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Response of evergreen perennial tree crops to gibberellic acid is crop load-dependent. I: GA_3 increases the yield of commercially valuable 'Nules' Clementine Mandarin fruit only in the off-crop year of an alternate bearing orchard

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ABSTRACT

Worldwide, gibberellic acid (GA_3) is used routinely to increase fruit number and size of seedless mandarins. The efficacy of seven combinations of GA_3 concentrations and application times to maximize total yield and yield of commercially valuable fruit (diameter 57.2–76.2 mm) of 'Nules' Clementine mandarin (*Citrus reticulata* Blanco) was determined in a commercial orchard. GA_3 applied during the period of intense flower abscission failed to reduce the total number of abscised flowers in both the light off- and heavy on-bloom years. No GA_3 treatment reduced fruit abscission when trees were setting the low yield off-crop. However, all trees receiving GA_3 in the high yield on-crop year had fewer abscised fruit than untreated control trees ($P = 0.0188$) and GA_3 applied 10 days after 75% petal fall and in July increased the number of fruit retained on tagged branches >20% compared to control trees ($P = 0.0005$). Maximum air temperature was not related to flower or fruit abscission. In the off-crop year (548 fruit per untreated control tree), it was necessary to apply 15 or 25 mg L^{-1} GA_3 at 60% bloom, 90% bloom, 75% petal fall and 10 days after 75% petal fall to significantly increase the number of fruit per tree and yield of commercially valuable fruit (kilograms and number per tree) ($P < 0.0001$) above that of control trees, with no reduction in total kilograms per tree. In the following on-crop year, it was better not to apply GA_3: no treatment increased total yield or fruit size and five of seven GA_3 treatments tested reduced total yield as kilograms and number of fruit per tree ($P = 0.0003$). The results provide strong evidence that GA_3 efficacy is crop load-dependent and dictate that crop load should be considered when using GA_3 to increase fruit set or fruit size of mandarins.

1. Introduction

In recent years, California growers have planted thousands of hectares of Clementine mandarins (*Citrus reticulata* Blanco), with 'Nules' (also called Clemenules or De Nules) the predominant cultivar. 'Nules' Clementine is a seedless mandarin of good fruit quality (Saunt, 2000) and the leading Clementine cultivar produced around the world, despite the fact that its productivity is compromised by low fruit set and small fruit size. In addition to the presence or absence of seeds, many factors, such as endogenous carbohydrate, nitrogen, and hormone concentrations, or the environment, can affect fruit set of citrus (Deidda and Agabbio, 1977; Duarte and Guardiola, 1996; Garcia-Luis et al., 1988; García-Papí and García-Martínez, 1984; Lovatt et al., 1992; Talon et al., 1992). Several plant hormones are essential to fruit development, but a single application of gibberellic acid (GA_3) has been shown to induce pollination-independent fruit development (parthenocarpy) in several plant species (Vivian-Smith et al., 2001). GA_3 is known for its capacity to increase source activity and redistribute carbohydrate, resulting in increased sink strength of developing fruit, either through increased cell division or enhanced cell size (Iqbal et al., 2011; Zhang et al., 2007). GA_3 has also been shown to increase fertilizer-use efficiency. Thus, to overcome the problem of low fruit set of 'Nules' and other seedless mandarins, growers apply GA_3 during bloom and post-bloom to enhance fruit set and yield, especially of seedless fruit (Del Rivero et al., 1969; El-Otmani et al., 1992, 2000; Erner, 1989; Fornes et al., 1992; García-Martínez and García-Papí, 1979; Hield et al., 1965; Van Rensburg et al., 1996). Information on the current label for the use of GA_3 to increase fruit set of Clementine mandarin in California was based on experiments conducted in foreign countries and by private companies in California. The label provides no detailed information on when to apply GA_3, what concentration to apply, or how much spray volume to use. Growers usually apply more than two applications per season.

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However, up to five applications of GA_3, each at 14.5 g a.i. ha^{-1}, have been used by growers in some instances. The lack of knowledge about how to use GA_3 to increase fruit set of Clementine mandarins in California has lead to ineffective treatments and variable results. There was also concern that the use of GA_3 at high concentrations or with great frequency might have a negative effect on flowering and yield the following year (Guardiola et al., 1982). Further, for 'Nules' Clementine mandarin trees grown under California climatic conditions, the absence of data identifying periods of intense abscission of flowers and young fruit in relation to temperature compromised knowing whether abscission was due to high temperatures occurring early in the season or to endogenous tree factors independent of climate. Additionally, the lack of information regarding flower and fruit abscission periods made it impossible to know whether GA_3 applications were timed appropriately. The research presented herein addressed these issues with the goal of developing a strategy of properly timed GA_3 applications at the optimal concentration to increase the yield of commercially valuable large size fruit and grower income.

2. Materials and methods

2.1. Plant material

This experiment used 6-year-old 'Nules' Clementine mandarin trees on 'Carrizo' citrange rootstock (*C. sinensis* L. Osbeck × *Poncirus trifoliata* L. Raf.) in a commercial orchard near Grapevine, CA (34.94°N, 118.83°W). The soil was a sandy loam that formed in alluvium derived from mixed but predominantly granite rock sources in the San Joaquin series. The experiment was initiated in spring of an off-crop bloom.

2.2. Gibberellic acid treatments

The experimental design was a randomized complete block design with 14 treatments replicated on 16 individual trees per treatment. There were buffer trees between treated trees within a row and buffer rows between treated rows. GA_3 concentrations tested ranged from 5 to 25 mg L^{-1} applied two to four times starting as early as 60% open flowers in the southwest (SW) tree quadrant (25 April to as late as 10 July). The treatments are listed in Table 1. GA_3 was applied to open flowers to reduce flower abscission and to stimulate parthenocarpic fruit development and to flowers at petal fall to reduce both flower and fruit abscission. The objective of both treatments was to increase fruit set and yield. GA_3 was also applied during the period of exponential fruit growth in July to increase fruit size. GA_3 treatments were prepared from ProGibb (4% GA_3, Valent BioSciences, Corp.) and contained Silwet L-77 Surfactant (Helena Chemical Co.) at a final concentration of 0.05%. All treatments were applied in 1869 L of water per ha with a 2758 kPa handgun sprayer. Treatments were applied according to tree phenology (calendar dates for years 1 and 2, respectively, are given in parentheses): 60% open flowers in the SW tree quadrant (25 April and 4 May); 90% open flowers in the SW tree quadrant (3 May and 10 May); 75% petal fall in the northeast (NE) tree quadrant (12 May and 22 May); and 10 days after 75% petal fall in the NE tree quadrant (24 May and 1 June). For two treatments, GA_3 was applied during the anticipated middle of the June drop period on 7 July and 10 July in years 1 and 2, respectively. To test for potential negative effects of GA_3 application in year 1 on return flowering and yield in year 2, five GA_3 treatments (i.e., treatments 1, 3, 7, and 9) were duplicated in year 1 as treatments 2, 4, 8, and 10, respectively, and only treatments 1, 3, 7 and 9 were applied again in year 2 (Table 1). Nets were placed under two trees in each of the following treatments: 1, 3, 5, 6, 7, 9, 11, 13 and 14 (Table 1). Starting at 60% open flowers each year, contents of the nets were collected on a weekly basis for three months and then bi-weekly until harvest in order to determine intense periods of flower and fruit drop and their relationship to ambient air temperature. Maximum and minimum average air temperatures for the two years of the research were downloaded from the California Irrigation Management Information System (CIMIS) website (California Department of Water Resources, 2009) for Arvin-Edison station #125 (lat. 35.12°N, 118.46°W, elevation 152 m) and verified using temperature data collected on site. The contents of the nets under the GA_3-treated trees were also quantified to determine the effectiveness of each GA_3 treatment relative to the untreated control and each other. In year 2, for the two trees in each treatment with nets placed under them, three branches bearing fruit were tagged in each of the four quadrants of the tree [NE, southeast (SE), SW, and northwest (NW)]. The initial number of fruit set was determined on 6 July and percent fruit abscission was determined weekly through 31 August and thereafter bi-weekly until harvest.

