Fruit development in almond is influenced by early Spring temperatures in California

By S. TOMBESI[1], R. SCALIA[2], J. CONNELL[3], B. LAMPINEN[4] and T. M. DEJONG[4]*

[1]Dipartimento di Scienze Agrarie ed Ambientali, Università degli Studi di Perugia, Borgo XX Giugno 74, 06100, Perugia, Italy

[2]Dipartimento di Ingegneria e Tecnologie Agroforestali, Università degli Studi di Palermo, viale delle Scienze Ed.4, 90128, Palermo, Italy

[3]University of California Cooperative Extension, Butte County, 2279 Del Oro Ave. # B, Oroville, CA 95965, USA

[4]Department of Plant Sciences, University of California, One Shields Ave., Davis, CA 95616, USA
(e-mail: tmdejong@ucdavis.edu)

SUMMARY

The period from full bloom (FB) to fruit maturity for individual cultivars of peach, nectarine, plum, and prune is influenced by daily temperatures between the start of FB and 30 d after FB (DAFB). Typically, warm Springs accelerate fruit development. Almond is closely-related to peach, but the date of fruit maturity is not always closely-related to the date of harvest. Normally the date of "hull-split" (HS) signals the beginning of fruit maturity. The aim of this study was to determine if the length of the period between FB and HS in several important Californian almond cultivars was related to temperatures shortly after the start of FB. Data on the dates of FB and HS from three locations in the Central Valleys of California (North, Central, and South) were analysed over 8 years to determine the effect of Spring temperatures on the duration of fruit development. Data on 28 cultivars were evaluated, but only the results for 12 of the most important cultivars are reported here. The length of the period of fruit development from FB to HS was negatively correlated with the accumulation of degree-days between FB and 90 DAFB (mean R^2 = 0.51 ± 0.3), with generally poorer correlations with degree-days to 30 or 50 DAFB (mean R^2 = 0.31 ± 0.02 and 0.36 ± 0.3, respectively). These results suggest that temperatures in the first 90 DAFB are the primary factor influencing the time of nut maturity in almond cultivars in California. This information will be used to develop a harvest prediction model to assist growers in planning harvest dates. To facilitate this, we are in the process of developing a webpage on the UC Davis Fruit and Research Information Website similar to the one for peach and plum growers (http://fruitsandnuts.ucdavis.edu/Weather_Services/Harvest_Prediction_About_Growing_Degree_Hours.htm).

Temperatures in the first several weeks after the start of flowering affect the length of the period of fruit development in temperate deciduous fruit crops such as peach (Blake, 1930; Weinberger, 1948) and apple (Berg, 1990). In peach, fruit growth is a function of a genetically determined pattern of development for each specific cultivar and the availability of carbohydrate resources (Grossman and DeJong, 2005; DeJong, 1999; Lopez *et al.*, 2008). The rate of fruit development has been correlated with temperatures soon after the start of flowering (Weinberger, 1948; Marra *et al.*, 2002). Specifically, fruit development was related to the accumulation of "growing degree hours" (GDH30) in the first 30 d after full bloom (DAFB) (Ben Mimoun and DeJong, 1999; Lopez *et al.*, 2007; Lopez and DeJong, 2007; Day *et al.*, 2008). Similar data have also been collected for nectarine, Japanese plum (*Prunus salicina* L.), and prune (*P. domestica* L.) in California (Ben Mimoun and DeJong, 1999; Day *et al.*, 2008; DeBuse *et al.*, 2010).

