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Effect of foliar-applied plant bioregulators on 'Hass' avocado yield

Efecto de la aplicación foliar de biorreguladores de plantas en la producción de aguacate 'Hass'

Yusheng Zheng, Toan Khuong, and Carol J. Lovatt (Department of Botany and Plant Sciences-072, University of California, Riverside, CA 92521-0124, USA)

Abstracts

Plant bioregulators (PBRs) are powerful tools for maximizing yield, fruit size and quality, and increasing net dollar return to growers. The objective of this research was to screen 6-benzyladenine (BA), gibberellic acid (GA_3), prohexadione-calcium (Pro-Ca), N-2-chloro-4-pyridinyl-N-phenylurea (CPPU), 2,4-dichlorophenoxyacetic acid (2,4-D), 3,5,6-trichloro-2-pyridyloxyacetic acid (3,5,6-TPA), and aminoethoxyvinylglycine (AVG) for their ability to increase fruit set, fruit size and yield without reducing fruit quality. Crop load influenced the effect of PBRs on yield. For most PBRs having a positive effect on yield and/or fruit size, the result was statistically significant only in the ON-crop year. In ON-crop years, GA_3 (25 mg/L) at the cauliflower stage of inflorescence development consistently increased total yield and yield of commercially valuable large fruit (178-325 g/fruit); BA (25 mg/L) consistently increased yield of large fruit (≥ 270 g/fruit) without reducing total yield. GA_3 applied at the end of July followed by Pro-Ca 30 days later increased total yield and yield of commercially valuable fruit under very high and low crop loads.

Resumen

Los biorreguladores de plantas (BRPs) son potentes herramientas para maximizar producción, calidad y tamaño de fruta, e incrementar las ganancias netas de los productores. El objetivo de esta investigación fue probar 6-benciladenina (BA), ácido giberélico (AG_3), prohexadiona de calcio (Pro-Ca), N-2-cloro-4-piridil-N-fenilurea (CPFU), ácido 2,4-diclorofenoxiacético (2,4-D), ácido 3,5,6-tricloro-2-piridiloxiacético (3,5,6 ATP), y aminoetoxivinilglicina (AVG), para su capacidad de incrementar el cuajado, tamaño de fruto y producción sin reducir la calidad de la fruta. La cantidad de cosecha influyó en el efecto de los BRPs en la producción. Para la mayoría de BRPs que tuvieron efectos positivos en producción y/o tamaño de fruta, el resultado fue estadísticamente significativo sólo en árboles de año ON. En dichos árboles, la aplicación de AG_3 (25 mg/L) en inflorescencias en estado de coliflor incrementó consistentemente la producción total y la producción de fruta de buen calibre comercialmente valorable (178-325 g/fruit); BA (25 mg/L) incrementó consistentemente la producción de fruta de buen calibre (≥ 270 g/fruit) sin reducir la producción total. La aplicación de AG_3 a finales de Julio seguida de Pro-Ca 30 días después incrementó la producción total y la producción de fruta de buen calibre comercialmente valorable bajo condiciones de alta y baja cosecha anterior.

Key words. Fruit size, fruit quality, alternate bearing, ON-crop, OFF-crop, tree phenology

Introduction

The ever-increasing costs of inputs (water, fertilizer, labor) to avocado production dictate that avocado growers increase production per hectare to remain profitable. Plant bioregulators (PBRs) are powerful tools for manipulating tree growth, fruit set, fruit size, and fruit quality to increase grower revenue. In many avocado-producing countries, 'Hass' avocado growers are able to solve production problems using PBRs that are not available to California growers due to strict regulatory controls within the United States in general and California in particular. To provide growers with PBR strategies for use in commercial avocado production as quickly as possible, our goal is to have 'Hass' avocado added to the existing label of a PBR that has already been approved for commercial use on other edible crops in California. This approach should reduce or, in the case of PBRs that are generally recognized as safe (GRAS) such as gibberellic acid (GA_3), completely eliminate the need to complete PBR residue analyses of avocado fruit to establish tolerances. The PBRs gibberellic acid (GA_3), 6-benzyladenine (BA), prohexadione-calcium (Pro-Ca), 2,4-dichlorophenoxyacetic acid (2,4-D), N-2-chloro-4-pyridinyl-N-phenylurea (CPPU), aminoethoxyvinylglycine (AVG), and 3,5,6-trichloro-2-pyridyloxyacetic acid (3,5,6-TPA) were screened for their capacity to increase total yield and yield of commercially valuable fruit (178-325 g/fruit, packing carton sizes 60 + 48 + 40) for the California domestic market or to increase the yield of larger fruit (≥ 270 g/fruit, ≥ packing carton size 40) that command a higher market price, without negatively affecting fruit quality. The objectives of the experiments undertaken were to identify the optimal concentration or range of concentrations and the best application time(s) for each PBR and to obtain efficacy data required by the California Department of Pesticide Registration for adding avocado to an existing PBR label (PBRs are considered pesticides in the United States). Results of some of the first PBR strategies tested in California are reported herein.

