Yield characteristics of 'Hass' avocado trees under California growing conditions

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Production charcteristics of 'Hass' avocado trees in California were determined using yield data from ~3,000 trees in commercial coastal and inland valley orchards (33° 18' N, 116° 58' W to 35°16' N, 120° 39' W) from 1992 to 2012. Over the 20 years, the majority of the trees produced at least 28 kg/tree (industry median), with 30% producing > 45 kg/tree and 16% producing > 90 kg/tree. As total yield increased to 190 kg/tree, yield of commercially valuable size fruit (178-325 g/fruit) increased to ~150 kg/tree; yield of small fruit (99-177 g/fruit) also increased, but remained a low percentage of the total. As yield increased above 190 kg/tree, yield of commercially valuable size fruit continued to increase. Less than 20% of the trees produced < 10 kg/tree; back-to-back yields < 10 kg/tree occurred in only 2% of the trees. Adverse climatic events causing the low yields initiated alternate bearing. For 66% of the trees, the alternate bearing index (ABI), a measure of the severity of alternate bearing, was 0.5 to 1 (50%-100% differences in yield between on- and off-crop years); 47% of these trees had an ABI between 0.75 and 1.0. To increase the yield of commercially valuable size fruit and net income, California 'Hass' avocado growers need to increase total yield per tree annually, which requires mitigating alternate bearing to reduce the occurrence of off-crops.

Keywords: Alternate bearing index, Yield of commercially valubale large fruit (178-325 g/fruit), Yield of small fruit (99-177 g/fruit), Fruit quality, Climate, Soil type.

INTRODUCTION

Yield characteristics were determined for 'Hass' avocado trees (Persea americana Mill.) under California growing conditions using a data set that included total yield, fruit size distribution (pack out) and fruit quality for 'Hass' avocado trees from more than 15 commercially producing orchards representing the coastal and inland valley avocado growing-areas of California for the period from 1992 to 2012 (~3,000 harvested trees). Climate data (maximum and minimum temperatures, relative humidity, precipitation and wind speed) and information on soil type and depth were included in the data set. The objective was to identify relationships among yield parameters, including fruit size and quality and alternate bearing, that were independent of rootstock and cultural practice and prevailed across the climate conditions and soil types of California's avocado-growing areas or conversely to identify those climatic conditions and/or soil types that promoted or limited productivity in specific microclimates or edaphic zones. The data are specific enough and sufficiently expansive that they can be used to successfully identify rootstocks that promote or limit yield, orchards with excellent or poor cutural management and physiological limitations within the 'Hass' avocado tree related to total yield and fruit size or the tree's capacity to sustain high yields in consecutive years. The results of the first phase of our analysis are reported here. The overall goal of the research is to identify key determinants of 'Hass' avocado yield, fruit size and fruit quality that can be used to develop strategeies to increase grower revenue per unit land and thereby offset ever-increasing production costs in order to sustain the avocado industry. To our knowledge, this is the first large-scale, in-depth analysis of this type of the California avocado industry.

MATERIALS AND METHODS

'Hass' avocado trees on different but known clonal and seedling rootstocks in commercially producing orchards were used in this research. The trees were located in more than 15 orchards in Irvine, Pauma Valley, Temecula, Somis, Fillmore, Santa Paula, Carpinteria, Santa Barbara and San Luis Obispo (Table 1). All trees were in good health with no visible signs of nutrient deficiencies or pest problems. The orchards were managed according to each grower's standard cultural practices.

Table 1. Location, altitude and average annual climate parameters for the 'Hass' avocado-growing areas of California represented by orchards used in this research

Orchard	Latitude	Longitude	Altitude (m)	Average annual[z]				
				Max temp. (°C)	Min temp. (°C)	Precip. (mm)	Rel. Humid. (%)	Wind Speed (kph)
Pauma Valley	33º20' N	117º01' W	200	25.0	8.1	223.5	68.7	6.4
Irvine	33º40' N	117º49' W	23	23.0	11.2	342.9	66.7	6.1
Temecula	33º29' N	117º08' W	307	24.4	11.2	442.0	63.5	6.3
Somis	34º15' N	118º59' W	93	22.1	9.4	315.0	70.8	5.3
Fillmore	34º23' N	118º55' W	142	22.6	9.5	220.1	67.5	7.1
Santa Paula	34º21' N	119º03' W	85	23.4	9.2	228.6	65.9	6.6
Carpinteria	34º23' N	119º31' W	8	20.9	10.4	467.4	72.2	4.8
Santa Barbara	34º25' N	119º41' W	12	19.4	7.5	335.3	74.0	7.4
San Luis Obispo	35º16' N	120º16' W	71	22.5	7.6	301.4	72.8	9.8

z California Irrigation Management Information System.