Almond [*P. dulcis* (Mill.) DA Webb] is the most important tree crop in California, with more than 300,000 ha under cultivation. Most cultivars are self-sterile and hence two or more cultivars are usually inter-planted (Asai *et al.*, 1996). Almond is closely-related to peach, but the date of harvest is not always closely-related to the date of fruit maturity. Harvesting can be delayed until the fruits are dry enough to harvest, because of shortages of labour and equipment. The nuts are shaken from the trees and picked-up by machines from the orchard floor. A timely harvest is essential to maintain nut quality and to minimise post-harvest microbial contamination (Danyluk *et al.*, 2007). Nuts from each cultivar must be harvested separately from other cultivars in order to optimise hulling, shelling, and marketing. Hence, the maturity dates of individual almond cultivars in the same orchard must be sufficiently different to prevent undesirable mixing of the nuts. Consequently, harvest maturity is an important consideration when choosing cultivars for an orchard. In addition, the nuts of late cultivars can be difficult to dry on the ground due to shortened days, cool weather, or early rains. These can also reduce nut quality due to delays in harvesting and can increase harvesting costs by extending harvest operations and drying times. Because of the large area of land devoted to almond cultivation in California, and the logistics of scheduling late-season orchard management practices (especially irrigation) as well as harvesting operations, it would be beneficial to be