All fruit were harvested in November each year. Total yield was determined as kilograms per tree. A randomly selected sample of 100 fruit per tree, representing ∼10–17% of the average total number of fruit on a tree for the two years of the study, was collected for each data tree and the transverse diameter of each fruit was measured with an electronic caliper. The weight of a specified number of fruit in each size category was determined. These data were used to calculate pack-out, i.e., the kilograms of fruit of each packing carton size category per tree and the total number fruit and number of fruit in each packing carton size category per tree. The following fruit size categories based on fruit transverse diameter (mm) were those used commercially at the time of the research: tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59). In addition, at harvest, 25 fruit were selected randomly per tree for analysis of fruit quality, including total soluble solids (°Brix by refractometry, adjusted for acidity), fruit weight, juice weight, percent juice (calculated), percent acid (by titration), and the ratio of total soluble solids to acid (Sunkist Growers Inc, 1983).

2.3. Statistical analysis

Repeated measure analysis was used to test for treatment effects with year as the repeated measure. This analysis was performed using the General Linear Model procedure of the SAS 9.2 statistical program (SAS Inst., Inc., Cary, NC). Analysis of variance was used to test 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 a specific year and for 2-year cumulative yield. Means were separated using Fisher's Protected LSD test at $P = 0.05$. In year 1, yield data for trees in duplicated treatments (i.e., 1 and 2, 3 and 4, 5 and 6, 7 and 8, 9 and 10, and 11 and 12) within the same replicate were combined before statistical analysis. Pearson's correlation coefficient was calculated to determine the relationship between the total amounts of GA_3 applied (concentration × number of applications) and total yield and yield of fruit in different size categories per tree.

3. Results

3.1. Effect of gibberellic acid on flower abscission

In year 1, floral intensity was low on 'Nules' Clementine mandarin trees, which is a characteristic of an off-crop year. The average total number of flowers that abscised from 60% open flowers (25 April) through 16 June was 4666 for all the trees in the experiment

Table 1
Concentrations and time of gibberellic acid (GA_3) applications to 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA.

Treatment[z]	Off-crop year ($mg L^{-1}$)					On-crop year ($mg L^{-1}$)				
	Open flowers		Petal fall			Open flowers		Petal fall		
	60%[y]	90%	75%	75% +10 d	July	60%[x]	90%	75%	75% +10 d	July
(1) 5 $mg L^{-1}$ $GA_3 \times 4$	5	5	5	5	–	5	5	5	5	–
(2) 5 $mg L^{-1}$ $GA_3 \times 4$ (yr 1 only)	5	5	5	5	–	–	–	–	–	–
(3) 10 $mg L^{-1}$ $GA_3 \times 4$	10	10	10	10	–	10	10	10	10	–
(4) 10 $mg L^{-1}$ $GA_3 \times 4$ (yr 1 only)	10	10	10	10	–	–	–	–	–	–
(5) 10 $mg L^{-1}$ $GA_3 \times 3$ 60%	10	–	10	–	10	10	–	10	–	10
(6) 10 $mg L^{-1}$ $GA_3 \times 3$ 90%	–	10	–	10	10	–	10	–	10	10
(7) 15 $mg L^{-1}$ $GA_3 \times 4$	15	15	15	15	–	15	15	15	15	–
(8) 15 $mg L^{-1}$ $GA_3 \times 4$ (yr 1 only)	15	15	15	15	–	–	–	–	–	–
(9) 25 $mg L^{-1}$ $GA_3 \times 4$	25	25	25	25	–	25	25	25	25	–
(10) 25 $mg L^{-1}$ $GA_3 \times 4$ (yr 1 only)	25	25	25	25	–	–	–	–	–	–
(11) 15 $mg L^{-1}$ $GA_3 \times 2$	15	–	15	–	–	15	–	15	–	–
(12) 15 $mg L^{-1}$ $GA_3 \times 2$ (yr 1 only)	15	–	15	–	–	–	–	–	–	–
(13) Water	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O	H_2O
(14) Control	–	–	–	–	–	–	–	–	–	–

[x] Phenological stages corresponded to the following calendar dates in year 2: 60% open flowers in the SW tree quadrant, 4 May; 90% open flowers in the SW tree quadrant, 10 May; 75% petal fall in the NE tree quadrant, 22 May; 10 days after 75% petal fall in the NE tree quadrant, 1 June; and 10 July.
[y] Phenological stages corresponded to the following calendar dates in year 1: 60% open flowers in the southwest (SW) tree quadrant, 25 Apr.; 90% open flowers in the SW tree quadrant, 3 May; 75% petal fall in the northeast (NE) tree quadrant, 12 May; 10 days after 75% petal fall in the NE tree quadrant, 24 May; and 7 July.
[z] All treatments were applied in 1869 L of water per ha.

with nets under them. No GA_3 treatment significantly reduced the total number of flowers that abscised (data not shown). Flower abscission was greatest over the period from 60% open flowers on 25 April through 10 days after 75% petal fall on 24 May (Fig. 1). No GA_3 treatment significantly reduced flower abscission during this period. Maximum air temperature during the flower abscission period reached 32 °C on 25 May. Over the next 5 days, flower abscission decreased to an average total of 551 flowers, then to 386 flowers over the next 6 days. Subsequently, only 58 total flowers abscised from 7 June to 16 June. In contrast, in year 2, flowering was intense, which is typical of an on-crop year. The average total number of flowers that abscised from 90% open flowers on 10 May to 15 June was 6753 and significantly greater than the number of flowers that abscised in the off-crop year ($P = 0.0006$) (Fig. 2). No GA_3 treatment significantly reduced the total number of flowers that abscised. Flower abscission in the on-crop year was greatest (2500 total flower per week) from 60% open flowers on 4 May to 75% petal fall on 22 May. No GA_3 treatment significantly reduced flower abscission during this period. During the period of greatest flower abscission in the on-crop year, maximum air temperature reached 32 °C on 15 May, which was between 60% open flowers and 75% petal fall. From 22 May to 1 June, flower abscission decreased to a total of only 550 flowers, to just 100 flowers over the next 7 days, and an average of only 23 flowers abscising from 8 June to 15 June. All trees that received a GA_3 application at 90% open flowers (10 May) had significantly less flower abscission during the period from 1 June to 8 June ($P = 0.0447$) than trees receiving other GA_3 treatments and the untreated control trees.

