Scientia Horticulturae 143 (2012) 184–188

Contents lists available at SciVerse ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

'Hass' Avocado tree growth on four rootstocks in California. I. Yield and flowering

Michael V. Mickelbart*, Paul W. Robinson, Guy Witney, Mary Lu Arpaia

Department of Botany and Plant Sciences, University of California, Riverside, CA 92521-0124, United States

ARTICLE INFO

Article history:
Received 17 February 2012
Received in revised form 6 June 2012
Accepted 12 June 2012

Keywords:
Rootstocks
Fruit size
Fruit abscission
Alternate bearing
Flowering

ABSTRACT

Two experiments were conducted to assess the relationship between alternate bearing, flowering, fruit set, and fruit growth in mature 'Hass' avocado (*Persea americana* Mill.) in Irvine, California. In the first experiment, trees were grown on four clonal rootstocks ('Thomas', 'Topa Topa', 'Duke 7', or 'D9'), and data collected on yield, number of fruit per tree, average fruit weight, and the timing and duration of flowering over five seasons. In the second experiment, 'Hass' trees were grown on 'Duke 7' rootstock and data collected on the rate of fruit retention and fruit volume growth over three years. In Experiment 1, the trees exhibited "on" and "off" years in most cropping cycles. Heavy yields were associated with a higher number of fruit per tree, lower average fruit weight, and early and longer periods of flowering. Although yield varied among rootstocks, especially in heavy crop load years, trees growing on different rootstocks had similar cropping patterns. In Experiment 2, fruit abscission varied over years, but rates of volume increase were similar over years. Low yields in 'Hass' avocado trees appear to be related to later and shorter flowering periods and fewer and larger fruit at harvest.

1. Introduction

Annual production of avocado (*Persea americana* Mill.) in California fluctuates due to alternate bearing. Trees in "off" years typically yield approximately 40% less than trees in "on" years (Anonymous, 2000). Dramatic variations in crop volume from year to year result in the loss of revenue during low-yield years and in oversupply during high-yield years.

Although there are 1–2 million flowers on a mature avocado tree (Bergh, 1986; Cossio-Vargas et al., 2007), usually less than 0.1% of them set fruit, and most of the fruit that set abscise before fruit are mature (Whiley and Schaffer, 1994; Garner and Lovatt, 2008). Other factors also influence flowering and fruit set, including temperature (Sedgley and Annells, 1981), the presence and variety of pollinizers (Degani et al., 1997), and the use of insect pollinators (Ish-Am and Eisikowitch, 1991, 1993).

We examined shoot and root growth, flowering, and yield of 'Hass' avocado trees on different rootstocks under semi-arid subtropical conditions in California. 'Thomas' and 'Duke 7' rootstocks are commonly used due to their tolerance to root rot caused by *Phytophthora cinnamomi*, whereas 'D9' is less popular, dwarfing, and useful as a breeding parent (J. Menge, Dept. of Plant Pathology, University of California, personal communication). 'Topa Topa' was widely used as a seedling rootstock prior to the adoption of clonal material. For uniformity, clonal 'Topa Topa' rootstocks were used in this study. We were interested in determining the relationship between alternate bearing and flowering, fruit set, and fruit growth. The objectives of these studies were to (1) determine the relationship between vegetative and reproductive growth and yield, and (2) determine the effect of rootstock on these traits and relationships. This information will help guide future research on avocado by establishing the important factors affecting productivity.

2. Materials and methods

2.1. Plant material and field environment

'Hass' avocado trees on clonal 'Thomas', 'Topa Topa', 'Duke 7', or 'D9' rootstocks (all Mexican race) were planted at the University of California South Coast Research and Extension Center in Irvine (latitude, 33°44′N; longitude, 117°49′W). The trees were planted in a randomized complete block design. Rows (north–south orientation) acted as blocks, and each rootstock was represented one time in each of 10 blocks. With the exception of trees on 'Thomas' rootstock, which were planted in 1987, all other trees were planted in 1986. Ten trees per rootstock were used for all measurements, except for shoot extension, where five trees per rootstock were used.