Materials and Methods

Plant material. The research was conducted with bearing 'Hass' avocado trees in three commercial orchards in Irvine (33° 40' 9" N and 117° 49' 20" W) and one in Carpinteria (34° 23' 56" N and 119° 31' 3" W), California. The trees, which ranged in age from 7 to 12 years old, were maintained using the standard grower practices for each orchard. Trees in all orchards were irrigated properly, had no nutrient deficiencies based on leaf nutrient analyses and exhibited no symptoms of disease for the duration of the research. PBRs were applied to the tree canopy at specific stages of tree phenology in 1869 L of water (containing 0.05% Silwet L77® surfactant) per ha using a 2758 KPa handgun sprayer to give full canopy coverage. In each experiment, there were 25 individual tree replications per treatment, including an untreated control, in a randomized complete block design. At harvest, total yield was determined as kilograms fruit per tree. A randomly selected sub-sample of 100 to 150 fruit per tree, representing approximately 20% to 100% of the fruit per tree depending on whether it was an OFF- or ON-crop year, was collected for each data tree. The weight of each fruit in the sub-sample was determined. These data were used to determine pack out, i.e., kilograms of fruit of each commercial packing carton size per tree, and to estimate the total number of fruit per tree and number of fruit of each packing carton size. The following commercial packing carton fruit sizes (g/fruit) were used: 84 (99-134); 70 (135-177); 60 (178-212); 48 (213-269); 40 (270-325); 36 (326-354); and 32 (355-397). In addition, at harvest, two fruit were selected randomly per tree and allowed to ripen at 22 ± 2 °C. The number of days from harvest to "eating ripe" was recorded. When ripe, fruit internal mesocarp quality was evaluated for discoloration, vascularization (presence of vascular bundles and associated fibers), stem-end decay and seed germination and rated on a scale from 0 (normal) to 4 (high incidence of discoloration, vascularization, stem-end decay and seed germination). In addition, fruit length, fruit width, mesocarp width on each side of the seed in a fruit cut longitudinally, and seed diameter were measured.

Stages of 'Hass' avocado tree phenology targeted for foliar-applied PBRs included the following (months given in parentheses are the approximate calendar dates in California): (*i*) cauliflower stage of inflorescence development (CSID), which is when the final stages of pollen and gynoecium development occur in the 'Hass' avocado flower (~March) (Salazar-García, Lord and Lovatt, 1998); (*ii*) full bloom (FB), the period of peak flower opening, early fruit set, and vegetative shoot growth, including growth of the vegetative shoot apex of indeterminate floral shoots (~April); and (*iii*) when fruit are 17-20 mm in diameter (transverse), which occurs just prior to the period of June fruit drop, exponential fruit growth, initiation of summer vegetative shoot growth and root growth (late June-early July).

Gibberellic acid (GA_3). $\underline{GA_3}$ (25 mg/L; ProGibb® Valent BioSciences Corporation, Libertyville, IL) was applied to the canopy of bearing 'Hass' avocado trees in two different orchards: (*i*) at CSID in Irvine; (*ii*) at FB in Carpinteria; and (*iii*) when fruit were 17-20 mm in diameter in Carpinteria.

Aminoethoxyvinylglycine (AVG), 2,4-dichlorophenoxyacetic acid (2,4-D) and 3,5,6-trichloro-2-pyridyloxyacetic acid (3,5,6-TPA). <u>AVG</u> (250 mg/L; ReTain® Valent BioSciences Corporation, Libertyville, IL) was applied to the canopy of 'Hass' avocado trees: (*i*) at CSID; (*ii*) at FB; (*iii*) when fruit were 17-20 mm in diameter; and (*iv*) at FB and again when fruit were 17-20 mm in diameter. <u>2,4-D</u> (111 g acid equivalents/ha; CitrusFix® AMVAC Chemical Corporation, Commerce, CA) was applied to the canopy when fruit were 17-20 mm in diameter. <u>3,5,6-TPA</u> (15 mg/L; Maxim® Agriphar, S.A., Ougrée, Belgium) was applied when fruit were ~24 mm in diameter, per the manufacturer's instructions to prevent excessive fruit thinning. This research was conducted in a single orchard in Irvine.