Yield for each site included data for 2 years up to 10 years, enabling us to determine the degree to which climate and/or soil type influenced total yield and yield of commercially valuable size fruit and fruit quality. Fruit were harvested between March and October at ³ 20.8% dry mass content, the legal maturity standard for 'Hass' avocado fruit in California. At harvest, total yield was determined as kilograms per tree. A randomly selected sample of 100 to 150 fruit per tree, representing ~10% to 100% of the mean total number of fruit per tree for each year, was collected from each data tree and the mass of each fruit in the subsample was determined. These data were used to calculate fruit size distribution (pack out), i.e., the kilograms of fruit of each packing carton size per tree and to estimate the total number fruit and number of fruit in each packing carton size category per tree. The following packing carton fruit size categories (grams per fruit) were used: size 84 (99 to 134 g), size 70 (135 to 177 g), size 60 (178 to 212 g), size 48 (213 to 269 g), size 40 (270 to 325 g), size 36 (326 to 354 g), and size 32 (355 to 397 g). An additonal two fruit were selected randomly per tree and allowed to ripen at 18 to 21 °C to "eating soft". When ripe, external and internal fruit quality were evaluated for decay and discoloration. Vascularization (presence of vascular bundles and associated fibers) of the mesocarp was also determined. Fruit quality parameters were rated on a scale from 0 (normal) to 4 (high incidence of decay, discoloration, or vascularization).

To determine the severity of alternate bearing for orchards in California, the alternate bearing index (ABI) was calculated for each data tree for each pair of consecutive harvests using the following equation: ABI = (the absolute value of year 1 yield minus year 2 yield)/(sum of year 1 yield and year 2 yield); yield was defined as total kilograms of fruit per tree (Pearce and Dobersek-Urbanc, 1967). The range for ABI is from 0 (no alternate bearing) to 1 (complete alternate bearing).

Statistical analyses were performed using the General Linear Models procedure of SAS (version 9.2; SAS Institute, Cary, NC). Analysis of variance was used to test for the effects of individual factors on yield parameters. Pearson correlation coefficients were calculated to determine the strength of these relationships; strong relationships were further analyzed using least-square linear regression analysis. In this context, a stepwise strategy was employed and only significant data (P £ 0.05) were used in the next step of the analysis. Means were separated using Fisher's Protected LSD Test at P = 0.05.

RESULTS

Yield characteristics. The mean yield for all trees in the data set was 51 kg/tree (13,862 kg ha-1 at a typical California planting density). However, the median yield was only 28 kg/tree (7,610 kg ha-1). Thus, half of the trees yielded less than 28 kg/tree and half of the trees yielded more than 28 kg/tree. Based on frequency of individual tree yields, 50% of the trees in the data set yielded from 10 to 70 kg/tree (2,718 kg ha-1 to 19,026 kg ha-1). In figure 1, the greater frequency of trees yielding less than 10 kg/tree relative to trees yielding more than 70 kg/tree is clearly seen. Note that trees yielding greater than 160 kg per tree were considered outliers since they represented less than 2.5% of the trees in the data set. Yields (kg/tree) of both commercially valuable large fruit (packing carton sizes 60+48+40; 178-325 g/fruit) and small fruit (packing carton sizes 84+70; 99-177 g/fruit) increased as total yield increased (Figure 1). Large fruit (178-325 g/fruit) were consistently a greater proportion of the total yield up to 190 kg/tree. On average up to 190 kg/tree, 73% of the total yield were commercially valuable large fruit (178-325 g/fruit), larger fruit (326-397 g/fruit) were only 2% of the crop, and smaller fruit (99-177 g/fruit) made up approximately 25% of the total yield.

