 2. Annual chill-hour and heat-hour accumulations calculated from Blackwell (Station 54) and Kettleman (Station 21) CIMIS network weather data for the period of 15 Nov.–15 Feb. from 1985 or 1987 to 2015. The ‘fitted’ linear least-squares trend lines are shown.

2012; Luedeling and Gassner, 2012; Luedeling et al., 2009).

In the combined model for the three orchards, not only were measures of chill not positively correlated with subsequent yield but were inversely related. Variable 19, the variable measuring chill-hour accumulations below 7.2 °C (Table 1), was inversely related to subsequent yield in the combined regression (Table 2), suggesting greater levels of winter chilling suppressed subsequent yield. If Variable 19 was eliminated from the regression, Variable 22 became significant almost at the same level as Variable 19, and it was also inversely related to subsequent yield. Similarly, if Variables 19 and 22 were eliminated from the regression, Variable 21 became significant (and inversely related), and this process continued as the previously significant chill-related variables were eliminated from the analysis, and Variable 23 and then Variable 20 were substituted. Thus, this inverse relationship of the various chill-related variables with subsequent yield was persistent and appears to be related to some low yields in orchards A and B in the “off” years in the late 1980s and early 1990s when chill-hour accumulations were >1200 h (Fig. 3). A simple polynomial function fit to the combined orchard data of yield vs. Variable 19 suggests that the relationship between yield and chilling hours for ‘Kerman’ and ‘Peters’ may be curvilinear (Fig. 3), and thus, the existence of a level of chill-hour accumulation which maximizes subsequent yield for a reason currently unknown and which our data are too limited to identify. This polynomial correlation (r -value = 0.29) of subsequent yield against Variable 19 (Fig. 3) explains more of the

Fig. 3. Pistachio nut yield as a function of accumulated chilling hours <7.2 °C during the period of 15 Nov.–15 Feb. from the Blackwell or Kettleman CIMIS stations from 1985 to 2015 from three orchards in the San Joaquin Valley of California. The “fitted” quadratic least-squares trend line is shown ($r = 0.29$).

variation present in the combined orchard data than does the simple linear regression. However, when the square of Variable 19 was included in the multiple regression of the combined data, it was removed from the model by the forward stepwise regression process in favor of a linear Variable 19. An explanation of why increases in chill-hour accumulations of Ta less than 7.2 °C (15 Nov.–15 Feb.) should linearly reduce subsequent yield is not clear. This negative correlation was not found in the stepwise regression model when the CP-related variables were substituted for those that used hourly accumulations below 7.2 °C. There may be collinearity effects among the selected variables that this analysis was unable to identify. However, no reason could be found to eliminate the chilling variables (Variables 19–24) from the regression based on this potential problem. The explanation for why yield decreases with increasing chilling hours may be as simple as the male and female cultivars displaying reduced bloom synchrony and yield after a fall and winter of higher chill-hour accumulation after an “on” year. As discussed previously, the highest chill-hour accumulations in this study occurred in the 1980s and 1990s and have been decreasing (Fig. 2), and thus, additional data points to explore this possible phenomenon are not available. The possibility also exists that the methods used in this study to estimate chilling do not adequately estimate the fall and winter “rest” or “dormancy” requirements of pistachio. Perhaps excessive hourly accumulations of cooler temperatures in February reduce ‘Kerman’ yield potential in

some way. According to the combined regression model, Variable 19 appears to have predictive power, but perhaps, should be considered a Ta variable useful in predicting yield, but not the effectiveness of estimating whether the “rest” or “dormancy” requirements of the tree are adequate.

The negative effect of increased hourly chill accumulation on subsequent yield was found only in the combined model. If Variable 19 is eliminated, arbitrarily, from the combined model, while retaining the Variables 11, 18, and the square of previous yield, the resulting regression based on these remaining variables maintains an adjusted R^2 value of 0.57. The regression equation for the combined model with Variable 19 removed is as follows:

$$\begin{aligned} \text{Subsequent yield} = & 7276 - 19.1(\text{Variable 11}) \\ & - 7.90(\text{Variable 18}) \\ & - 0.776(\text{Previous yield})^2 \end{aligned}$$

The negative association of hourly accumulations >26.7 °C during the bloom and early fruit set period and subsequent yield suggests that high Ta during bloom reduced subsequent yield. Similarly, high temperatures during bloom have been found to negatively affect fruit set in olive [*Olea europaea* (Cuevas et al., 1994)] and in stone fruit such as apricot [*Prunus armeniaca* (Burgos et al., 1991)], peach [*P. persica* (Kozai et al., 2004)], and cherry [*P. avium* (Hedhly et al., 2007)]. The reasons why high Ta during the bloom period should reduce subsequent yield in pistachio is not clear;

however, it does not appear to be related to pollen germination, which can remain high up to 39 °C in the pollinizer ‘Peters’ (Polito et al., 1988).

The absence of highly significant GDD variables in the models (Table 2) suggests that spring or summer heat was not a limitation for pistachio yield on the western side of the San Joaquin Valley.

Conclusions

Of the 27 regression variables examined in this study, the following, which were all negatively correlated with subsequent yield, explained the greatest proportion of the variability present in predicting the subsequent yield of ‘Kerman’ pistachio in the combined model: the square of the yield of the previous-year harvest, hourly Ta accumulations above 26.7 °C from 20 Mar. to 25 Apr., hourly Ta accumulations below 7.2 °C from 15 Nov. to 15 Feb., and hourly Ta accumulations above 18.3 °C from the calendar period from 15 Nov. to 15 Feb. These four variables explained 65% of the variation in yield of ‘Kerman’ pistachio in the combined model for three orchards from 1985 through 2015.

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