Use of Foliar Fertilization to Offset Effects on Navel Orange Yield Due to Reduced Water and Fertilizer Applied by Partial Root Zone Drying Versus Conventional Irrigation

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Abstract

With increasing costs, reduced availability of quality irrigation water and the possibility that California growers might have to produce citrus with 30% less water, our research goal was to meet the challenge of California's water shortage crisis by demonstrating that yield of commercially valuable large navel orange fruit can be sustained despite irrigating citrus trees with 25% or 50% less water. The efficacy of using partial root zone drying (PRD) to reduce the amount of water and irrigation-applied fertilizer used to produce navel oranges, combined with foliar fertilization to sustain the yield of commercially valuable large-size fruit and, thus, increase grower net income was tested. Specific objectives were: (1) to reduce annual water use in a commercial navel orange orchard by alternately wetting and drying the root zone on two sides of the tree (PRD) at irrigation rates 25% and 50% less than the well-watered control under conventional irrigation (CI); (2) to compare PRD treatments with CI at 25% and 50% less water (CI-RR) than the well-watered control; (3) to determine the effect of supplementing PRD and CI-RR treatments with foliar fertilization (especially N and K to ensure adequate nutrition to sustain yields of large-size fruit) on yield, fruit size and quality compared to well-watered control trees receiving irrigation-applied fertilizer; and (4) to provide a cost:benefit analysis. Even modest reductions of only 20% in the amount of irrigation water applied during the critical period of exponential fruit growth reduced the yield of commercially valuable fruit (packing carton sizes 88, 72, and 56) and grower income. Neither foliar-applied fertilizers, nor irrigation-applied cytokinin (6-benzyladenine) mitigated the effects of reduced irrigation rates on yield or fruit size. Savings in annual water use at reduced irrigation rates did not offset the revenue losses resulting from lower yields and smaller fruit size caused by reduced irrigation rates.

INTRODUCTION

For California citrus growers, the cost of irrigation water is a major expense associated with citrus production. Moreover, the future availability of water necessary for crop production is in question; growers may have to produce their crops with 30% less water (http://www.latimes.com/news/local/la-me-water21nov21,1,1338299.story, http://www.fresnobee.com/business/story/222120.html). Micro-jet and drip irrigation systems have contributed significantly to increasing water-use efficiency and reducing the amount of water used annually in citrus orchards. Citrus orchards in southern California and orchards ≤ 10 years old in the San Joaquin Valley, where the greatest amount of citrus is grown in California, predominantly use micro-jets. Regulated deficit irrigation (RDI) and partial root zone drying (PRD) were developed to improve water-use efficiency further in perennial fruit tree crops in order to reduce water use and expense even further (Kriedemann and Goodwin, 2003). Both methods limit the vigor of vegetative shoot growth in favor of crop development with the goal that neither the current nor return yield is negatively affected. Reduced flushing of vegetative shoots is considered an important factor in controlling Asian Citrus Psyllid populations and the spread of Huanglongbing in citrus. With RDI, water deficit is applied in an orchard in a carefully controlled manner during a specific period in the phenology of the tree. When using RDI, timing is critical. RDI was shown to have limited utility in navel orange production in California (Goldhamer, 2003). In contrast, PRD is the practice of alternately wetting and drying the root zone on two sides of the tree. With PRD, timing is flexible, and PRD is employed year-round. PRD has been tested in commercial sweet orange production in Australia. In a 4-year field study, 40% less water was applied by PRD than the fully irrigated control, resulting in significant savings in water use (32%-43% less than the district average for citrus orchards) with no significant effect on fruit number or size (Loveys et al., 1999). Our research objective was to meet the challenge of California's water shortage crisis by demonstrating that yield of commercially valuable large-size navel orange fruit can be sustained despite irrigating citrus trees with 25% or 50% less water. To meet this objective, we tested the efficacy of using PRD to reduce the amount of water and soil (irrigation-applied) fertilizer used in citrus production combined with foliar fertilization, with and without irrigation-applied cytokinin, to sustain the yield of commercially valuable large fruit (Boman, 2002; Lovatt, 1999) and, thus, increase grower net profit. This research was not only timely; it might prove critical to the sustainability of California's citrus industry.