3.2. Effect of gibberellic acid on fruit abscission

In the off-crop year, abscission of young, developing 'Nules' Clementine mandarin fruit was greatest over the period from 16 June to 28 June (Fig. 1), averaging 140 fruit per day. Trees that

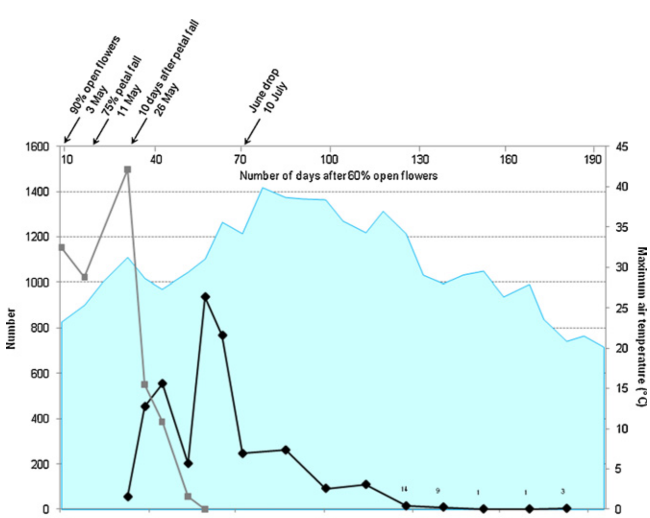

Fig. 1. Maximum air temperature (blue area plot) and the average total number of flowers (-■)-and fruit (-♦-) that abscised from control trees per week in May through July and bi-weekly in August through October during the off-crop year of 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

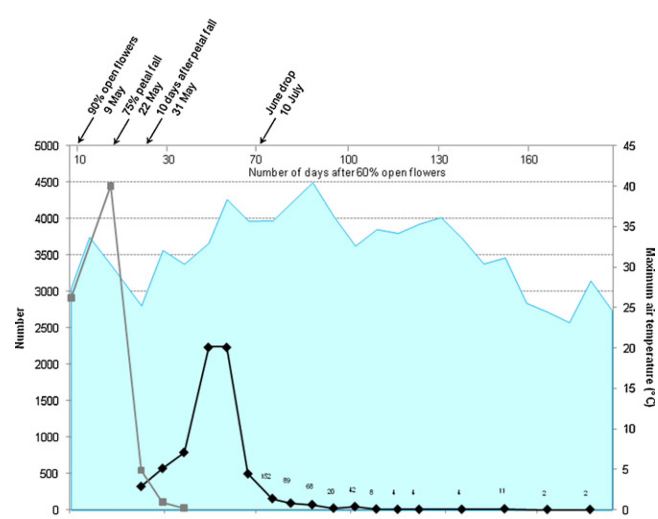

Fig. 2. Maxium air temperature (blue area plot) and the average total number of flowers (-■-). and fruit (-♦-) that abscised from control trees per week in May through August and bi-weekly in September and October during the on-crop year of 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

received a GA_3 application (5, 10, 15, or 25 mg L^{-1}) 10 days after 75% petal fall (24 May) had significantly less fruit abscission over this period (P = 0.0273) than all other treatments (data not shown). Fruit abscission decreased to 35 fruit per day by 5 July, 5 days before the July (last) GA_3 application in some treatments. Ambient air temperature reached 35 °C on 1 July, when fruit abscission was ~250 fruit per day, and 40 °C on 17 July, with fruit abscission remaining at ~250 fruit per day. In the off-crop year, the average total number of fruit that abscised from 25 May to harvest in November was 3706 for all the trees in the experiment with nets. No GA_3 treatment significantly reduced total fruit abscission in the off-crop year. In contrast, during the on-crop year, the average total number of fruit that abscised was 7470 and significantly greater than in the off-crop year (P < 0.0001). All trees receiving GA_3 had significantly less abscised fruit than the untreated control (P = 0.0188) (data not shown). The greatest period of fruit abscission was from 15 June to 29 June (Fig. 2), with an average drop of ~350 fruit per day. All trees receiving GA_3 at 10, 15 and 25 mg L^{-1} at 10 days after 75% petal fall (1 June) had significantly less fruit abscission over this period (P = 0.0504) (data not shown). In the on-crop year, ambient air temperature reached 35 °C on 26 June, which was during the period of greatest fruit drop. Air temperature reached 40 °C on 25 July. During the 7-day collection period that included 25 July, an average total of 68 fruit abscised, with an average total of only 20 fruit abscising the following week (Fig. 2).

To quantify the effect of GA_3 treatments on retention of fruit after the June drop period, the number of fruit that abscised from tagged branches was determined from 6 July through harvest. During this period, untreated control trees had the lowest percent fruit retention (45%). All GA_3 treatments, except 15 mg L^{-1} GA_3 applied only two times, at 60% open flowers and 75% petal fall, significantly increased fruit retention on the tagged branches by more than 20% compared to the tagged branches on untreated control trees (P = 0.0005) (data not shown), indicating that GA_3 applications at 10 days after 75% petal fall or in July had a positive effect on fruit retention.

3.3. *Effect of gibberellic acid on yield, fruit size and fruit quality*

In the off-crop year, no GA_3 treatment significantly increased total yield as kilograms fruit per tree (Table 2). GA_3 at 15 or 25 mg L^{-1} applied at 60% open flowers, 90% open flowers, 75% petal fall, and 10 days after 75% petal fall significantly increased the total number of fruit per tree (Table 3). Only these two GA_3 treatments significantly increased the yield of fruit of packing carton sizes medium (transverse diameter 50.81–57.15 mm), large (diameter 57.16–63.50 mm), and jumbo (diameter 63.51–69.85 mm) and the yield of commercially valuable large size fruit in the combined pool of fruit of packing carton sizes large + jumbo + mammoth (diameter 57.16–76.20 mm) (as kilograms and number of fruit per tree) compared to the untreated control trees and trees sprayed with water only (Tables 2 and 3). The negative effect of five water applications on total yield is consistent with previous results demonstrating that foliar sprays remove flowers and young fruit and that foliar-applied plant growth regulator or fertilizer treatments that successfully increase yield clearly do more than just overcome the negative effect of the application itself. The significant loss in reproductive structures resulting from the five water sprays significantly increased the yield of fruit of packing carton size colossal (as both number and kilograms of fruit per tree) compared to all other treatments and super colossal compared to all other treatments except the untreated control. Colossal and super colossal fruit have no commercial value. Three applications of GA_3 at 10 mg L^{-1} at 90% open flowers, 10 days after 75% petal fall and 7 July also increased the total number of fruit per tree, but not the kilograms of fruit per tree and increased the number and kilograms of fruit of packing carton size medium (diameter 51.81–57.15 mm) and jumbo (diameter 63.51–69.85 mm) (Tables 2 and 3).

Trees receiving three or four applications of GA_3 at 5, 10, 15 or 25 mg L^{-1} during the on-crop year had significantly reduced total yields as kilograms and number of fruit per tree compared to untreated control trees, with the exception that three applications of GA_3 at 15 mg L^{-1} starting at 90% open flowers reduced fruit number but not kilograms per tree (Tables 4 and 5). Two applications of GA_3 at 15 mg L^{-1} had no effect on yield as kilograms or number of fruit per tree relative to untreated control trees. In the on-crop year, no GA_3 treatment increased total yield or yield of commercially valuable large size fruit (as kilograms or number of fruit per tree) to a value significantly greater than the untreated control trees.