Prohexadione-calcium (Pro-Ca), 6-benzyladenine (6-BA), and 1-(2-chloro-4-pyridyl)-3-phenylurea (CPPU). <u>Pro-Ca</u> (125 mg/L; Apogee® BASF, Ludwigshafen, Germany) was applied at FB. $\underline{GA_3}$ (25 mg/L; ProGibb® Valent BioSciences Corporation, Libertyville, IL) was applied when fruit were 17-20 mm in diameter followed by a foliar application of <u>Pro-Ca</u> (125 mg/L) 30 days later. The objective of this combination was to stimulate summer vegetative shoot growth and then stop shoot growth in order to promote the transition of shoot apical buds from vegetative to floral development to increase floral intensity and yield the following year. 6-BA (25 mg/L, MaxCel® Valent BioSciences, Libertyville, IL) was applied at FB. CPPU (forchlorfenuron, KT-30) (15 mg/L; CPPU Kim-C1® Kim-C1, LLC, Fresno, CA) was applied when fruit were 17-20 mm in diameter. This research was conducted in an orchard in Irvine.

Statistical Analyses. The data were analyzed using the General Linear Model procedure of the SAS 9.2 statistical program (SAS Inst., Inc., Cary, N.C.). Analysis of variance was used to test for treatment effects on total yield in kilograms and number of fruit per tree, kilograms and number of fruit in each size category per tree, and fruit quality parameters. For presentation in this paper, PBR effects on fruit quality parameters were averaged across the years of the experiment using repeated measure analysis with year as the repeated measure. Means were separated using Duncan's Multiple range test or Fisher's Protected LSD at *P* = 0.05.

Results

Gibberellic acid (GA$_3$). In the ON-crop year, but not in the OFF-crop year, GA$_3$ applied at the cauliflower stage of inflorescence development significantly increased total yield and yield of commercially valuable fruit (178-325 g/fruit) as both kilograms and number of fruit per tree (Table 1). The increase in yield in the ON-crop year resulted in significant increases in 2-year cumulative total yield and yield of valuable size fruit as kilograms and number of fruit per tree (Table 1).

Table 1. Effect of GA$_3$ (25 mg/L) applied at the cauliflower stage of inflorescence development (CSID) (~March) on yield and fruit size as kilograms and number of fruit per tree in an alternate bearing 'Hass' avocado orchard in Irvine, CA.

	OFF-crop year		ON-crop year		2-year cumulative	
GA$_3$ Treatment	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)
			kg fruit/tree			
GA$_3$ CSID	4.0 a^z	3.3 a	41.8 a	30.8 a	45.8 a	34.0 a
Control	5.7 a	4.6 a	24.6 b	18.7 b	30.3 b	23.4 b
P-value	0.4215	0.4879	0.0029	0.0037	0.0105	0.0212
			no. of fruit/tree			
GA$_3$ CSID	16 a	13 a	215 a	141 a	229 a	153 a
Control	23 a	19 a	122 b	83 b	143 b	101 b
P-value	0.4153	0.4802	0.0042	0.0026	0.0074	0.0107

^{z} Values in a vertical column followed by different letters are significantly different at specified *P*-values by Duncan's Multiple Range Test.

GA$_3$ did not change fruit length or width, mesocarp width or seed diameter relative to fruit from untreated control trees (Table 2). GA$_3$ had no effect on the number of days after harvest that it took for fruit to soften to the "eating ripe" compared to fruit from untreated control trees, but fruit in the ON-crop year ripened 1.4 days earlier than fruit in the OFF-crop Year (Table 2). The incidence of mesocarp discoloration, vascularization and stem-end decay was extremely low and not affected by GA$_3$ or the OFF- or ON-crop status of the trees (data not shown).

Table 2. Effect of GA$_3$ (25 mg/L) applied at the cauliflower stage of inflorescence development (CSID) (~March) on fruit quality parameters averaged over the OFF- and ON-crop years in an alternate bearing 'Hass' avocado orchard in Irvine, CA.