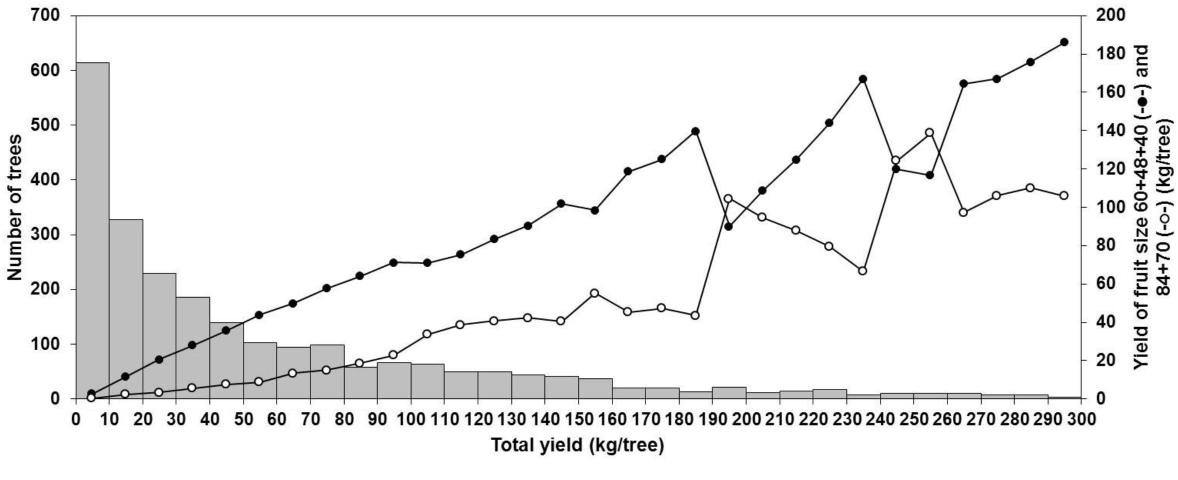

Figure 1. The gray bars are the number of trees in the data set having total yields of 0-9.99 kg/tree, 10-19.99 kg/tree, 20-29.99 kg/tree, etc. Black circles indicate the average kilograms of commercially valuable large fruit (packing carton sizes 60+48+40; 178-325 g/fruit) per tree and white circles indicate the average kilograms of small fruit (packing carton size 84+70; 99-177 g/fruit) per tree for trees in each total yield category, respectively.

For 'Hass' avocado trees in California, as total kilograms of fruit per tree increased, the yield of fruit in all size categories (kg/tree) increased, including commercially valuable large fruit of packing carton sizes 60+48+40 (r = 0.89, P = < 0.0001).

An unbiased mean yield was determined to correct for prejudice caused by having significantly more trees at one site than other sites. The unbiased mean yield was 43 kg/tree (11,687 kg ha-1) with an unbiased yield of 31 kg/tree of commercially valuable large fruit (73% of the total yield).

When yield was based on the number of fruit per tree, yields of both commercially valuable large fruit (178-325 g/fruit) and small fruit (99-

177 g/fruit) also increased as total yield increased (Figure 2). The number of commercially valuable large fruit remained a greater proportion of the total yield up to approximately 800 fruit per tree. For trees with yields greater than 800 fruit per tree, as total yield increased the number of small fruit increased more dramatically, than the number of large fruit, becoming equal to or greater than the number of commercially valuable large fruit per tree (Figure 2). However, in general, the yield of commercially valuable large fruit did not decrease. Thus, even with a dramatic increase in total yield (kg/tree or number of fruit per tree) above the current production levels, California 'Hass' avocado growers are unlikely to experience a concomitant decline in the yield of commercially valuable large fruit (packing carton sizes 60+48+40; 178-325 g/fruit).