Comparing the effects on yield of GA_3 treatment applications in the off- versus on-crop year provided strong evidence that GA_3 should not be applied in the on-crop year. Trees treated with four applications of 5, 10, 15 or 25 mg L^{-1} GA_3 in the off-crop, but not in the on-crop year, produced yields (both number and kilograms of fruit per tree) that were significantly greater than trees receiving these treatments in both years of the study, respectively (Tables 4 and 5). Moreover, there was a weak but significant positive relationship between the total amount of GA_3 applied (concentration × number of applications) in the off-crop year and total yield, yield of fruit of packing carton sizes small, medium, large and jumbo or the yield of commercially valuable fruit in the combined pool of fruit of packing carton sizes large + jumbo + mammoth (Table 6). However, in the on-crop year, the relationship between the total amount of GA_3 applied and total yield, yield of commercially valuable large fruit of packing carton sizes large + jumbo + mammoth was significant and negative (Table 7). In addition, in the off-crop year, trees receiving four applications of GA_3 at 5, 10, 15 or 25 mg L^{-1} had increased concentrations of total soluble solids in the juice of the fruit relative to the untreated control (P = 0.0019). For all other GA_3 treatments, the total soluble solids content of the juice was not significantly different from that of fruit from the untreated control trees. There were no significant treatment effects on juice weight, percent juice or total soluble solids to acid ratio. In the on-crop year, there were no treatments effects on any of these fruit quality parameters.

Interestingly, the average kilograms of fruit per tree for all treatments in the on-crop year was only 18% greater than in the off-crop year, but the average total number of fruit per tree in the on-crop year represented a 72% increase over the off-crop year (Tables 8 and 9). The differences in crop load between the off- and on-crop years had a significant effect on fruit size and the yield of commercially valuable size fruit. In year 1, the off-crop year, averaged across all treatments, trees produced significantly more fruit of packing carton sizes jumbo, mammoth, colossal and super colossal (transverse diameter 63.51–101.59 mm) than in the on-crop year (Tables 8 and 9). This resulted in significantly more commercially valuable fruit in the pool of fruit of packing carton sizes large + jumbo + mammoth (diameter 57.16–76.20 mm) in the off-crop year than in the on-crop year (Tables 8 and 9). In contrast, in year 2, the on-crop year, averaged across all treatments, trees had significantly more fruit of packing carton sizes tiny, small, medium and large (fruit transverse diameter less than 44.5–63.50 mm). Averaged across the off- and on-crop years of the study (Tables 8 and 9) or as 2-year cumulative yield (data not shown), no GA_3 treatment significantly increased total yield (as kilograms or number of fruit per tree) compared to the untreated control trees. However, trees receiving four applications of GA_3 in the off-crop year only at 15 mg L^{-1} produced significantly more fruit of packing carton size jumbo and those receiving GA_3 at 25 mg L^{-1} produced significantly more fruit of packing carton sizes

Table 2
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees during an off-crop year on total yield and fruit size distribution (based on transverse diameter) as kilograms fruit per tree.

Treatments	Total	Fruit packing carton size[z] (kg/tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
(1) 5 mg L^{-1} $GA_3 \times 4$	76.4 a[y]	0.0 a	0.6 a	3.4 bc	12.1 bc	27.3 abc	24.6 a	6.8 c	1.7 c	64.0 ab
(3) 10 mg L^{-1} $GA_3 \times 4$	74.4 a	0.2 a	0.9 a	4.4 ab	13.5 abc	25.0 bc	21.9 a	7.0 bc	1.4 c	60.5 ab
(5) 10 mg L^{-1} $GA_3 \times 3$ 60%	71.3 a	0.0 a	0.5 a	3.6 bc	11.4 bc	28.4 abc	20.6 a	5.0 c	1.9 c	60.4 ab
(6) 10 mg L^{-1} $GA_3 \times 3$ 90%	77.3 a	0.2 a	0.7 a	4.7 ab	12.2 bc	28.8 ab	22.4 a	6.9 bc	1.3 c	63.4 ab
(7) 15 mg L^{-1} $GA_3 \times 4$	77.4 a	0.0 a	0.9 a	5.1 ab	14.9 ab	29.3 ab	20.5 a	5.5 c	1.3 c	64.6 a
(9) 25 mg L^{-1} $GA_3 \times 4$	77.9 a	0.1 a	1.0 a	5.4 a	16.1 a	29.7 a	20.1 a	4.7 c	0.7 c	65.9 a
(11) 15 mg L^{-1} $GA_3 \times 2$	76.1 a	0.1 a	0.7 a	4.1 ab	13.0 abc	28.2 abc	21.9 a	6.0 c	2.0 bc	63.1 ab
(13) Water	61.2 b	0.1 a	0.4 a	1.5 d	6.7 d	17.9 d	19.4 a	12.2 a	3.4 a	44.0 c
(14) Control	74.1 a	0.0 a	0.4 a	2.1 cd	10.3 c	24.2 c	23.1 a	9.2 b	3.3 ab	57.7 b
P-value	0.0009	0.2988	0.2347	0.0005	0.0001	0.0002	0.3453	<0.0001	0.0031	<0.0001

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 3
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees during an off-crop year on total yield and fruit size distribution (based on transverse diameter) as number of fruit per tree.

Treatments	Total	Fruit packing carton size[z] (fruit no./tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
(1) 5 mg L^{-1} $GA_3 \times 4$	602 abc[y]	1 a	11 a	45 bc	123 bc	218 abc	160 a	37 c	7 c	501 ab
(3) 10 mg L^{-1} $GA_3 \times 4$	603 abc	4 a	16 a	58 ab	137 abc	200 bc	143 a	39 bc	6 c	480 ab
(5) 10 mg L^{-1} $GA_3 \times 3$ 60%	569 bc	1 a	9 a	47 bc	116 bc	226 abc	135 a	28 c	8 c	476 ab
(6) 10 mg L^{-1} $GA_3 \times 3$ 90%	623 ab	4 a	13 a	62 ab	124 bc	230 ab	146 a	38 bc	6 c	500 ab
(7) 15 mg L^{-1} $GA_3 \times 4$	637 a	1 a	15 a	67 ab	151 ab	234 ab	133 a	31 c	6 c	518 a
(9) 25 mg L^{-1} $GA_3 \times 4$	653 a	3 a	19 a	71 a	163 a	237 a	131 a	26 c	3 c	532 a
(11) 15 mg L^{-1} $GA_3 \times 2$	613 abc	4 a	12 a	55 ab	132 abc	225 abc	143 a	33 c	9 bc	500 ab
(13) Water	448 d	2 a	6 a	20 d	68 d	143 d	126 a	67 a	15 a	337 c
(14) Control	548 c	1 a	6 a	27 cd	105 c	193 c	151 a	51 b	14 ab	449 b
P-value	<0.0001	0.2988	0.2347	0.0005	0.0001	0.0002	0.3453	<0.0001	0.0031	<0.0001

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 4
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees during an on-crop year on total yield and fruit size distribution (based on transverse diameter) as kilograms fruit per tree.