*Author for correspondence.

able to predict the date of harvest maturity as early in the season as possible. This information also would be important for marketing decisions.

"Hull-split" (HS) signals the beginning of fruit maturity in almond. The control of navel orangeworm, *Amyelois transitella* (Walker), the principal insect pest of almonds in California, is dependent on the timing of HS because the nuts are only susceptible to infection after HS. The length of time between HS and harvest determines whether or not the nuts are exposed to egg-laying from one or two generations of navel orangeworm. Rapid nut maturity from the initiation of HS to 100% HS, and a timely harvest can shorten the time that the nuts are exposed to the pest. Early or

timely harvest is the principal method of avoiding damage to soft-shelled almond cultivars (Connell *et al.*, 1989).

The objective of this study was to determine whether the length of time between FB and HS was related to temperatures in early Spring for the most important Californian almond cultivars. We collected data on the dates of FB and 1% HS, and tree yields, for 28 almond cultivars growing at three different locations in the Central Valleys of California. We also evaluated the effect of mid-season air temperatures and potential evapo-transpiration (ET) on the length of time between FB and HS in order to determine how such multiple stresses might interact to influence fruit development.
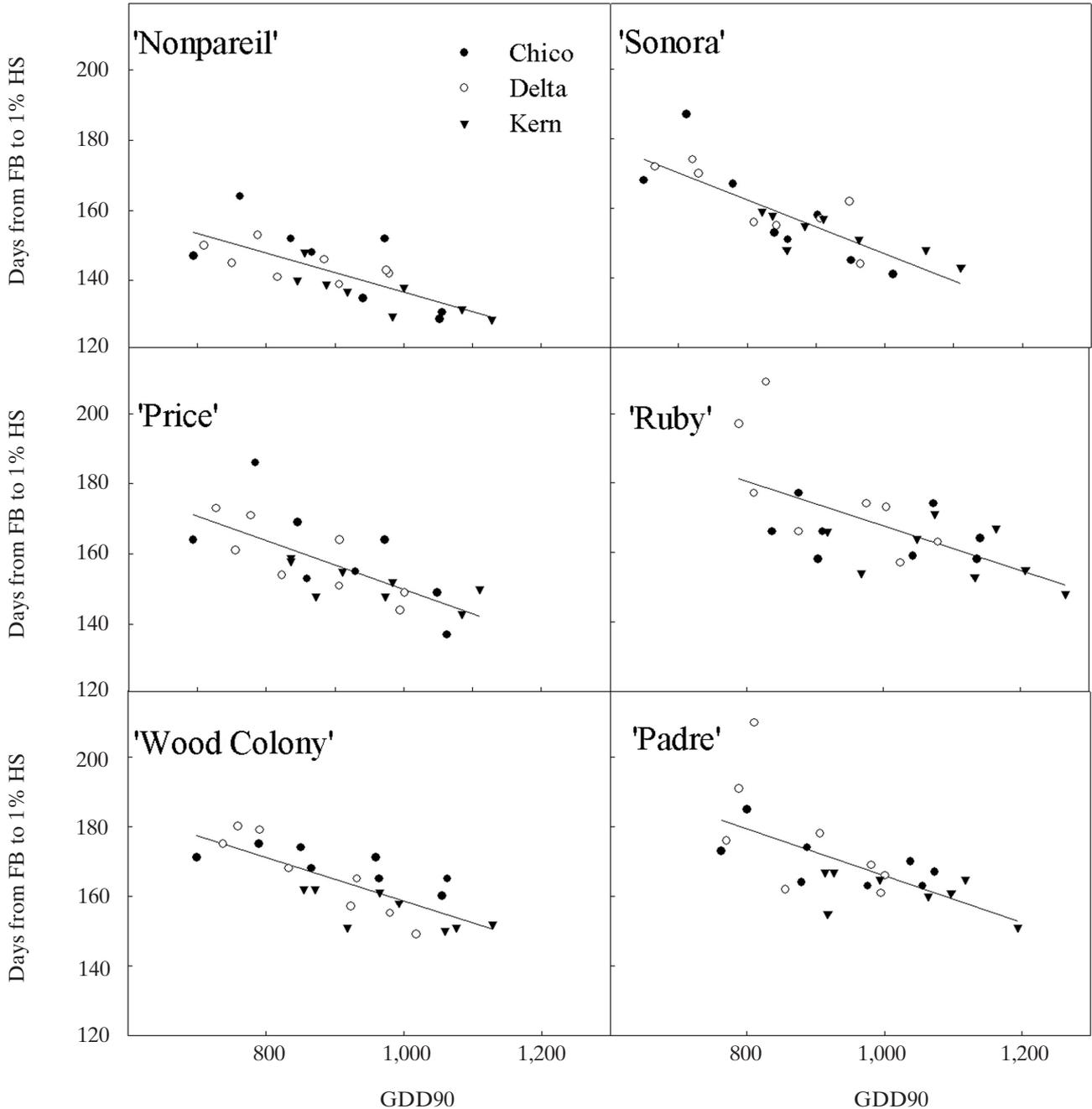