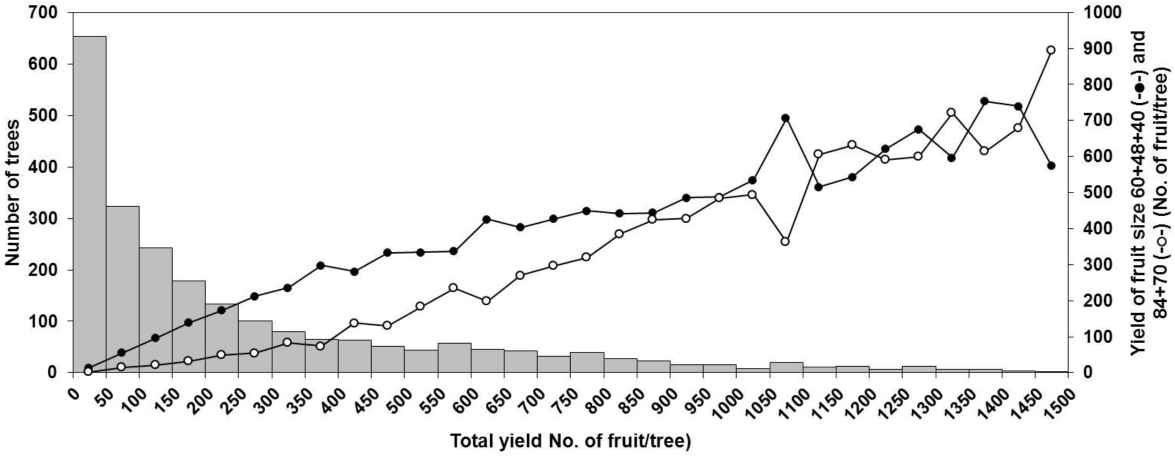

Figure 2. The gray bars are the number of trees in the data set having total yields of 0-49 fruit/tree, 50-99.99 fruit/tree, 150-199.99 fruit/tree, etc. Black circles indicate the average number of commercially valuable large fruit (packing carton sizes 60+48+40; 178-325 g/fruit) per tree and white circles indicate the average number of small fruit (packing carton size 84+70, 99-177 g/fruit) per tree for trees in each total yield category, respectively.

Alternate bearing. It should be noted that the majority of low yielding trees (< 10 kg/tree) produced low yields in response to adverse climatic conditions, including multiple years with freezing temperatures and one year of excessively high temperatures during fruit set. The low yields were not the result of poor cultural management practices or disease, nematode or insect pest damage as only 2% of the trees produced back-to-back yields of less than 10 kg/tree. The adverse climate events resulting in low yields (off crops) initiated alternate bearing.

Alternate bearing was a characteristic of the majority of the orchards in the data set. Only 17% of the trees in the data set had an ABI less than or equal to 0.25, 17% had an ABI greater than 0.25 up to 0.50, 19% had an ABI greater than 0.50 to 0.75 and 47% of the trees had an ABI greater than 0.75 up to 1.0 (an ABI of 1.0 means complete alternate bearing - crop one year, no crop the other year). Thus, over the period from 1992-2012, 66% of the 'Hass' avocado trees in the data set were severely alternate bearing with 50% to 100% differences in yield from one year to the next. The severity of alternate bearing was independent of orchard location and no avocado-producing area was more or less prone to alternate bearing. The incidence and severity of alternate bearing for trees having an ABI from 0 to 0.75 was independent of crop load (Table 2), but trees having an ABI greater than 0.75 but less than 1.0 produced both heavier on crops and greater yields in the off-crop years and thus had significantly greater 2-year cumulative yields, than trees with an ABI from 0 to 0.75 (P < 0.0001). These greater yielding trees did not suffer a reduction in 2-year cumulative yield of commercially valuable large fruit (packing carton sizes 60+48+40), but produced significantly more small fruit (84+70) than trees in all other ABI categories (P < 0.0001) (Table 2).

Table 2. Chacteristics of the 2-year cumulative yields associated with ranges in alternate bearing index

Alternate bearing index		2-year cumulative yield			
		Median yield	Average yield	Yield range for 50% of trees	
		------------------------------ kg/tree	------------------------------		
0.00 - 0.25	Total	57.4	77.2	31.9	94.4
	60+48+40[z]	44.5	60.8	25.5	71.5
	84+70	7.9	13.7	4.1	14.4
> 0.25 - 0.50	Total	62.2	78.6	41.6	100.3
	60+48+40	48.7	59.9	30.4	78.0
	84+70	10.0	16.2	4.9	17.1
> 0.50 - 0.75	Total	56.9	71.3	33.6	100.0
	60+48+40	42.9	51.3[y]	24.8	70.9
	84+70	9.1	18.9	4.0	21.1
> 0.75 - 1.00	Total	84.7	94.3[x]	43.0	126.2
	60+48+40	52.9	59.2	26.4	83.4
	84+70	15.1	34.1[w]	5.5	44.9

z Packing carton sizes 60+48+40 (178-325 g/fruit) and 84+70 (99-177 g/fruit).
y 2-year cumulative yield of commercially valaauble large fruit 60+48+40 was significantly less than that of trees in all other ABI categories ($P < 0.0001$).
x 2-year cumulative total yield was significantly greater than that of trees in all other ABI categories ($P < 0.0001$).
w 2-year cumulative yield of small fruit (84+70) was significantly greater than that of trees in all other ABI categories ($P < 0.0866$).