Treatments	Total	Fruit packing carton size[z] (kg/tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
(1) 5 mg L^{-1} $GA_3 \times 4$	83.5 cdef[y]	0.5 ab	6.4 e	36.7 bcd	31.5 abcd	6.8 a	0.9 abc	0.4 b	0.4 a	39.2 ab
(2) 5 mg L^{-1} $GA_3 \times 4$ (year 1 only)	101.9 a	0.5 ab	11.2 ab	48.8 a	31.5 abcd	8.3 a	0.7 bc	0.5 ab	0.4 a	40.5 ab
(3) 10 mg L^{-1} $GA_3 \times 4$	76.8 f	0.8 a	8.3 bcde	35.0 cd	28.0 bcde	4.4 a	0.4 c	0.0 b	0.0 a	32.8 bcd
(4) 10 mg L^{-1} $GA_3 \times 4$ (year 1 only)	93.6 abc	0.4 ab	8.9 bcde	39.0 bcd	34.3 ab	8.2 a	1.4 ab	1.1 a	0.3 a	43.9 a
(5) 10 mg L^{-1} $GA_3 \times 3$ 60%	84.6 cdef	0.6 ab	10.6 abc	42.4 abc	24.6 de	6.2 a	0.3 c	0.0 b	0.0 a	31.1 cd
(6) 10 mg L^{-1} $GA_3 \times 3$ 90%	87.8 bcdef	0.2 b	7.7 cde	41.9 abcd	32.2 abc	4.9 a	1.0 abc	0.0 b	0.0 a	38.1 abc
(7) 15 mg L^{-1} $GA_3 \times 4$	78.4 def	0.6 ab	8.7 bcde	34.8 d	27.4 cde	6.2 a	0.2 c	0.5 ab	0.0 a	33.8 bcd
(8) 15 mg L^{-1} $GA_3 \times 4$ (year 1 only)	91.9 abc	0.5 ab	10.6 abc	43.0 ab	29.4 abcde	7.8 a	0.3 c	0.2 b	0.0 a	37.6 abc
(9) 25 mg L^{-1} $GA_3 \times 4$	78.16 ef	0.31 ab	10.39 abcd	38.96 bcd	23.79 e	4.30 c	0.41 c	0.00 b	0.00 a	28.50 d
(10) 25 mg L^{-1} $GA_3 \times 4$ (year 1 only)	93.43 abc	0.61 ab	7.43 de	40.79 bcd	35.92 a	7.68 ab	0.40 c	0.59 ab	0.00 a	44.01 a
(11) 15 mg L^{-1} $GA_3 \times 2$	89.91 bcd	0.30 ab	8.19 bcde	42.22 abcd	32.93 abc	4.92 bc	0.63 bc	0.39 b	0.34 a	38.48 abc
(12) 15 mg L^{-1} $GA_3 \times 2$ (year 1 only)	89.37 bcde	0.42 ab	8.94 bcde	43.72 ab	28.93 bcde	5.57 abc	1.79 a	0.00 b	0.00 a	36.29 abcd
(13) Water	88.4 bcde	0.4 ab	8.8 bcde	38.9 bcd	31.8 abc	7.0 a	1.1 abc	0.4 b	0.3 a	39.9 ab
(14) Control	97.4 ab	0.6 ab	13.3 a	43.2 ab	31.9 abc	6.9 a	0.7 bc	0.4 b	0.5 a	39.5 ab
P-value	0.0003	0.6793	0.0026	0.0238	0.0265	0.1159	0.0342	0.0546	0.6557	0.0031

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 5
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees during an on-crop year on total yield and fruit size distribution (based on transverse diameter) as number of fruit per tree.

Treatments	Total	Fruit packing carton size[z] (fruit no./tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
(1) 5 mg L^{-1} GA_3 × 4	951 cde[y]	11 a	114 e	451 bcd	311 abcd	55 a	6 abc	2 b	2 a	372 abc
(2) 5 mg L^{-1} GA_3 × 4 (year 1 only)	1199 a	11 a	200 ab	600 a	310 abcd	68 a	5 bc	3 ab	2 a	383 abc
(3) 10 mg L^{-1} GA_3 × 4	911 e	19 a	148 bcde	430 cd	277 bcde	36 a	3 c	0 b	0 a	315 cde
(4) 10 mg L^{-1} GA_3 × 4 (year 1 only)	1069 abcd	11 a	158 bcde	479 bcd	339 ab	67 a	9 ab	6 a	1 a	414 ab
(5) 10 mg L^{-1} GA_3 × 3 60%	1019 cde	13 a	189 abc	521 abc	243 de	51 a	2 c	0 b	0 a	295 de
(6) 10 mg L^{-1} GA_3 × 3 90%	1020 cde	4 a	137 cde	515 abcd	317 abc	40 a	6 abc	0 b	0 a	363 abcd
(7) 15 mg L^{-1} GA_3 × 4	922 e	14 a	155 bcde	428 d	270 cde	50 a	1 c	3 ab	0 a	322 cde
(8) 15 mg L^{-1} GA_3 × 4 (year 1 only)	1087 abc	13 a	189 abc	528 ab	291 abcde	64 a	2 c	1 b	0 a	357 abcd
(9) 25 mg L^{-1} GA_3 × 4	945 de	8 a	186 abcd	479 bcd	235 e	35 a	3 c	0 b	0 a	272 e
(10) 25 mg L^{-1} GA_3 × 4 (year 1 only)	1072 abcd	15 a	133 de	502 bcd	355 a	63 a	3 c	3 ab	0 a	420 a
(11) 15 mg L GA_3 × 2	1045 bcde	7 a	146 bcde	519 abcd	325 abc	40 a	4 bc	2 b	1 a	369 abcd
(12) 15 mg L^{-1} GA_3 × 2 (year 1 only)	1049 bcde	10 a	160 bcde	538 ab	286 bcde	45 a	11 a	0 b	0 a	342 bcde
(13) Water	1023 bcde	8 a	156 bcde	478 bcd	314 abc	57 a	7 abc	2 b	1 a	378 abc
(14) Control	1162 ab	16 a	237 a	531 ab	315 abc	57 a	4 bc	2 b	2 a	375 abc
P-value	0.0011	0.6793	0.0026	0.0238	0.0265	0.1159	0.0342	0.0546	0.6557	0.0042

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 6
Pearson correlation coefficients (*r*) between the total amount of gibberellic acid (GA_3) applied in the off-crop year and total yield and yield of fruit of different packing carton size categories (kg/tree) of 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA.

	Total	Fruit packing carton size[z]								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
r-Value	0.1728	0.0525	0.2014	0.3003	0.3074	0.2324	−0.1003	−0.3066	−0.2720	0.2386
P-Value	0.0096	0.4360	0.0026	<0.0001	<0.0001	0.0005	0.1363	<0.0001	<0.0001	0.0003

[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

large and jumbo and fruit in the combined pool of packing carton sizes large + jumbo + mammoth compared to untreated control trees.