The trees were planted at a spacing of 6.1 m × 6.1 m on slightly raised 1.5 m wide by 0.5 m high berms to facilitate water drainage. The soil was a Hanford sandy loam. The trees were irrigated with low-volume microsprinklers. Air and soil temperatures, relative

* Corresponding author. Present address: Department of Horticulture and Landscape Architecture, Purdue University, West Lafayette, IN 47907-2010, United States. Tel.: +1 765 494 7902; fax: +1 765 499 0391.
E-mail address: mickelbart@purdue.edu (M.V. Mickelbart).

0304-4238/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.scienta.2012.06.023

humidity, and precipitation were monitored during the experiment by the California Irrigation Management Information System (CIMIS) weather station approximately 1.3 km from the trees. Water demand was calculated based on evapotranspiration data from CIMIS (Snyder et al., 1985). Standard fertilization for avocado trees in California (Goodall et al., 1981) was practiced. The experimental block had no pollinizer cultivars. However, immediately adjacent to the north side of the block was a row of seedling avocados of mixed origin. Analysis of yield in the block in relation to proximity to the seedling row did not reveal a significant ($P < 0.05$) effect on yield. Pollination was not supplemented with bee hives.

2.2. Measurements

'Hass' trees flower in February to May in southern California and the fruit mature (based on commercially standardized measurements of dry matter percentage) within approximately six to eight months (Lee et al., 1983). The fruit may remain on the tree, however, for an additional 10 months. Trees in this study were harvested in April, approximately 12–14 months after fruit set. Yield (fruit weight and number) was measured and average fruit fresh weight calculated.

Trees were assessed for presence of flowers every two to three weeks during flowering, and estimates of the timing and duration of flowering were made. Flowering was estimated to begin at first anthesis and to end at last anthesis.

Fruit growth and abscission were measured in 1994, 1995, and 1996 on a different set of 'Hass' trees on 'Duke 7' rootstock in a field adjacent (within 30 m) to the main experiment. Care of these trees (planted in 1987) was as described above. An average of 55 individual fruit on each of 10 trees were tagged shortly after fruit set, and fruit length (l) and width at the widest point (w) measured approximately every three weeks until harvest. Fruit volume (V) was calculated using the formula for a prolate spheroid, $V = 4/3\pi(1/2w)^2(1/2l)$. This formula provided a sufficiently accurate estimate of volume based on measurements of actual volume (measured by water displacement).

2.3. Statistical analysis

The trees in the main experiment were planted as a randomized complete block design. Analysis of variance was conducted using the PROC GLM procedure of SAS (SAS, Cary, NC, USA). Rootstock and block were considered fixed and random effects, respectively. When multiple measurements were made on an individual tree (e.g., shoot length), the experimental error (rootstock × block) was used to test rootstock effects. Mean separation was done with Fisher's Protected Least Significant Difference test. For graphical representation, data from heavy (1992 and 1994) or light crop load (1993, 1995, and 1996) years were pooled and the means presented.

3. Results

3.1. Weather

Apart from high winter rainfall in 1992, all average yearly mean winter and summer temperatures and RH, and total winter and summer rainfall (Table 1) were average for this area. These values do not indicate short-term variations in weather.

3.2. Yield

Yield varied across years and among rootstocks within most years, but there were no consistent differences among rootstocks (Table 2). Trees exhibited alternate bearing from 1992 to 1995 with higher yields in 1993 and 1995 and lower yields in 1994 and 1996. Based on alternate bearing patterns, a heavy yield was expected in 1997, but a lower than expected yield occurred. Differences were reflected in both weight and number of fruit per tree (Table 2). Fruit size was not different among rootstocks except in 1995, when the average fruit size on 'Topa Topa' was 16% smaller (on a weight basis) than fruit on the other rootstocks (Table 2). Average fruit fresh weight tended to be highest in 1992, 1994, and 1996 when the yield was lower (Table 2).