For trees with year 1 off crops from 0 to 69.99 kg/tree, the year 2 return yield was approximately 75 kg/tree (Figure 3). Surprisingly, for trees with year 1 off crops from 70 to 199 kg/tree, the year 2 return yields increased from 125 to 225 kg/tree for each increase in respective yield category. Thus, the relative (%) increase in total yield from year 1 (off-crop year) to year 2 (on-crop year) decreased as the categories for total yield increased (Figure 3).

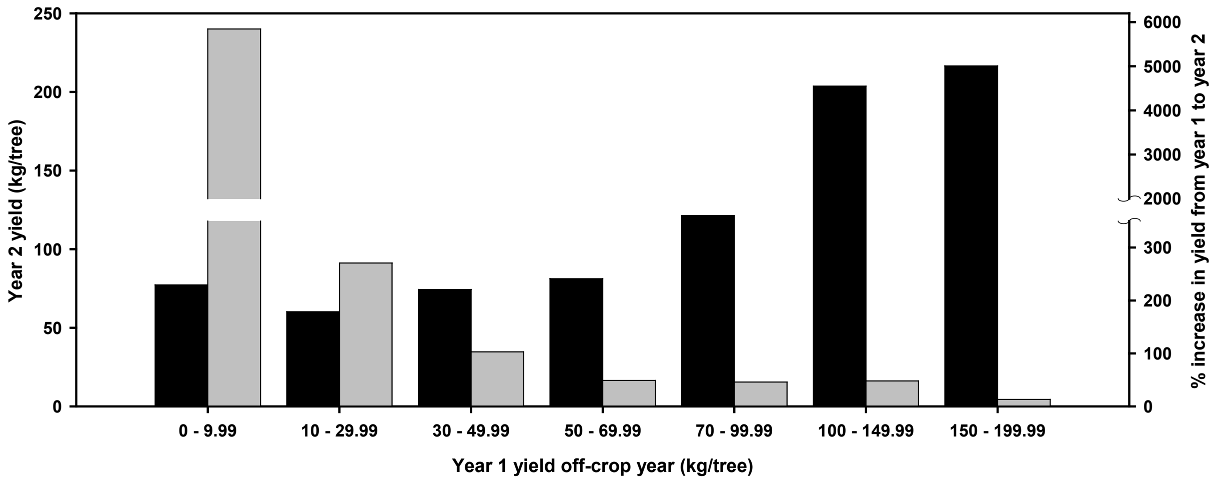

Figure 3. The black bars represent the year 2 total yield (kg/tree) for year 1 off-crop trees having total yields of 0-9.99 kg/tree, 10-29.99 kg/tree, 30-49.99 kg/tree, etc. The gray bars indicated the percent increase in yield from year 1 (off-crop year) to year 2 (on-crop year).

Trees having year 1 on-crop yields in the categories from 0-9.99 up to 70-99.99 kg/tree produced 70% less fruit the following year (Figure 4). When the year 1 on-crop yields exceeded 150 kg/tree, the year 2 off-crop yields were 85% to 95% less than the year 1 yields, but strikingly these higher-yielding trees produced more fruit in year 2 than the lower-yielding trees. It is clear in Figures 3 and 4 that trees in the greater yield categories in either the on- or off-crop year produced greater yields the following year than trees in the lower yield categories and thus, produced greater 2-year cumulative yields than their poorer-yielding counterparts. These trees also had greater ABIs than the poor-yieldig trees, consistent with the results reported in Table 2. However, it is important to note that following an on crop, all trees regardless of yield category produced less than 35 kg/tree.