Fig. 1.
The relationships between the number of days after full bloom (DAFB) to 1% HS and the accumulated GDD between FB and 90 DAFB (GDD90) for six "early" almond cultivars grown at three different orchard sites in California (Chico, Delta, and Kern plots) over 8 years. The regression statistics are shown in Table I.

MATERIALS AND METHODS

The experimental orchards were located near Chico in the northern Sacramento Valley (Chico plot), at Manteca at the northern end of the San Joaquin Valley (Delta plot), and at Shafter in the southern end of the San Joaquin Valley (Kern plot). Meteorological data were obtained from the CIMIS (California Irrigation Management Information System) stations (http://wwwcimis.water.ca.gov/cimis/welcome.jsp) nearest to each of the experimental orchards. The three CIMIS stations were: # 12 (Durham), # 70 (Manteca), and # 5 (Shafter) for the Chico, Delta and Kern plots, respectively.

The orchards were planted in 1993 to evaluate 34 almond cultivars. In this study, we analysed data from 28 cultivars but, for brevity we are only reporting data on 12 of the most commercially important cultivars. All cultivars were planted at densities of 158, 185, and 213 trees ha^{-1} at the Chico, Delta and Kern plots, respectively. Cultivars were planted in single rows of 20 – 25 trees, alternating with rows of the standard cultivars, 'Nonpareil' or 'Mission', for cross-pollination and data comparisons. The dates of FB for each cultivar, over each of the 8 years, were determined by daily or alternate-day visits to each orchard. Fruit nearing maturity were monitored each week to estimate the percentage of nuts
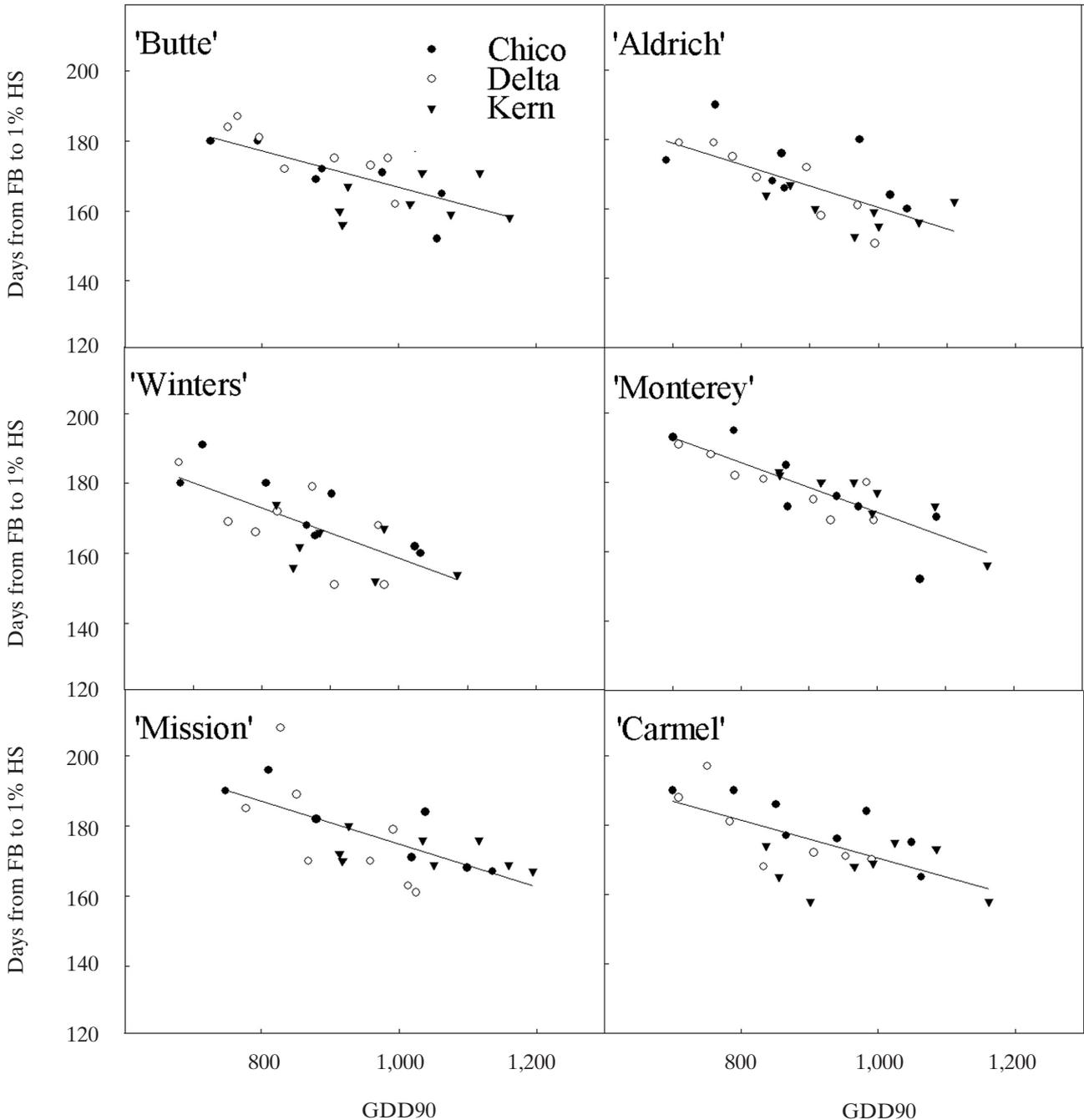

FIG. 2.
The relationships between the number of days after full bloom (DAFB) to 1% HS and the accumulated GDD between FB and 90 DAFB (GDD90) for six "late" almond cultivars grown at three locations in California (Chico, Delta, and Kern plots) over 8 years. The regression statistics are shown in Table I.

with split hulls. "Hull-split" (HS) was defined as the time when nuts with green hulls cracked from the suture to the shell.