3.4. Economic impact of gibberellic acid application

The interaction between the amount of GA_3 applied and total yield not only affected fruit size in the off- and on-crop years, but also impacted the value of the crop. In the off-crop year, all trees receiving GA_3 produced crops with a higher dollar value than the untreated control trees and trees treated with water, with the exception of trees receiving three or four applications of GA_3 at 10 mg L^{-1} starting at 60% open flowers, which produced crops of equal value to the control ($P < 0.0001$) (data not shown). In the on-crop year, trees receiving four applications of GA_3 at 5, 10, 15 and 25 mg L^{-1} or three applications of GA_3 at 10 mg L^{-1} starting at 60% open flowers in both the off- and on-crop years of the study produced a crop of significantly lower dollar value than the untreated control trees ($P = 0.0005$) (data not shown). Furthermore, no GA_3 treatment significantly increased the 2-year cumulative dollar value of the crop over that of the untreated control trees (Table 10). Whether trees were treated with GA_3 only in the off-crop year or in both years of the study had no significant effect on the 2-year cumulative dollar value of the crop. However, achieving an equivalent 2-year cumulative yield and crop value would be more cost-effective by treating in 1 year only rather than both years. Only trees receiving five applications of water had a 2-year cumulative crop value less than the untreated control, but it was not significantly different from trees treated in both years of the study with four applications of 10 or 15 mg L^{-1} GA_3 or three applications of 10 mg L^{-1} GA_3 starting at 60% open flowers.

4. Discussion

'Nules' Clementine mandarin originated in the Mediterranean coastal area of eastern Spain. During the period of flowering and

Table 7
Pearson correlation coefficients (*r*) between the total amount of gibberellic acid (GA_3) applied during the on-crop year and total yield and yield of fruit of different packing carton size categories (kg/tree) of 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA.

	Total	Fruit packing carton size[z]								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
r-Value	−0.2434	−0.0278	−0.0151	−0.0876	−0.2285	−0.1454	−0.1418	−0.0942	−0.1542	−0.2581
P-Value	0.0033	0.7406	0.8576	0.2964	0.0059	0.0820	0.0900	0.2614	0.0650	0.0018

[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 8
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees on total yield and fruit size distribution (based on transverse diameter) as kilograms per tree averaged across the off- and on-crop years in a commercial orchard in Grapevine, CA.

Treatments	Total	Fruit packing carton size[z] (kg/tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
Treatment										
(1) 5 mg L^{-1} GA_3 × 4	79.0 bcd[y]	0.2 a	3.5 d	20.0 b	21.7 bc	17.4 abc	12.2 a	3.6 bc	0.4 d	51.3 abc
(2) 5 mg L^{-1} GA_3 × 4 (year 1 only)	90.1 a	0.3 a	5.9 ab	26.1 a	21.9 abc	17.4 abc	13.2 a	3.7 bc	1.7 ab	52.5 ab
(3) 10 mg L^{-1} GA_3 × 4	75.5 cd	0.5 a	4.6 bcd	20.1 b	21.4 bc	13.6 de	11.7 a	2.8 cd	0.8 cd	46.7 bcd
(4) 10 mg L^{-1} GA_3 × 4 (year 1 only)	84.1 abc	0.2 a	4.9 bcd	21.3 b	23.4 ab	17.7 abc	11.1 a	4.7 ab	0.8 cd	52.2 abc
(5) 10 mg L^{-1} GA_3 × 3 60%	78.0 bcd	0.3 a	5.5 abc	23.0 ab	18.0 c	17.3 abc	10.4 a	2.5 cd	0.9 bcd	45.7 cd
(6) 10 mg L^{-1} GA_3 × 3 90%	82.5 abcd	0.2 a	4.2 cd	23.3 ab	22.2 ab	16.8 abc	11.7 a	3.5 bcd	0.7 cd	50.7 abc
(7) 15 mg L^{-1} GA_3 × 4	77.4 bcd	0.3 a	4.8 bcd	20.1 b	20.5 bc	16.9 abc	10.6 a	3.6 bc	0.6 cd	48.0 bcd
(8) 15 mg L^{-1} GA_3 × 4 (year 1 only)	85.2 ab	0.3 a	5.7 abc	23.9 ab	22.8 ab	19.4 a	10.1 a	2.3 cd	0.7 cd	52.3 ab
(9) 25 mg L^{-1} GA_3 × 4	78.3 bcd	0.2 a	5.9 ab	22.0 b	20.1 bc	16.5 abcd	10.3 a	2.9 cd	0.4 d	46.9 bcd
(10) 25 mg L^{-1} GA_3 × 4 (year 1 only)	85.4 ab	0.4 a	4.1 cd	23.2 ab	25.9 a	19.2 ab	10.2 a	2.1 d	0.3 d	55.3 a
(11) 15 mg L^{-1} GA_3 × 2	83.4 abcd	0.2 a	4.6 bcd	23.4 ab	22.9 ab	17.4 abc	11.2 a	2.9 cd	0.9 cd	51.4 abc
(12) 15 mg L^{-1} GA_3 × 2 (year 1 only)	82.4 abcd	0.3 a	4.7 bcd	23.7 ab	21.1 bc	16.1 bcd	11.9 a	3.3 bcd	1.3 abc	49.1 abc
(13) Water	74.8 d	0.2 a	4.7 bcd	20.8 b	19.7 bc	12.3 e	9.9 a	6.1 a	1.8 a	41.9 d
(14) Control	85.8 ab	0.4 a	7.0 a	23.3 ab	21.4 bc	15.3 cde	11.5 a	4.7 ab	1.8 a	48.3 bcd
Year										
Year 1	74.9 b	0.1 b	0.7 b	4.1 b	12.9 b	27.1 a	21.7 a	6.6 a	1.7 a	61.7 a
Year 2	88.2 a	0.5 a	9.2 a	40.7 a	30.3 a	6.4 b	0.7 b	0.3 b	0.2 b	37.4 b
P-value										
Treatment (*T*)	0.0202	0.5223	0.0048	0.0785	0.0764	0.0027	0.5784	<0.0001	<0.0001	0.0115
Year (*Y*)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
$T \times Y$	<0.0001	0.7264	0.0154	0.0197	0.0013	0.0034	0.7023	<0.0001	0.0119	<0.0001

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

fruit set, this area of Spain has a milder climate on average than the San Joaquin Valley of California. Thus, it was anticipated that higher concentrations and/or more frequent applications of GA_3 would be necessary to set commercially viable crops of 'Nules' Clementine mandarin on an annual basis in California than are typically required in Spain. In Spain, GA_3 is usually applied at 5–10 mg L^{-1} during 90–100% petal fall to increase fruit retention and yield (Del Rivero et al., 1969; El-Otmani et al., 2000; Fornes et al., 1992). In Morocco, which also has higher temperatures during the fruit set period of Clementine mandarin cultivars than Spain, GA_3 applications are initiated earlier (full bloom) and continued through petal fall at higher concentrations, 10–20 mg L^{-1} (El-Otmani et al., 1992). During the two years of the study presented here, flower abscission reached its maximum at 10 days after 75% petal fall (26 May) in the off-crop year and at 75% petal fall (22 May) in the on-crop year. Thus, applications at 60% and 90% full bloom were too early to be effective. The major period of fruit abscission was between 16 and 28 June in the off-crop year and 15 and 29 June in the on-crop year. No GA_3 applications were made during this period in the present study. GA_3 applications that target this period should be tested. Air temperature reached 35 °C on 1 July and 26 June and 40 °C on 17 July and 25 July of the off- and on-crop years, respectively. In each case, no dramatic increase in flower or fruit abscission resulted. The results of this research reinforce the need for field testing the efficacy of a plant growth regulator strategy used successfully on a crop in one geographical area before implementing its use even on the same crop in a different growing area.