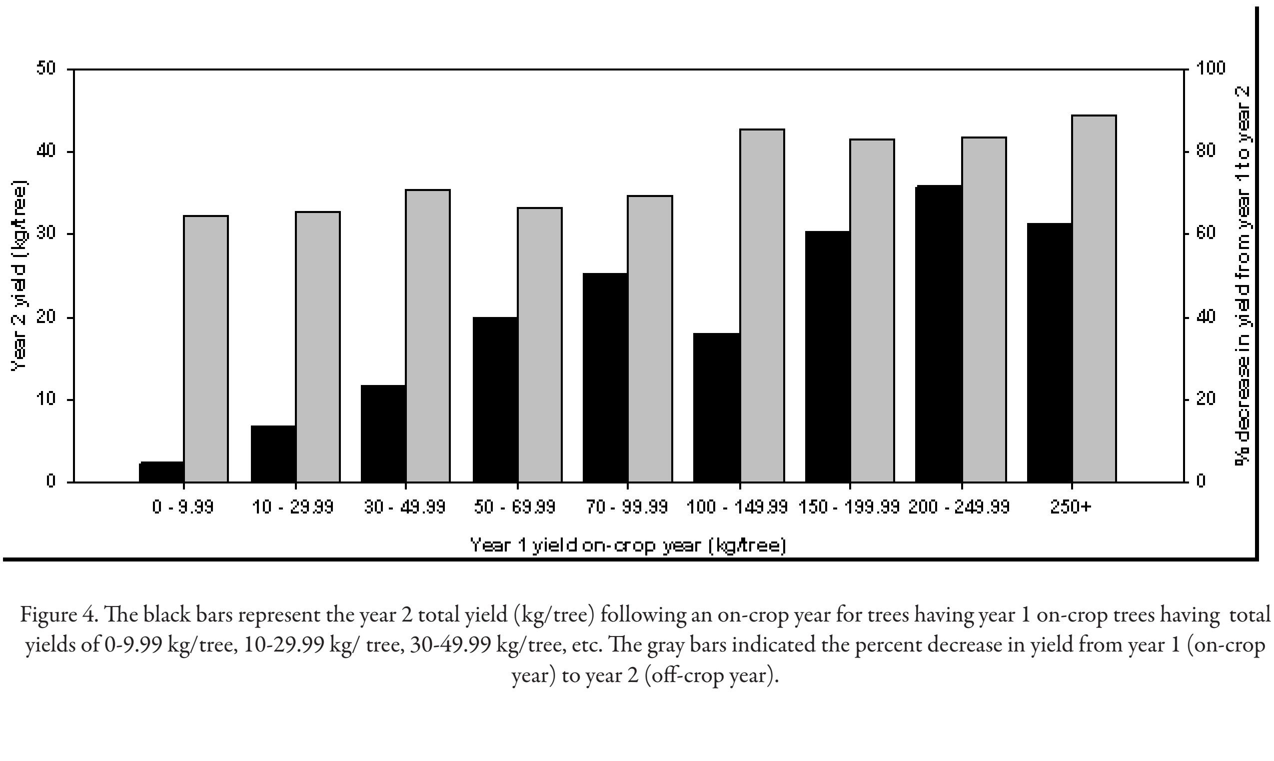

Figure 4. The black bars represent the year 2 total yield (kg/tree) following an on-crop year for trees having year 1 on-crop trees having total yields of 0-9.99 kg/tree, 10-29.99 kg/ tree, 30-49.99 kg/tree, etc. The gray bars indicated the percent decrease in yield from year 1 (on-crop year) to year 2 (off-crop year).

Fruit quality. Stem end rot, discoloration of the mesocarp (edible portion of the fruit), vascularization of the mesocarp, and seed germination within the fruit were each rated 0 (absent) to 4 (high incidence of the problem) for two fruit per tree collected at harvest for each tree in our data set (~6,000 fruit). The fruit were ripened at 18 to 21 °C to "eating soft" and then evalauted. Statistical analysis of the fruit quality data provided strong evidence that the quality of 'Hass' avocado fruit produced in California is excellent. The majority of trees in the majority of orchards across the majority of years produced fruit that were rated 0 or 1 for these disorders. For stem end rot, 83% of all fruit were rated 0, 14% as 1, with less than 1% rated a 3 or 4. For mesocarp discoloration, 80% of all fruit were rated 0, with another 15% rated 1; only 1.9% were rated a 3 and 0.3% were rated a 4. For vascularization of the mesocarp, 86% of all fruit were rated 0 or 1; only 1.4 % of all trees produced fruit that were rated a 3 and only 0.2% of the trees produced fruit that were rated a 4. For seed germination, 72% of all fruit were rated 0, with 11% rated 1, 6% rated 2, 9% rated 3 and 2% rated 4. Whereas the incidence of seed germination within the fruit was very low, this disorder was the more prevalent, but no factors were identified that influenced its occurrence. Across all orchards and years, vascularization of the mesocarp was weakly ($r < 0.50$) but significantly related to progressively later harvest dates ($P < 0.0001$) and weakly, negatively related to leaf calcium concentrations ($P < 0.0001$). The number of days after harvest required for fruit to ripen to "eating soft" was weakly, positively related with total yield (kg/tree) ($P = 0.0179$) and weakly, negatively correlated with harvest date ($P = 0.00353$).