Treatment	Days to ripen	Fruit length	Fruit width	Mesocarp width	Seed diameter	Seed germination
			mm			
GA$_3$ CSID	12.2 b^z	93.6 a	68.0 a	29.8 a	38.2 a	0.0 a
Control	12.4 a	94.9 a	68.5 a	30.5 a	38.1 a	0.1 a
Tree status						
OFF	12.8 a	94.7 a	68.6 a	30.4 a	38.2 a	0.1 a
ON	11.4 b	93.3 a	67.6 a	29.7 a	38.0 a	0.0 a
P-value						
Treatment	0.0402	0.6279	0.3148	0.3525	0.5723	0.2970
Status	0.0405	0.1867	0.9119	0.8873	0.7532	1.0000
T x S	0.0634	0.8755	0.2990	0.6665	0.2971	1.0000

^{z} Values in a vertical column followed by different letters are significantly different at specified *P*-values by Fisher's LSD Test.

GA$_3$ applied at full bloom had no significant effect on yield in the OFF- or ON-crop years or on 2-year cumulative yield compared to untreated control trees (Table 3). The later application of GA$_3$ when fruit were 17-20 mm in diameter significantly increased 2-year cumulative total yield as kilograms, but not number of fruit, per tree compared to the untreated control, suggesting that the later application of GA$_3$ had a stronger effect on fruit size than fruit set. Consistent with this interpretation, application of GA$_3$ when fruit were 17-20 mm in diameter significantly increased the yield of commercially valuable fruit (178-325 g/fruit) as both kilograms and number of fruit per tree. GA$_3$ applied at full bloom or when fruit were 17-20 mm in diameter increased total yield as number of fruit per tree compared to the untreated control only at the 10% confidence level.

Table 3. Effects of GA$_3$ (25 mg/L) applied at full bloom (FB) (~April) or when fruit were 17-20 mm in diameter (17-20 mm) (late June-early July) on yield and fruit size as kilograms and number of fruit per tree in an alternate bearing 'Hass' avocado orchard in Carpinteria, CA.

	OFF-crop year		ON-crop year		2-year cumulative	
GA$_3$ Treatments	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)
			kg fruit/tree			
GA$_3$ FB	6.5 a^z	6.1 a	82.9 a	67.6 b	89.5 b	78.5 b
GA$_3$ 17-20 mm	12.4 a	9.7 a	105.5 a	91.9 a	117.9 a	100.1 a
Control	7.5 a	6.6 a	83.3 a	70.9 ab	90.8 b	77.4 b
P-value	0.3420	0.5677	0.1457	0.0713	0.0569	0.0532
			no. of fruit/tree			
GA$_3$ FB	30 a	26 a	402 a	304 a	448 a	347 b
GA$_3$ 17-20 mm	59 a	43 a	491 a	406 a	548 a	439 a
Control	32 a	28 a	391 a	313 a	420 b	338 b
P-value	0.1063	0.5318	0.2383	0.0825	0.0960	0.0522

^{z} Values in a vertical column followed by different letters are significantly different at specified *P*-values by Duncan's Multiple Range Test.

Neither GA$_3$ treatment had an effect on the incidence of mesocarp discoloration, vascularization or stem-end decay (the only fruit quality parameters evaluated in this experiment; data not shown). The occurrence of mesocarp discoloration was low, but significantly lower in the OFF-year fruit than ON-year fruit. In contrast, the average rating for vascularization of the mesocarp was 1.1 (i.e., ~25% of the mesocarp had vascular bundles and associated fibers present) for fruit in all treatments in both the OFF- and ON-crop years of the experiment.

Aminoethoxyvinylglycine (AVG), 2,4-dichlorophenoxyacetic acid (2,4-D) and 3,5,6-trichloro-2-pyridyloxyacetic acid (3,5,6-TPA). These PBR treatments had no effect on yield in the OFF-crop year (Table 4). For the ON-crop year, only 2,4-D applied when fruit were 17-20 mm in diameter increased total yield as kilograms, but not number of fruit, per tree compared to untreated control trees, suggesting that 2,4-D had a greater effect on fruit size than fruit set. Consistent with this interpretation, 2,4-D increased the yield of commercially valuable fruit (178-325 g/fruit) as both kilograms and number of fruit per tree in the ON-crop year. AVG applied at full bloom also significantly increased the kilograms of commercially valuable size fruit in the ON-crop year, without a reduction in total yield. However, only 2,4-D increased the 2-year cumulative yield of commercially valuable fruit as both kg and number of fruit per tree.