3.3. Flowering

Flowering began as new shoots emerged. The beginning of flowering was quite variable and ranged from mid-February to early April (Table 3). The end of flowering from early to mid-May was more consistent.

Earlier and longer flowering periods preceded heavy yields compared with light yields (Tables 2 and 3). When flowering data were separated into two groups, heavy crop (1992 and 1994) and light crop (1993 and 1995) years, differences in the beginning and duration of flowering were significantly ($P < 0.001$) different between the two groups. The mean date for the start of flowering for the subsequent heavy and light crops was 28 February and 27 March, respectively. The mean durations of flowering were 77 and 49 days, respectively (data not shown).

Rootstock did not have a significant ($P < 0.05$) effect on the timing or duration of flowering except in 1996, when trees on 'Thomas' flowered earlier and longer than trees on other rootstocks (data not shown). There was no clear relationship between air temperatures prior to and during flowering in January through March and the timing or duration of flowering (data not shown).

3.4. Fruit growth

Fruit abscission occurred throughout fruit development but was heaviest 70–100 days after set (Fig. 1A). Fruit abscission was greatest in 1995, when only 12% of the fruit remained on the tree at harvest, compared with 63% and 64% in 1994 and 1996, respectively.

Fruit set began in early April (130th day of the year) (Fig. 1). The period of maximum fruit growth rate occurred up to mid-August (230th day of the year) (Fig. 1B). From mid-August until harvest, the fruit growth rate slowed substantially. The same pattern was observed in each year.

4. Discussion

Rootstock can affect alternate bearing in 'Hass' avocado, but the four rootstocks used in the current study did not have different alternate-bearing indices in a larger experiment that included 10 rootstocks (Mickelbart et al., 2007). Although avocado is alternate bearing, factors other than crop load can disrupt the response (Hodgson, 1947). Examination of yield records for an entire growing region or an individual grove reveals a general alternate bearing pattern, but disruptions to the pattern are common (Lomas, 1988). The fact that the trees in this study did not follow a regular alternate bearing pattern suggests that this pattern can be disturbed by cultural or environmental events. While freezes or droughts may disrupt the alternate bearing pattern, more subtle events may also play a role. Although there were no temperature extremes in 1996 that would have resulted in the lower than expected yields, temperature cannot be ruled out as a potential factor. Temperatures may affect fruit set and yield by altering the timing of male and female flowering (Sedgley and Grant, 1983).

Table 1
Average daily maximum and minimum air temperature and mean soil temperature (15 cm below surface), relative humidity (RH), and precipitation at the University of California South Coast Research and Education Center in Irvine, California, during the experiment.

Year	Max temp. (°C)		Min temp. (°C)		Soil temp. (°C)		RH (%)		Precipitation (cm)	
	W[a]	S[b]	W	S	W	S	W	S	W	S
1992	20.7	26.6	9.8	15.1	14.5	21.3	60.1	68.3	110	6
1993	20.9	25.2	9.3	14.0	16.9	24.6	59.5	70.4	30	3
1994	20.3	25.5	8.1	14.1	17.2	24.8	62.9	74.3	14	5
1995	20.4	26.1	9.6	13.7	18.9	23.7	72.1	65.5	30	5
1996	20.2	26.2	9.4	14.1	18.2	23.9	64.6	65.1	41	4

[a] Winter (W) = average of October through March.
[b] Summer (S) = average of April through September.

Table 2
Effect of rootstock on yield, fruit production, and average fruit fresh weight of 'Hass' avocado trees growing on four clonal rootstocks at the University of California South Coast Research and Education Center in Irvine, California ($n = 10$). Yield numbers shown represent fruit harvested in the given year, but they are the result of the previous year's flowering period; e.g., 1992 flowering resulted in 1993 average yield of 115.2 kg tree^{-1}.