Effect of climate on yield. Temperature extremes were a factor that impacted yield. Freezes in 1990-91, 1998-99 (only parts of the California avocado industry), and 2006-07 (only 5% crop loss in Ventura, but 50-75% crop loss in San Diego, Santa Paula, Carpinteria, Santa Barabara and San Luis Obispo) impacted the yields of trees in the data set. Excessively, high temperatures for several days during fruit set in 2008-09 had a devastating effect on yield from San Diego to Santa Paula, impacting the yields of trees in the data set. Extreme climatic events in any given year became the main factor controlling yield and fruit size. In the absence of extreme climatic events, annual maximum and minimum temperatures, either on a monthly basis or during key phenological stages (bloom, fruit set, exponential fruit growth, winter imposed quiescence, exponential growth of mature fruit, and preharvest fruit drop) were not significantly related to total yield or fruit size. There was a significant positive relationship between March precipitation over the range from 0.2 to 151 mm of rain and total yield (kg/tree) ($r = 0.54$, $P < 0.0001$). March (Northern Hemisphere) corresponds to two key phenological events: (i) floral development has reached the cauliflower stage of the inflorescence when the final stages of pollen and gynoecium development occur; and (ii) mature fruit are entering the second period of exponential growth (fruit are harvested 12-18 months after bloom in California). These results indicate the importance of adequate irrigation, or precipitation in rainfed orchards, at this stage of 'Hass' avocado tree phenology.

Effect of soil factors on yield. Statistical analysis of the relationships among yield parameters (maximum total yield or yield of commercially valuable large or small fruit and fruit quality) and soil composition identified a positive relationship between the maximum total yield attained in an orchard and the percent sand in the orchard soil ($r = 0.52$; $P = 0.0001$), with a concomitant negative relationship between total yield and percent clay in the soil ($r = -0.51$; $P = 0.0001$); the relatioship between total yield and percent silt in the soil was weak but also negative and significant ($P = 0.0001$). The sand, clay and silt content of an orchard soil would have a critical effect on drainage and aeration and soil microflora and therefore on root health and tree productivity. Soil composition can become a factor that overrides the optimal nutrient status of trees in an orchard if not managed properly (Crowley, 2007). These results emphasize the importance of soil type as one of the criteria for selecting a site for a new orchard. Soil depth was greater than 200 cm in 60% of the orchards and was not related to yield. Orchards having soils with a greater percent sand or a greater soil depth were not clustered in one particular avocado-growing area.