Table 4. Effects of AVG (250 mg/L) applied at full bloom (FB) (~April), when fruit were 17-20 mm in diameter (late June-early July) or at FB and again at 17-20 mm fruit diameter, 2,4-D (111 g acid equivalents/ha) applied when fruit were 17-20 mm in diameter, and 3,5,6-TPA (15 mg/L) applied when fruit were ~24 mm in diameter on yield and fruit size as kilograms and number of fruit per tree in an alternate bearing 'Hass' avocado orchard in Irvine, CA.

	OFF-crop year		ON-crop year		2-year cumulative	
PBR Treatment	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)	Total fruit	Valuable size fruit (178-325 g)
			kg fruit/tree			
AVG FB	9.9 a[z]	7.0 a	88.8 b	70.6 ab	98.3 a	76.1 ab
AVG 17-20 mm	7.6 a	5.7 a	95.5 ab	68.4 bc	103.8 a	75.8 ab
AVG FB+17-20 mm	7.9 a	5.5 a	87.6 b	64.7 bc	95.0 a	69.1 b
2,4-D 17-20 mm	6.1 a	3.9 a	110.4 a	87.8 a	116.0 a	90.2 a
3,5,6-TPA 24 mm	7.7 a	5.4 a	88.4 b	69.5 b	95.8 a	73.4 ab
Control	8.3 a	7.1 a	82.1 b	51.3 c	90.9 a	60.9 b
P-value	0.8913	0.8088	0.0955	0.0070	0.2344	0.0625
			no. of fruit/tree			
AVG FB	34 a	25 a	423 a	308 b	432 a	318 ab
AVG 17-20mm	27 a	21 a	481 a	304 b	481 a	321 ab
AVG FB+17-20mm	27 a	20 a	433 a	285 b	436 a	293 b
2,4-D 17-20mm	20 a	14 a	539 a	390 a	535 a	388 a
3,5,6-TPA 24mm	28 a	21 a	412 a	299 b	423 a	308 b
Control	32 a	28 a	431 a	232 b	439 a	261 b
P-value	0.8726	0.7846	0.2455	0.0097	0.3110	0.0562

[z] Values in a vertical column followed by different letters are significantly different at specified *P*-values by Fisher's Protected LSD Test.

AVG, 2,4-D and 3,5,6-TPA had no significant effects on fruit quality (Table 5). Fruit in the OFF-crop year softened to "eating ripe" in 1.1 days less than fruit in the ON-crop year. Fruit in the OFF-crop year were wider, had more mesocarp on each side of the seed when the fruit was cut longitudinally and had a larger seed. The incidence of mesocarp discoloration, vascularization or stem-end decay was extremely low and not influenced by AVG, 2,4-D and 3,5,6-TPA or the OFF- or ON-crop status of the trees (data not shown).

Table 5. Effects of AVG (250 mg/L) applied at full bloom (FB) (~April), when fruit were 17-20 mm in diameter (late June-early July) or at FB and again at 17-20 mm fruit diameter, 2,4-D (111 g acid equivalents/ha) applied when fruit were 17-20 mm in diameter, and 3,5,6-TPA (15 mg/L) applied when fruit were ~24 mm in diameter on fruit quality parameters averaged across the OFF- and ON-crop years in an alternate bearing 'Hass' avocado orchard in Irvine, CA.

Treatment	Days to ripen	Fruit length	Fruit width	Mesocarp width	Seed diameter	Seed germination
			mm			
AVG FB	10.2 a[z]	97.0 a	69.6 a	31.9 a	37.7 a	0.6 a
AVG 17-20 mm	10.0 a	98.5 a	70.1 a	31.6 a	38.5 a	0.5 a
AVG FB+17-20 mm	10.2 a	98.4 a	69.7 a	32.8 a	36.9 a	0.5 a
2,4-D 17-20 mm	10.3 a	98.2 a	69.4 a	31.6 a	37.8 a	0.5 a
3,5,6-TPA 24 mm	10.5 a	99.6 a	69.7 a	33.0 a	36.8 a	0.6 a
Control	9.9 a	97.4 a	69.1 a	31.9 a	37.2 a	0.6 a
Tree status						
OFF	9.6 b	99.1 a	72.7 a	33.3 a	39.5 a	0.4 a
ON	10.7 a	97.4 a	66.7 b	31.1 b	35.6 b	0.6 a
P-value						
Treatment	0.8068	0.4613	0.6558	0.2505	0.2069	0.9574
Status	<0.0001	0.1171	<0.0001	<0.0001	<0.0001	0.0410
T x S	0.7218	0.6943	0.3955	0.7678	0.2245	0.4932

[z] Values in a vertical column followed by different letters are significantly different at specified *P*-values by Fisher's Protected LSD Test.