Rootstock	Year					
	1992	1993	1994	1995	1996	1997
Yield (kg tree^{-1})						
'Thomas'	11.9[a]	79.8c	0.6	83.1b	10.0c	14.8
'Topa Topa'	2.0	130.8ab	0.1	147.5a	25.5bc	14.4
'Duke 7'	8.9	137.1a	0.1	132.2a	41.9ab	21.2
'D9'	10.5	115.4b	1.3	88.8b	49.4a	15.8
Mean of *F*[b]	8.3[n.s.]	115.2[*]	0.5[‡]	112.4[***]	31.4[**]	17.4[n.s.]
Number of fruit (fruit tree^{-1})						
'Thomas'	61.1	380.9c	2.1	384.3c	40.0c	75.8
'Topa Topa'	9.0	638.8ab	0.3	779.1a	108.9bc	74.0
'Duke 7'	51.1	657.1a	0.2	602.1b	176.4ab	124.4
'D9'	51.6	551.2b	4.6	388.4c	227.9a	79.7
Mean of *F*	43.0[n.s.]	554.1[***]	1.9[‡]	536.8[***]	137.2[**]	95.4[n.s.]
Mean fruit fresh weight (g fruit^{-1})						
'Thomas'	205	208	305	219a	260	198
'Topa Topa'	227	205	260	188b	244	194
'Duke 7'	224	209	315	224a	245	216
'D9'	226	211	299	231a	229	212
Mean of *F*	220[n.s.]	208[n.s.]	300[n.s.]	215[***]	245[n.s.]	208[n.s.]

[a] Means within a column with no letter(s) in common are significantly different based on Fisher's Protected Least Significant Difference test at $P = 0.05$.
[b] n.s., non-significant.
[*] Significant at $P \leq 0.05$
[**] Significant at $P \leq 0.01$
[***] Significant at $P \leq 0.001$
[‡] Data not suitable for ANOVA.

In general, flowering was earlier and longer before a heavy crop and later and shorter before a light crop (Table 3). Other studies have shown that heavy crops delay and shorten flowering (Hodgson and Cameron, 1935a). However, this may not be the case in all climates and cultivars (Davenport, 1986). Temperature can also influence flower initiation and synchrony (Sedgley and Annells, 1981).

The timing of flowering from March to April in 'Hass' was similar to that reported in California (Bergh, 1967; Hodgson and Cameron, 1937; Schroeder, 1951), Florida (Davenport, 1982), and Israel (Blumenfield and Gazit, 1974). The duration of flowering at our site ranged from 5 to 12 weeks. This is much longer than reported for 'Hass' trees in Australia (Alexander, 1975) and Israel (Levin, 1981), but is similar to the range reported in Florida (Davenport, 1982) and in California (Winslow and Enderud, 1955). Yield may be related to conditions during flowering (Hodgson and Cameron, 1935b) more than the length of flowering (Cameron et al., 1952). Yield was correlated with the timing of flowering (Table 3) in this study, but not with temperature, suggesting that temperatures were moderate for avocado production.

The maximum rate of fruit growth occurs in the first four to six months, as shown by Marsh (1935), Schroeder (1953), and Undurraga et al. (1987), and our data confirm this (Fig. 1). Fruit were smaller in years with heavy crops (Table 2), but not because the period of rapid fruit growth was shorter, as previously reported for 'Fuerte' (Marsh, 1935).

In 1995 it was warmer than normal in May when fruit were setting and cooler than normal in June when fruit were abscising. These conditions may have caused the heavy fruit drop. Fruit set of 'Hass' was described by Davenport (1986) as "Type I," which has an initially heavy fruit set, followed by a significant abscission. In our study, most fruit abscised within the first month (Fig. 1), as shown previously (Papademetriou, 1976). Abscission did not increase with

Table 3
The timing and duration of flowering of 'Hass' avocado trees at Irvine, California. Data are the means of 40 trees pooled across four rootstocks.