DISCUSSION

Despite problems of low yield, small fruit size and alternate bearing, the 'Hass' avocado dominates the global avocado industry (Garner et al., 2011). The average (unbiased) yield in California avocado orchards included in this research was at a production level acceptable to the industry, 43 kg/tree (11,687 kg ha-1), with 73% of the yield commercially valuable large fruit (packing carton sizies 60+48+40; 178-325 g/fruit). The problem is that 50 % of the trees in the data set produced at a level well below the average at less than 28 kg/tree, the median yield (< 7,610 kg ha-1). Further, the yield of commercially valuable large size fruit remained at 73% of these lower total yields, reducing grower income. Although the frequency was low, there were trees within 'Hass' avocado orchards included in the research that produced very high yields and trees with the capacity to produce back-to-back yields greater than 70 kg/tree (Figure 3), which would translate to yields of greater than 19,026 kg ha-1. The next step is to identify these high-yielding trees and orchards within the data set, as well their low-yielding counterparts (each tree x year x site x treatment has a distinct number), to obtain detailed information, which was collected as part of the original research, on tree age, rootstock, aspects of cultural management, irrigation water quality, climate, soil characteristics and tree nutrient status (leaf nutrient analyses were determined according to the stardard protocol in California [Embleton et al., 1959] for all trees in the data set). This information should prove valuable in identifying key determinates of yield that can be translated into useful strategies for increasing the median yield of 'Hass' avocado orchards in California and possibly elsewhere. The results of the first phase of this research provided evidence that the proportion of sand versus clay in the composition of the orchard soil was a factor influencing total yield, with a high percentage of sand having a positive effect on yield and conversely a high percentage of clay having a negative impact. An orchard soil with a greater proportion of sand to clay would have better drainage and aeration, which would contribute to improved root health with consequent benefits on tree productivity. The results also suggested a benefit from irrigation or precipitation in March (Northern Hemisphere) when floral development is at the cauliflower stage of inflorescence development and mature fruit are beginning the second period of exponential fruit growth in California.

Whereas California 'Hass' avocado trees suffer from low yield, the industry has not experienced the 'Hass' "small fruit" problem (Cutting, 1993). Based on the results of this research, 'Hass' avocado yields can increase dramatically to 190 kg/tree, or 800 fruit, per tree with no negative effect on the yield of the commercially valuable large fruit preferred by the California industry, fruit of packing carton sizes 60+48+40 (178-325 g/fruit). Whereas the yield of small fruit will also increase at the higher yields, the absolute yield of large size fruit does not decrease, only its relative proportion decreases. Further, California's warm, dry Mediterranean climate and industry-wide high standard of cultural management result in fruit of excellent quality.

Alternate bearing was demonstrated to be a major problem for California 'Hass' avocado growers, with 66% of the trees in the data set exhibiting severe alternate bearing during the period from 1992 to 2012; ABI was greater than 0.5 to 1.0 indicating 50% to 100% differences in yield from one year to the next. Moreover, nearly half of all trees in the data set (47%) had an ABI greater than 0.75 to 1.0 over the 20-year period. The effect of alternate bearing on yield was dramatic, following an on crop, trees in all yield categories produced less than 35 kg/tree. Despite the severity of alternate bearing in 'Hass' avocado orchards in California, the results of this research identified a few trees with the capacity to produce consecutive yields greater than 70 kg/tree. A subsequent more detailed investigation of these trees may provide new insights for maintaining high yields annually.

CONCLUSION

To sustain the California 'Hass' avocado industry in an era of increasing production costs (land, water, labor, fertilizer, etc.) and greater competition within the US avocado fresh fruit market, avocado growers must increase their yields of high quality commercially valuable large fruit (178-325 g/fruit) per unit land. Taken together, the results of this research provide strong evidence that the yield of commercially valuable large fruit of excellent quality, and hence grower income, can be increased annually by increasing total yield per tree annually. The results demonstrated that yield of commercially valuable large fruit was positively and significantly correlated with total yield (kg/tree) over a very broad range of yields ($r = 0.88593$, $P = < 0.0001$). However, with the severity of alternate bearing that characterizes 'Hass' avocado orchards in California, increasing total yield annually will require mitigating alternate bearing to reduce the occurrence of off-crop years, which had average yields of less than 35 kg/tree. It is anticipated that further investigation of 'Hass' avocado trees (orchards) having the capacity to produce consecutive yields greater than 70 kg/tree identified in this research will provide important insight into sustaining high yields annually despite alternate bearing. Understanding the yield characteristics of 'Hass' avocado trees under California growing conditions was the first phase in our research to increase yield of commercially valuable large fruit, improve grower annual revenue and sustain the avocado industry of California.

ACKNOWLEDGEMENTS

This research was supported in part by the University of California Citrus Research Center and Agricultural Experiment Station and by grants from the California Avocado Commission, California Department of Food and Agriculture Fertilizer Research and Education Program, and California Avocado Development Organization. The authors thank the growers and ranch managers who particpated in the many research projects that were the source of the 'Hass' avocado harvest data: John Grether, Gus Gunderson, Brycen Ikeda, Sam MacIntyre, Jess Ruiz, Jaimé Serrato, Rick Shade, Chris Taylor and the late Dick Whiley, Warren Currier, and Len Francis.

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