Prohexadione-calcium (Pro-Ca), 6-benzyladenine (6-BA), and 1-(2-chloro-4-pyridyl)-3-phenylurea (CPPU). The PBR treatments had no effect on yield in Year 1 (Table 6). In Year 2, Pro-Ca and 6-BA applied at full bloom and CPPU applied when fruit were 17-20 mm in diameter significantly increased the yield of large fruit (≥ 270 g/fruit) as both kilograms and number of fruit per tree without reducing total yield (Table 6). GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later produced a yield of large size fruit that was intermediate to and not significantly different from the other PBR treatments and the control trees in Year 2. In Year 3, GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later resulted in significantly more large fruit (≥ 270 g/fruit) per tree than all other treatments as both kilograms and number of fruit per tree, with the exception of 6-BA applied at full bloom (Table 6). Trees treated with 6-BA at full bloom produced more large fruit than the untreated control trees as both kilograms and number of fruit per tree, but these yields were equal to and not significantly different from the yields of large size fruit produced by trees receiving the other PBR treatments. Also in Year 3, GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later increased the total number of fruit per tree compared to the untreated control and trees that received CPPU when fruit were 17-20 mm in diameter. Only 6-BA applied at full bloom and GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later significantly increased the 3-year cumulative yield of large fruit (≥ 270 g/fruit) as both kilograms and number per tree compared to untreated control trees.

Table 6. Effects of Pro-Ca (125 mg/L) applied at full bloom (FB) (~April), GA_3 (25 mg/L) applied when fruit were 17-20 mm in diameter (late June-early July) followed 30 days later with foliar-applied Pro-Ca (125 mg/L), 6-BA (25 mg/L) at FB, and CPPU (15 mg/L) when fruit were 17-20 mm in diameter on yield and fruit size as kilograms and number of fruit per tree in a 'Hass' avocado orchard in Irvine, CA.

	Year 1		Year 2		Year 3		3-year cumulative	
PBR Treatments	Total fruit	Large fruit (≥270 g)	Total fruit	Large fruit (≥270 g)	Total fruit	Large fruit (≥270 g)	Total fruit	Large fruit (≥270 g)
				kg fruit/tree				
Pro-Ca FB	37.5 a[z]	18.1 a	23.1 ab	2.8 a	19.2 a	6.1 bc	79.8 a	27.1 ab
6-BA FB	39.1 a	18.7 a	22.3 ab	2.9 a	17.5 a	10.9 ab	78.9 a	34.6 a
CPPU 17-20 mm	29.5 a	11.6 a	30.6 a	2.8 a	9.2 a	4.7 bc	69.3 a	21.9 ab
GA_3 17-20 mm + Pro-Ca @ 30d	40.1 a	16.8 a	16.7 b	1.7 ab	20.5 a	13.0 a	77.3 a	32.6 a
Control	46.6 a	11.0 a	21.1 ab	1.3 b	9.2 a	4.0 c	76.9 a	18.3 b
P-value	0.5645	0.1303	0.0828	0.0944	0.2205	0.0336	0.9495	0.0812
				no. of fruit/tree				
Pro-Ca FB	65 a	58 a	70 ab	9 a	39 abc	19 bc	178 a	87 ab
6-BA FB	78 a	60 a	66 ab	10 a	44 ab	35 ab	188 a	111 a

CPPU 17-20 mm	67 a	37 a	82 a	9 a	26 bc	15 bc	175 a	71 ab
GA_3 17-20 mm + Pro-Ca @ 30d	85 a	55 a	54 b	6 ab	52 a	42 a	192 a	106 a
Control	79 a	36 a	63 ab	4 b	24 c	13 c	166 a	60 b
P-value	0.3009	0.1364	0.0997	0.0912	0.0201	0.0325	0.6964	0.0811

[z] Values in a vertical column followed by different letters are significantly different at specified *P*-values by Fisher's Protected LSD Test.