Year	Date of first anthesis[a]	Date of last anthesis[b]	Duration[c] (days)
1992	19 Feb	13 May	84
1993	4 Apr	12 May	38
1994	9 Mar	18 May	70
1995	20 Mar	19 May	60
1996	26 Mar	5 May	40

[a] Date on which approximately 1% of the flowers were open.
[b] Date on which all of the flower petals were abscised.
[c] Number of days between the beginning and end of flowering.

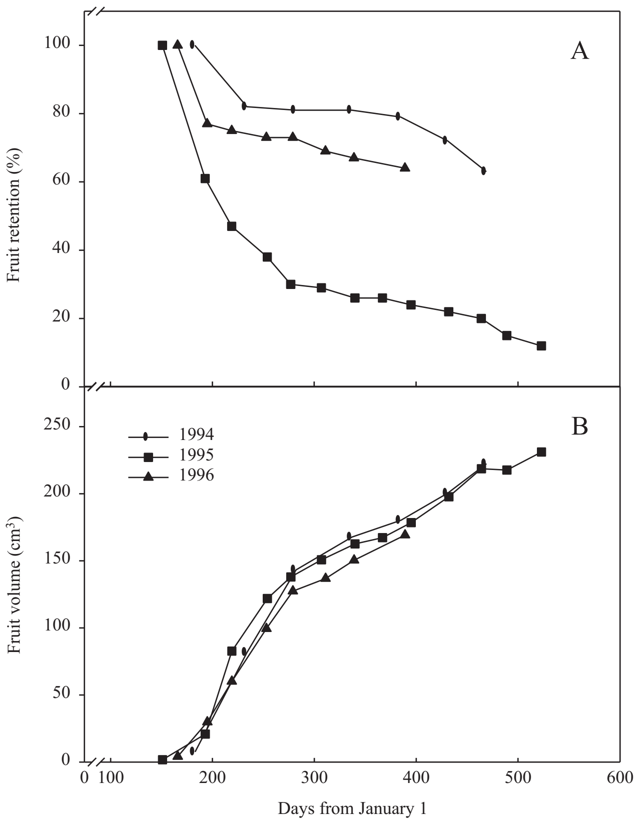

Fig. 1. Seasonal changes in fruit retention (A; % of individual fruit originally tagged) and fruit volume (B) of 'Hass' trees on 'Duke 7' clonal rootstocks at Irvine, California, in 1994 (•), 1995 (■), and 1996 (♦). Data are the means of an average of 55 individual fruit on each of 10 trees.

the growth of summer shoots, in contrast to the observations of Wolstenholme et al. (1990). Fruit that abscised early were smaller ($P < 0.05$) than fruit that eventually grew to maturity (data not shown). Defective ovule development occurs in avocado, but it does not appear to be related to fruit abscission (Tomer et al., 1976; Sedgley, 1980). Other factors including pollinizers (Degani et al., 1997) and temperature conditions (Sedgley and Annells, 1981) may be more important in affecting fruit abscission.

The effect of temperature on avocado yields is unclear. Zamet (1990) determined that yield decreased as chilling units (10 °C base temperature) increased in a given year. However, Lomas (1988) found a poor correlation between yield and minimum temperature, and the correlation between yield and maximum temperature was only significant for years with temperatures above 33 °C. Temperatures can influence phenology in avocado (Sedgley et al., 1985), but temperatures rarely fall below 10 °C during flowering in Irvine. The timing and length of flowering may vary widely within individual groves, and within individual trees (Schroeder, 1951). Therefore, the lack of correlation between yield and temperatures during flowering is not surprising.