For each year and cultivar, the sum of the growing degree hours (GDH30) from full bloom (FB) to 30 DAFB was calculated using hourly temperatures (Anderson *et al*., 1986). In addition, for each year and cultivar, the sums of growing degree-days (GDD) from FB until 30, 50, and 90 DAFB were also calculated using the single sine method with horizontal cut-offs below 5°C and above 35°C (Zalom *et al*., 1983). To estimate the influence of environment on fruit development we considered the length of time between FB and 1% HS. Potential "stress" variables, including cumulative potential evapotranspiration (ET$_o$) for each month of the growing season, cumulative high temperatures above 30°C during the last half of fruit development, and crop load [yield data published by Lampinen *et al*. (2002) available from research reports to the California Almond Board on regional almond variety trials] were also analysed. The relationship of each of these variables to the length of time between FB and 1% HS were tested alone and in combination with Spring temperature variables.

Statistical analyses were conducted using Sigmaplot 8.0 (Systat Software Inc., San Jose, CA, USA) and SAS 9.1.3 (SAS Institute Inc., Cary, NC, USA). We considered coefficients of equations obtained by linear regression and coefficients of determination (R^2) as indices of the goodness-of-fit.

RESULTS

Considering the data from all three plots, the time period from FB to 1% HS for all cultivars varied by approx. 30 d, depending on plot and year (Figure 1; Figure 2). However, the seasonal variation for a given plot was closer to 20 d.

Relationship between fruit development and GDH

Attempts to relate fruit development to early Spring temperatures, as used in previous studies (i.e., GDH accumulated 30 DAFB; GDH30) were only partially successful. The relationships were particularly poor for the southern-most Kern plot; (mean $R^2 = 0.17 \pm 0.04$).

Relationship between fruit development and GDD

The period of fruit development for a given plot and year was negatively related to the accumulated GDD in the first 90 DAFB (GDD90; mean $R^2 = 0.51 \pm 0.02$; Figure 1; Figure 2). While there was some variation among cultivars, the relationships were generally stronger for accumulated GDD over 90 d than over 30 d or 50 d (mean $R^2 = 0.31 \pm 0.02$ and 0.36 ± 0.3, respectively; Table I). There was no clear relationship between the number of GDD between FB and 1% HS and temperatures over that same period (Table I). However, there were substantial differences in R^2 values associated with the GDD relationships among cultivars, with 'Monterey' and 'Sonora' exhibiting the strongest relationships, and 'Ruby' and 'Padre', the weakest. However, much of the decrease in R^2 values for the latter two cultivars appeared to have been due to one or two "outlying" points that may not have reflected the overall relationship. As expected, the southern-most orchard (Kern plot) tended to accumulate GDD more rapidly than the two more northerly plots over a year (Figure 1; Figure 2).

Effect of potential "stresses" on the rate of fruit development

Attempts to account for some of the variability among plots and years in the relationships depicted in Figure 1 and Figure 2 using weather [e.g., cumulative potential evapotranspiration (ET$_o$), or cumulative high temperatures above 30°C in the last half of fruit development] or crop load data were not successful. We found no consistent relationships between the duration of fruit development and these variables (data not shown).

DISCUSSION

Relationship between fruit development and GDH

Based on previous research with peach and nectarine (*P. persica*), plum (*P. salicina*; Ben Mimoun and DeJong, 1999; Day *et al*,. 2008), and prune (*P. domestica*; DeBuse *et al*., 2010) we anticipated that we would find similar relationships between fruit development and early Spring temperatures for almond (*P. dulcis*). However, initial attempts using GDH30 were only partially successful. These analyses were particularly poor for the most southerly Kern plot. The GDH30 calculation from Anderson *et al*. (1986) did not adequately capture the influence of Spring temperatures above 25°C. In retrospect, this was not surprising since their equation

TABLE I

Regression statistics (slopes, intercepts, and coefficients of determination) for the relationships between the number of days after full bloom (DAFB) to 1% HS and the accumulated GDD between FB and 30, 50, and 90 days DAFB and total accumulated GDD between FB and 1% HS in 12 almond cultivars over 8 years at three sites in California