The PBR treatments had no effect on fruit quality (Table 7). Year had a significant effect on the number of days from harvest to "eating ripe", fruit length, fruit width, mesocarp width, seed diameter, and seed germination. The effect of year was variable, suggesting that it was independent of yield. The incidence of mesocarp discoloration, vascularization or stem-end decay was extremely low and not influenced by any PBR treatment (data not shown). Year had a significant effect on the occurrence of mesocarp discoloration (P = 0.0148), vascularization (P < 0.0001), and stem-end decay (P < 0.0001), with the incidence of each disorder greatest in Year 1 ≥ Year 3 ≥ Year 2.

Table 7. Effects of Pro-Ca (125 mg/L) applied at full bloom (FB) (~April), GA_3 (25 mg/L) applied when fruit were 17-20 mm in diameter (late June-early July) followed 30 days later with foliar-applied Pro-Ca (125 mg/L), 6-BA (25 mg/l) at FB, and CPPU (15 mg/L) when fruit were 17-20 mm in diameter on fruit quality parameters averaged across the three years of the research in a 'Hass' avocado orchard in Irvine, CA.

Treatment	Days to ripen	Fruit length	Fruit width	Mesocarp width	Seed diameter	Seed germination
		mm				
Pro-Ca FB	11.8 a[z]	98.9 a	68.4 a	30.1 a	38.3 a	0.1 a
6-BA FB	11.4 a	99.9 a	69.0 a	30.3 a	38.7 a	0.2 a
CPPU 17-20 mm	12.2 a	98.1 a	68.0 a	29.9 a	38.1 a	0.1 a
GA_3 17-20 mm + Pro-Ca @ 30d	11.8 a	98.2 a	68.5 a	30.4 a	38.1 a	0.1 a
Control	12.1 a	97.1 a	66.7 a	30.5 a	36.3 a	0.1 a
Tree status						
Year 1	11.6 b	102.6 a	66.5 c	30.6 a	35.9 b	0.1 a
Year 2	13.9 a	95.6 b	67.8 b	28.9 b	38.9 a	0.0 b
Year 3	9.9 c	97.0 b	70.3 a	31.3 a	39.1 a	0.2 a
P-value						
Treatment	0.1973	0.3779	0.3713	0.8582	0.8554	0.1469
Year	<0.0001	<0.0001	<0.0001	0.0005	0.0002	<0.0001
T x Y	0.6205	0.0167	0.0199	0.2118	0.7493	0.0432

[z] Values in a vertical column followed by different letters are significantly different at specified *P*-values by Fisher's Protected LSD Test.

Discussion

Several PBR strategies tested in this research show promise for increasing total yield, yield of commercially valuable fruit (178-325 g/fruit, packing carton sizes 60 + 48 + 40) for the California domestic market, and for increasing the yield of larger fruit (≥ 270 g/fruit) that command a higher market price. Importantly, none of the PBR strategies tested had a negative effect on any fruit quality parameter evaluated in this study. Increases in fruit size were not associated with changes in fruit length to width ratio or increases in seed size at the expense of mesocarp width. In general, fruit quality was excellent. Year, in particular the OFF- or ON-crop status of the tree, had statistically significant but physiologically insignificant effects on fruit quality.

None of the PBR strategies tested significantly increased yield or fruit size in the OFF-crop year in an alternate bearing orchard. We attribute this to a lack of plasticity in the OFF-crop year. For example, when floral intensity is low as it is in an OFF-bloom, doubling fruit set will not dramatically increase yield. Additionally, fruit are large due to the low yield of the OFF-crop and there are too few fruit for a size increase to significantly shift pack out to a larger fruit size category. In contrast, there is a lot of plasticity in the ON-crop year. Increasing the number of fruit set by the heavy ON-bloom by only a small percentage would have a significant effect on total yield. Similarly, due to the large number of fruit per tree, increasing fruit size by as little as 50 g would dramatically increase the pack out of commercially valuable fruit or larger fruit that command a high market price. The successful PBRs had a positive effect on yield in the ON-crop year.