'Hass' avocado trees growing in California exhibited a typical alternate bearing pattern until the final year of the study. Trees with heavy yields had more but smaller fruit and longer flowering periods than trees with low yields. Overall, rootstock did not affect the alternate bearing habit, suggesting that phenological events monitored on trees of a particular rootstock can be extrapolated to other rootstocks. The relationship of yield and alternate bearing with vegetative growth is addressed in the second part of this report.

Acknowledgements

The authors thank Eric Focht, Michelle Gottlieb (deceased), William Manor, Stacey Ontai, Christine Reints, David Stottlemyer, and Angela Wang for assistance in the data collection, and Carol Adams (deceased) for data analysis. The research reported was funded in part by a grant-in-aid from the California Avocado Commission.

References

Alexander, D.McE., 1975. Flowering times of avocados in the Murray Valley. J. Aust. Inst. Agric. Sci. 41, 264–267.
Anonymous, 2000. Calif. Avocado Comm. Annu. Rpt. 1999–2000. 8 pp.
Bergh, B.O., 1967. Reasons for low yields of avocado. Calif. Avocado Soc. Yrbk. 51, 161–172.
Bergh, B.O., 1986. *Persea americana*. In: Halevy, A.H. (Ed.), Handbook of Flowering, vol. 5. CRC Press, Boca Raton, FL, pp. 253–268.
Blumenfield, A., Gazit, S., 1974. Development of seeded and seedless avocado fruits. J. Amer. Soc. Hortic. Sci. 99, 442–448.
Cameron, S.H., Mueller, R.T., Wallace, A., 1952. Nutrient composition and seasonal losses of avocado trees. Calif. Avocado Soc. Yrbk. 37, 201–209.
Cossio-Vargas, L.E., Salazar-Garcia, S., Gonzalez-Durán, I.J.L., Medina-Torres, R., 2007. Some reproductive aspects of 'Hass' avocado under semiwarm climate. In: Proc. VI World Avocado Congr. (Actas VI Congreso Mundial del Aguacate)p̂PC Viña Del Mar, Chile, 12–16 Nov,.
Davenport, T.L., 1982. Avocado growth and development 1982. Proc. Fl. State Hortic. Soc. 95, 92–96.
Davenport, T.L., 1986. Avocado flowering. Hortic. Rev. 8, 257–289.
Degani, C., El-Batsri, R., Gazit, S., 1997. Outcrossing rate, yield, and selective fruit abscission in 'Ettinger' and 'Ardith' avocado plots. J. Amer. Soc. Hortic. Sci. 122, 813–817.
Garner, L.C., Lovatt, C.J., 2008. The relationship between flower and fruit abcission and alternate bearing of 'Hass' avocado. J. Amer. Soc. Hortic. Sci. 133, 3–10.
Goodall, G.E., Embleton, T.W., Platt, R.G., 1981. Avocado Fertilization. Univ. Calif. Div. Agric. Sci., Oakland, CA (Leaflet 2024).
Hodgson, R.W., 1947. The California Avocado Industry. Univ. Calif. Agric. Ext. Ser. Circ, 43 pp.
Hodgson, R.W., Cameron, S.H., 1935a. Studies on the bearing behavior of the Fuerte avocado variety. Calif. Avocado Soc. Yrbk. 19, 156–165.
Hodgson, R.W., Cameron, S.H., 1935b. Temperature in relation to the alternate bearing behavior of the Fuerte avocado variety. Proc. Amer. Soc. Hortic. Sci. 33, 55–60.
Hodgson, R.W., Cameron, S.H., 1937. Girdling to induce bearing in the Fuerte avocado variety. Calif. Avocado Soc. Yrbk. 21, 149–153.
Ish-Am, G., Eisikowitch, D., 1991. New insight into avocado flowering in relation to its pollination. Calif. Avocado Soc. Yrbk. 75, 125–137.
Ish-Am, G., Eisikowitch, D., 1993. The behaviour of honey bees (*Apis mellifera*) visiting avocado (*Persea americana*) flowers and their contribution to its pollination. J. Apicult. Res. 32, 175–186.
Lee, S.K., Young, R.E., Schiffman, P.M., Coggins Jr., C.W., 1983. Maturity studies of avocado fruit based on picking dates and dry weight. J. Amer. Soc. Hortic. Sci. 108, 390–394.
Levin, A., 1981. Factors affecting inflorescence and vegetative development regulation in avocado (*Persea americana* Mill.). M.S. Thesis. Hebrew University of Jerusalem, Rehovot, Israel.
Lomas, J., 1988. An agrometeorological model for assessing the effect of heat stress during flowering and early fruit set on avocado yields. J. Amer. Soc. Hortic. Sci. 113, 172–176.
Marsh, R.H., 1935. Rate of growth of Fuerte fruit. Calif. Avocado Soc. Yrbk. 20, 89–91.
Mickelbart, M.V., Bender, G.S., Witney, G.W., Adams, C., Arpaia, M.L., 2007. Effects of clonal rootstocks on 'Hass' avocado yield components, alternate bearing, and nutrition. J. Hortic. Sci. Biotechnol. 82 (3), 460–466.
Papademetriou, M.K., 1976. Percentage fruit set in avocados (*Persea americana* Mill). Calif. Avocado Soc. Yrbk. 59, 135–142.
Schroeder, C.A., 1951. Flower bud development in the avocado. Calif. Avocado Soc. Yrbk. 36, 159–163.
Schroeder, C.A., 1953. Growth and development of the Fuerte avocado fruit. Proc. Amer. Soc. Hortic. Sci. 61, 103–109.
Sedgley, M., 1980. Anatomical investigation of abscissed avocado flowers and fruitlets. Ann. Bot. 46, 771–777.
Sedgley, M., Annells, C.M., 1981. Flowering and fruit-set response to temperature in the avocado cultivar 'Hass'. Sci. Hortic. 14, 27–33.
Sedgley, M., Grant, W.J.R., 1983. Effect of low temperatures during flowering on floral cycle and pollen tube growth in nine avocado cultivars. Sci. Hortic. 18, 207–213.
Sedgley, Scholefield, M., Alexander, P.B., D.Mc.E., 1985. Inhibition of flowering of Mexican- and Guatemalan-type avocados under tropical conditions. Sci. Hortic. 25, 21–30.
Snyder, R., Henderson, D.W., Pruitt, W.O., Dong, A., 1985. California irrigation management information system: final report. Department of Land, Air, and Water Resources, Univ. of Calif., Davis, Calif. Land, Air, and Water Resources Papers 10013 A, B, C.