Cultivar	DAFB *vs*. GDD30			DAFB *vs*. GDD50			DAFB *vs*. GDD90			DAFB *vs*. GDD total		
	a[¶]	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
'Nonpareil'	−0.13	172	0.34	−0.12	191	0.58	−0.06	192	0.54	0.03	89	0.12
'Sonora'	−0.18	197	0.45	−0.12	207	0.49	−0.08	224	0.67	0.06	44	0.27
'Price'	−0.16	192	0.32	−0.16	223	0.51	−0.07	219	0.53	0.05	53	0.39
'Ruby'	−0.15	207	0.33	−0.14	231	0.32	−0.06	232	0.40	0.05	47	0.37
'Wood Colony'	−0.14	196	0.35	−0.12	215	0.37	−0.06	221	0.60	0.03	86	0.17
'Padre'	−0.14	202	0.24	−0.14	228	0.23	−0.07	233	0.41	0.05	48	0.38
'Butte'	−0.09	192	0.19	−0.09	207	0.19	−0.05	219	0.45	0.02	113	0.13
'Aldrich'	−0.12	194	0.20	−0.13	219	0.33	−0.06	222	0.49	0.04	86	0.27
'Winters'	−0.17	205	0.33	−0.10	208	0.22	−0.07	230	0.50	0.04	72	0.38
'Monterey'	−0.15	212	0.40	−0.13	232	0.42	−0.07	243	0.71	0.03	100	0.23
'Mission'	−0.14	213	0.37	−0.11	225	0.26	−0.06	236	0.45	0.04	83	0.29
'Carmel'	−0.13	205	0.28	−0.12	223	0.44	−0.05	225	0.43	0.03	102	0.21

[¶]a = slope, b = *y* intercept, R^2 = coefficient of determination.

was developed for much lower temperatures than those typical for southern California.

Relationship between fruit development and GDD

The single sine method for calculation of GDD (Zalom *et al.*, 1983) resulted in more definitive relationships (Table I). Furthermore, when the accumulation of GDD was extended beyond 30 d, to 50 d or 90 d, even stronger relationships were obtained. The number of days between FB and 1% HS was more closely-related to GDD90 (i.e., between FB and 90 DAFB) than to the total GDD accumulated between FB and 1% HS. As with peach, nectarine, and plum (Ben Mimoun and DeJong, 1999), this indicates that early fruit development is quite sensitive to Spring air temperature. The first half of fruit development in stone fruit primarily involves cell division and differentiation (Zucconi, 1986), while the latter half primarily involves cell expansion. Thus, it is tempting to conclude that cell division and differentiation may be more sensitive to temperature than cell expansion. An alternative hypothesis is that limiting low temperatures are more prevalent in Spring than during mid-season and, thus, the responses of fruit growth to temperature are more apparent early in the season. In either case, it is clear that the rates of fruit development that occur early in the season can have a strong effect on "programming" development for the rest of the season.

Effect of potential "stresses" on the rate of fruit development

During the last month of fruit development, the fresh weights of the hull, shell, and kernel decrease as the ripening nuts begin to dry (Connell *et al.*, 1996). Previous research has reported that water deficits during this period can affect the timing of HS and harvest (Teviotdale *et al.*, 1995; 2001). Since potential evaporative demand can influence tree water status, we hypothesised that potential ET may be a useful variable to include in any model used to predict the date of HS. Similarly, we reasoned that crop load may influence the timing of HS, since heavy crops have been reported to delay fruit ripening in other stone fruit (Saenz *et al.*, 1997). However, these parameters did not appear to influence substantially the ripening rate of almond fruit in this study. This may have been because the orchards used in this study were managed to minimise stress in order to assess only genetic differences in the growth and yield characteristics of the different cultivars.

Predicting the initial HS date, 90 DAFB, should provide an opportunity for growers to improve their irrigation and pest management strategies and to plan for harvesting. To facilitate this, we are developing a webpage on the UC Davis Fruit and Research Information Website similar to that for peach and plum growers using GDH30 models (http://fruitsandnuts. ucdavis.edu/Weather_Services/Harvest_Prediction_About _Growing_Degree_Hours.htm).

Further research will be necessary to determine if the relationships developed for almond trees in California are applicable to other almond-growing regions. If so, they may be useful for comparing the weather characteristics of different regions and the suitability of specific almond cultivars for specific regions.

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