The results of this research provide strong evidence that the efficacy of GA_3 is crop load-dependent, with alternate bearing a critical factor in the yield response of 'Nules' Clementine mandarin to GA_3. In the off-crop year (548 fruit per untreated control tree), it was necessary to apply 15 or 25 mg L^{-1} GA_3 at 60% bloom, 90% bloom, 75% petal fall and 10 days after 75% petal fall to significantly increase the yield (as both kilograms and number of fruit per tree) of fruit of packing carton sizes medium (fruit transverse diameter 50.81–57.15 mm) ($P = 0.0005$), large (diameter 57.16–63.50 mm) ($P = 0.0001$), and jumbo (diameter 63.51–69.85 mm) ($P = 0.0002$) and the combined pool of commercially valuable fruit of packing carton sizes large + jumbo + mammoth (diameter 57.16–76.20 mm) ($P < 0.0001$) above that of untreated control trees, with no reduction in total kilograms of fruit per tree. In the off-crop year, these two treatments and three application of GA_3 at 15 mg L^{-1} starting at 90% open flowers increased the total number of fruit per tree. Thus, in the off-crop year, GA_3 effectively increased fruit set and fruit size despite the fact that no GA_3 treatment significantly reduced the total number of flowers or fruit that abscised. In the following on-crop year (1162 fruit per untreated control tree), it was better not to apply GA_3; no treatment increased total yield or fruit size and five of seven GA_3 treatments tested significantly reduced total yield as both kilograms and number of fruit per tree. These results are in contrast to the positive effect that GA_3 applied at 90% open flowers had on flower retention or applied at 10 days after 75% petal fall had on fruit retention. Moreover, yield reductions caused by GA_3 treatments did not cause a concomitant increase in yield of commercially valuable fruit compared to untreated control trees. Thus, in the on-crop year, the GA_3 treatments tested did not increase fruit set or fruit size.

The dramatically different responses to GA_3 applied in the off- and on-crop years are likely due to the significant differences in the number of flowers produced at bloom in years 1 and 2. The large number of flowers in the on bloom resulted in a large number fruit being set, with or without GA_3, that saturated the carrying capacity of the trees, consistent with previous findings demonstrating that yield is dependent largely on the initial number of flowers at bloom (Hanke et al., 2007). Thus, few sites were left on the trees in the on-crop year to set additional fruit and few reserves were left to support the retention and growth of the fruit initially set in response to GA_3 application, rendering even multiple applications at high concentrations ineffective. This interpretation is supported by the facts that the on-crop trees had dramatically greater flower and fruit abscission rates and produced 72% more fruit as number of fruit per tree, but only 18% more fruit as kilograms per tree

Table 9
Effect of gibberellic acid (GA_3) treatments applied to 'Nules' Clementine mandarin trees on total yield and fruit size distribution (based on transverse diameter) as number of fruit per tree averaged across the off- and on-crop years in a commercial orchard in Grapevine, CA.

Treatments	Total	Fruit packing carton size[z] (fruit no./tree)								
		Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal	Super colossal	Large + jumbo + mammoth
Treatment										
(1) 5 mg L^{-1} GA_3 × 4	771 cd[y]	6 a	62 d	248 b	215 bc	140 abc	80 a	20 bc	2 d	435 abc
(2) 5 mg L^{-1} GA_3 × 4 (year 1 only)	905 a	6 a	106 ab	323 a	218 abc	140 abc	86 a	20 bc	7 ab	443 ab
(3) 10 mg L^{-1} GA_3 × 4	761 d	13 a	81 bcd	250 b	213 bc	109 de	76 a	16 cd	3 cd	398 bcd
(4) 10 mg L^{-1} GA_3 × 4 (year 1 only)	832 abcd	6 a	87 bcd	263 b	232 ab	142 abc	72 a	26 ab	4 cd	446 ab
(5) 10 mg L^{-1} GA_3 × 3 60%	794 bcd	7 a	99 abc	284 ab	179 c	139 abc	68 a	14 cd	4 bcd	386 cd
(6) 10 mg L^{-1} GA_3 × 3 90%	821 abcd	4 a	75 cd	289 ab	221 abc	135 abc	76 a	19 bcd	3 cd	432 abc
(7) 15 mg L^{-1} GA_3 × 4	773 cd	7 a	86 bcd	249 b	204 bc	135 abc	69 a	20 bc	3 cd	409 bcd
(8) 15 mg L^{-1} GA_3 × 4 (year 1 only)	869 ab	7 a	101 abc	296 ab	227 ab	155 a	66 a	13 cd	3 cd	448 ab
(9) 25 mg L^{-1} GA_3 × 4	800 bcd	5 a	104 ab	273 b	200 bc	132 abcd	67 a	16 cd	2 d	399 bcd
(10) 25 mg L^{-1} GA_3 × 4 (year 1 only)	861 abc	9 a	73 cd	288 ab	258 a	154 ab	67 a	11 d	1 d	478 a
(11) 15 mg L^{-1} GA_3 × 2	836 abcd	6 a	81 bcd	289 ab	228 ab	139 abc	73 a	16 cd	4 cd	439 abc
(12) 15 mg L^{-1} GA_3 × 2 (year 1 only)	824 abcd	7 a	84 bcd	294 ab	210 bc	129 bcd	78 a	18 bcd	6 abc	416 bc
(13) Water	745 d	5 a	84 bcd	256 b	195 bc	98 e	65 a	34 a	8 a	358 d
(14) Control	865 abc	8 a	125 a	287 ab	213 bc	123 cde	75 a	26 ab	8 a	411 bcd
Year										
Year 1	601 b	3 b	13 b	54 b	131 b	216 a	141 a	37 a	7 a	488 a
Year 2	1034 a	11 a	165 a	500 a	299 a	52 b	5 b	2 b	1 b	356 b
P-value										
Treatment (*T*)	0.0344	0.4881	0.0048	0.0830	0.0757	0.0028	0.5822	<0.0001	<0.0001	0.0085
Year (*Y*)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
T × *Y*	<0.0001	0.7142	0.0154	0.0177	0.0013	0.0036	0.7031	<0.0001	0.0075	<0.0001

[y] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.