Tomer, E., Gottreich, M., Gazit, S., 1976. Defective ovules in avocado cultivars. J. Amer. Soc. Hortic. Sci. 101, 620–623.

Undurraga, P., Olaeta, J., Gardiazabal, F., 1987. Seasonal changes on chemical and physical parameters in six avocado (*Persea americana* Mill.) cultivars grown in Chile. S. Afr. Avocado Growers' Assn. Yrbk. 10, 138–140.

Whiley, A.W., Schaffer, B., 1994. Avocado. In: Schaffer, B., Andersen, P. (Eds.), CRC Handbook of Environmental Physiology of Fruit Crops. Subtropical and Tropical Crops, vol. 2. CRC Press, Inc., Boca Raton, FL, pp. 1–35.

Winslow, M., Enderud, J., 1955. Flowering behavior and yields of some avocado varieties at Riverside. Calif. Avocado Soc. Yrbk. 39, 133–135.

Wolstenholme, B.N., Whiley, A.W., Saranah, J.B., 1990. Manipulating vegetative:reproductive growth in avocado (*Persea americana* Mill with paclobutrazol foliar sprays. Sci. Hortic. 41, 315–327.

Zamet, D.N., 1990. The effect of minimum temperature on avocado yields. Calif. Avocado Soc. Yrbk. 74, 247–256.