For successful PBRs, earlier applications (cauliflower stage or full bloom) had an effect on total yield and yield of commercially valuable fruit (178-325 g/fruit, packing carton sizes 60 + 48+ 40) rather than on fruit size. Later application (when fruit were 17-20 mm in diameter) tended to have less effect on fruit set and a greater effect on the yield of commercially valuable fruit and larger fruit (≥ 270 g/fruit). However, the optimal application time was PBR-specific. Thus, for GA_3, application at the cauliflower stage of inflorescence development increased total yield and yield of commercially valuable fruit (178-325 g/fruit, packing carton sizes 60 + 48 + 40) in the ON-crop year and as 2-year cumulative yield compared to the untreated control, but the full bloom application had no effect on yield. Delaying the application of GA_3 until fruit were 17-20 mm in diameter resulted in a significant effect only on 2-year cumulative total yield and yield of commercially valuable fruit (both kg and number of fruit per tree) compared to the untreated control. The effect of 2,4-D applied when the fruit were 17-20 mm in diameter was on fruit size. The treatment increased both the kilograms and number of commercially valuable fruit in the ON-crop year and as 2-year cumulative yield. In this research, 3,5,6-TPA, which is putatively a more potent synthetic auxin than 2,4-D, was less effective, possibly due to the later application time or use of a less than optimal concentration. The 2-year-cumulative yields of commercially valuable fruit (178-325 g/fruit) obtained with AVG applied at full bloom or when fruit were 17-20 mm in diameter were intermediate to the yields obtained with 2,4-D and the untreated control. Subsequent research with AVG indicated that it should be applied at the cauliflower stage of inflorescence development during the OFF bloom and when the setting fruit of the ON crop are 17-20 mm in diameter to increase cumulative yield of commercially valuable fruit. 6-BA applied at full bloom gave a unique response in that this early application significantly increased the pack out of larger size fruit (≥ 270 g/fruit). Also unique was the increase in fruit size (≥ 270 g/fruit) in response to GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later. We anticipated an increase in total yield, not an increase in fruit size. Subsequent research with this PBR strategy resulted in increases in total yield, as well as the yield of large size fruit, in orchards with very high yields and those with consistently lower yields.

In one experiment, the PBRs were tested over a period of three years. The yield data (Table 6) clearly illustrated the different effects each PBR strategy had on yield in consecutive years, with some initiating alternate bearing and others mitigating it. This raises the question of whether PBRs should be applied annually or in only in the putative ON-crop years, given the lack of statistically significant effects of PBRs on yield and fruit size in OFF-crop years. It is our opinion that for the PBR strategies presented herein, the PBRs should be applied annually. There were no negative effects on yield or fruit size when the PBRs were applied in OFF-crop years. Moreover, there are examples in the yield data presented here, as well as other data not included, of a numerical, but not statistically significant, increase in yield and fruit size in response to PBR treatment in the OFF-crop year that contributes to a greater increase in cumulative total yield and yield of large size fruit above that obtained by applying the PBR in the ON-crop year only. In addition, in California mature fruit are still on the tree when cauliflower stage and full bloom PBR sprays are applied. We have documented that there are further benefits on yield, fruit size and fruit quality when the mature fruit receive this second PBR application (Salazar-García and Lovatt, 2000). An important factor in deciding the frequency of PBR application will be the cost of applying a PBR annually relative to the increased income generated from the increase in cumulative total yield, yield of commercially valuable fruit and/or yield of larger fruit. In California, the annual cost per ha of the PBRs used at the rates applied in this research was: GA_3 US\$40, 2,4-D US\$37, 6-BA US\$64 and Pro-Ca US\$212; the price of AVG has not been finalized, but is likely to be considerably higher than the other PBRs.

Conclusions

The results of this research demonstrated that GA_3, applied at the cauliflower stage of inflorescence development or when fruit were 17-20 mm in diameter, increased total yield and/or yield of commercially valuable fruit (178-325 g/fruit), respectively. At the standard planting density used for 'Hass' avocado trees in California (~275 trees/ha), the two GA_3 strategies increased 2-year cumulative yield of commercially valuable fruit above that of the untreated control by 2,915 and 6,243 kilograms per ha, respectively. 2,4-D produced a net increase in 2-year cumulative yield of commercially valuable fruit of 8,058 kilograms per ha. 6-BA applied at full bloom and GA_3 applied when fruit were 17-20 mm in diameter followed by Pro-Ca 30 days later resulted in a net increase in 3-year cumulative yield of larger fruit (≥ 270 g/fruit) compared to the untreated control of 4,483 and 3,933 kilograms of fruit per ha, respectively. These PBR strategies, which are cost effective, warrant further research and development.

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