[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

Table 10
Effect of gibberellic acid (GA_3) treatments on the 2-year cumulative crop value (US$/tree) of 'Nules' Clementine mandarin trees in a commercial orchard in Grapevine, CA. Fruit were packed by number (based on size). Fruit count per box was: small, 40; medium; 34, large, 26; jumbo, 19.5; and mammoth 15.[z] Average US dollars per box (retail) of fruit of each size category was: tiny, $0; small, $3.50; medium, $3.75; large, $4.10; jumbo, $4.10; mammoth, $4.10; colossal, $0; and super colossal, $0.[y]

Treatments	Crop value (US$/tree)									
	Total	Tiny	Small	Medium	Large	Jumbo	Mammoth	Colossal)	Super colossal	Large + jumbo + mammoth
(1) 5 mg L^{-1} GA_3 × 4	207.01 bcd[x]	0.00 a	10.79 e	50.98 bc	57.94 bc	50.11 abc	37.20 a	0.00 a	0.00 a	145.25 abc
(2) 5 mg L^{-1} GA_3 × 4 (year 1 only)	233.71 a	0.00 a	18.55 ab	66.40 a	58.71 abc	50.08 abc	39.97 a	0.00 a	0.00 a	148.76 ab
(3) 10 mg L^{-1} GA_3 × 4	197.66 de	0.00 a	14.25 bcde	51.40 bc	57.27 bc	39.16 de	35.58 a	0.00 a	0.00 a	132.01 bcd
(4) 10 mg L^{-1} GA_3 × 4 (year 1 only)	216.70 abcd	0.00 a	15.28 bcde	54.23 bc	62.50 ab	50.94 abc	33.75 a	0.00 a	0.00 a	147.19 abc
(5) 10 mg L^{-1} GA_3 × 3 60%	205.51 bcde	0.00 a	17.31 abcd	58.46 abc	48.24 c	49.76 abc	31.75 a	0.00 a	0.00 a	129.75 cd
(6) 10 mg L^{-1} GA_3 × 3 90%	215.94 abcd	0.00 a	13.12 de	59.45 abc	59.39 abc	48.34 abc	35.65 a	0.00 a	0.00 a	143.38 abc
(7) 15 mg L^{-1} GA_3 × 4	202.16 cde	0.00 a	15.03 bcde	51.21 bc	55.04 bc	48.55 abc	32.33 a	0.00 a	0.00 a	135.92 bcd
(8) 15 mg L^{-1} GA_3 × 4 (year 1 only)	226.29 abc	0.00 a	17.72 abcd	60.96 ab	61.07 ab	55.80 a	30.73 a	0.00 a	0.00 a	147.60 abc
(9) 25 mg L^{-1} GA_3 × 4	207.18 bcd	0.00 a	18.27 abc	56.26 bc	53.94 bc	47.34 abcd	31.39 a	0.00 a	0.00 a	132.66 bcd
(10) 25 mg L^{-1} GA_3 × 4 (year 1 only)	227.75 ab	0.00 a	12.81 de	59.25 abc	69.35 a	55.29 ab	31.04 a	0.00 a	0.00 a	155.68 a
(11) 15 mg L^{-1} GA_3 × 2	218.93 abcd	0.00 a	14.24 bcde	59.56 abc	61.31 ab	49.91 abc	33.91 a	0.00 a	0.00 a	145.13 abc
(12) 15 mg L^{-1} GA_3 × 2 (year 1 only)	214.03 abcd	0.00 a	14.68 bcde	60.43 abc	56.45 bc	46.22 bcd	36.25 a	0.00 a	0.00 a	138.92 abc
(13) Water	181.96 e	0.00 a	13.31 cde	50.54 c	51.82 bc	35.13 e	31.16 a	0.00 a	0.00 a	118.11 d
(14) Control	213.84 abcd	0.00 a	20.34 a	56.36 abc	55.80 bc	45.08 cd	36.26 a	0.00 a	0.00 a	137.14 bc
P-value	0.0145	–	0.0114	0.0733	0.0996	0.0023	0.5980	–	–	0.0191

[x] Mean values within a vertical column followed by different letters are significantly different at $P = 0.05$ based on Fisher's Protected LSD Test.
[y] Dollar values are based on the 3-year average FOB prices (free onboard price; price for the finished product, including the cost of loading onto the means of transport, but excludes the cost of transportation to the buyer) supplied by a large grower, packer, and shipper of mandarins in the Central San Joaquin Valley, CA.
[z] Fruit size categories based on fruit transverse diameters (mm): tiny (<44.45), small (44.45–50.80), medium (50.81–57.15), large (57.16–63.50), jumbo (63.51–69.85), mammoth (69.86–76.20), colossal (76.21–82.55), and super colossal (82.56–101.59).

compared with off-crop trees. In the off-crop year, the number of flowers, though lower than in the on-crop year, was sufficiently large that increasing fruit set had a positive effect on yield but still left adequate resources to support fruit growth. Thus, in the off-crop year, GA_3 increased both fruit number, fruit weight and fruit size (transverse diameter) in a dose-dependent manner.

Surprisingly, there was no cumulative benefit from using any of the GA_3 treatments tested only in the off-crop year and not in the following on-crop year compared to applying the treatment in both years. Application of 5 mg L^{-1} GA_3 at 60% bloom, 90% bloom, 75% petal fall and 10 days after 75% petal fall in the off-crop year and no GA_3 in the on-crop year resulted in a 2-year cumulative cash value for the crop that was significantly greater than five of seven GA_3 treatments, but not significantly different from control trees that never received GA_3.

The negative effect of GA_3 applied during the setting of an on-crop was independent of whether GA_3 was applied the year before or not. In a second 'Nules' Clementine mandarin orchard near Selma, CA (36.77°N), GA_3 treatments used in the present study were applied initially during the on-crop year (1189 fruit per untreated control tree). No GA_3 treatment increased total yield or yield of commercially valuable fruit above that of the untreated control either as kilograms or number of fruit per tree (Chao and Lovatt, 2006). Several GA_3 treatments significantly increased the yield of tiny and small size fruit (diameter < 44.45–50.80 mm) at the expense of commercially valuable large size fruit of packing carton sizes large, jumbo, and mammoth and the combined pool of fruit of large + jumbo + mammoth (diameter 57.16–76.20 mm) both as kilograms and number of fruit per tree. The overall effect was a significant reduction in total kilograms per tree but not in number of fruit per tree, and a loss in income per tree compared to the untreated control trees, confirming the results obtained in the present study. Whereas the interaction between GA_3 and crop load of Clementine mandarin, in this case 'Nules', was identified in California, it is likely that this interaction occurs in other geographical areas when orchards are alternate bearing.

The results of this research provided strong evidence that crop load influences the results obtained with foliar application of GA_3, dictating that the concentration and number of applications be adjusted for the light or heavy crop of an alternate bearing orchard. Over-use of GA_3, especially in a heavy on-crop year, had negative consequences on yield and pack out (fruit size distribution) of 'Nules' Clementine mandarin that negatively impacted the value of the crop. In the worst case, GA_3 applied four times at 10 mg L^{-1} in both the off- and on-crop years of the experiment reduced the value of the crop by $16 per tree compared with the untreated control. At planting densities from 412 to 1074 trees per hectare, such losses would be significant. When using GA_3 with the objective to increase fruit set or fruit size of mandarins, it is clear that crop load should be taken into consideration for determining the optimal application time and concentration. Thus, further research is required to develop reliably effective strategies for using GA_3, and likely other plant growth regulators, that take crop load into account to achieve a greater total yield and yield of commercially valuable large size fruit than untreated control trees to increase net dollar return to the growers of 'Nules' Clementine and other alternate bearing mandarin cultivars.

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