MATERIALS AND METHODS

The design was a randomized complete block with five irrigation treatments and five replications of each treatment in a commercial orchard of 45-year-old *Citrus sinensis* 'Washington' navel orange trees on 'Troyer' citrange rootstock (*C. sinensis* × *P. trifoliata*) at the University of California-Riverside Citrus Research Center and Agricultural Experiment Station (33°N, 117°W). Each treatment was applied to three parallel rows and the internal three trees of five consecutive trees in the middle row of the three rows were used for data collection. Thus, there were two buffer rows between data rows and two buffer trees within a row between data trees for different treatments. Irrigation treatments were: (1) well-watered control (based on evaporative demand), conventional irrigation (CI); (2) 25% PRD – 25% less water than well-watered control; (3) 50% PRD – 50% less water than well-watered control; (4) 25% CI-RR – 25% less water than well-watered control by conventional irrigation at the reduced rate (RR); and (5) 50% CI-RR – 50% less water than well-watered control. Trees in CI treatments had an emitter on each side of the five trees within the row so that both sides of the tree were watered at the same time; trees in PRD treatments had an emitter on each side of the five trees within the row, which alternated in delivery of water to one side of the tree and then the other. One Bermad flow meter was used per treatment to control the rate of irrigation. Pressure regulators were used to maintain pressure to ensure an accurate rate of delivery. The emitters were Bowsmith Fan Jets, which delivered 37.85 liters per hour. Irrigation amounts were based on California Irrigation Management Information System (CIMIS) evapotranspiration (ET) calculations using current and historic weather data to project the irrigation needs of the well-watered control trees for the up-coming 3 or 4 days to the next irrigation. This approach was an improvement over simply replacing the water the trees used the past 3 or 4 days during the warmest months of the year, an approach that only by coincidence met the actual water needs of the trees. Soil moisture content was measured at depths of 30 and 60 cm on each side of a PRD data tree in each treatment and one in the middle for each CI data tree in each treatment for five replications using Watermark Soil Moisture meters. All treatments were irrigated when soil moisture content was –30 cb at a depth of 30 cm for the well-watered control trees; thus, trees in other treatments might have experienced slightly lower soil moisture content prior to irrigation. Three to 4 days was the average length of time for the soil to reach –30 cb during the warmest months of the year.

Trees in PRD and CI-RR treatments received reduced soil (irrigation-applied) fertilizer proportional to reduced irrigation amount and foliar fertilizer as urea-N (56 kg low biuret urea/ha, 46% N, 0.25% biuret) in mid-January to increase floral intensity

(Lovatt, 1999), potassium nitrate (28 kg KNO_3/ha) in February and at 75% petal fall (end of April-early May) to increase fruit size (Bowman, 2002), and urea-N (56 kg urea/ha) at maximum peel thickness (early to mid-July) to increase fruit size (Lovatt, 1999). Fertilizers were applied with a 2758 KPa handgun sprayer in 1869 L of water per ha, adjusted to pH 5.5. In September, 40 spring flush leaves from non-fruiting terminals were collected from around each data tree at a height of 1.5 m. Samples were immediately stored on ice, taken to the Laboratory, washed thoroughly, oven-dried at 60ºC, ground to pass through a 40-mesh screen and sent to the Analytical Laboratory at UC-Davis for analysis of N, P, K, S, Ca, Mg, Fe, Mn, B, Zn, and Cu by atomic absorption spectrometry and inductively coupled plasma atomic emission spectrometry.

At harvest in November, total fruit number and fruit size distribution (pack out) per tree were determined. A sub-sample of 10 fruit per tree was used to determine fruit mass, juice mass, percent juice (juice fresh mass/fruit fresh mass), juice volume, total soluble solids (TSS), percent acid and TSS to acid ratio (TSS:acid) by the UC Lindcove Analytical Laboratory. Fruit were mechanically juiced with a commercial juice extractor; TSS concentration was determined using a refractometer and percent acidity was determined by titration to pH 8.2 ± 0.1 with 1M NaOH. Crop value was calculated, using the following prices by packing carton size: 48-US$ 20, 56-US$20, 72-US$16, 88-US$13, 113-US$11, 138-US$9, and < 138-US$0 (Redlands-Foothill Packing House), and used to estimate the cost: benefit. Fisher's Protected LSD Test at $P \leq 0.05$ was used to test for treatment effects. Analyses were performed using the SAS statistical program (SAS Institute, Cary, N.C.)

RESULTS

The liters of water applied per treatment per quarter from January to harvest in November for Years 1 and 2 are given in Table 1. Note that January to March is the period of inflorescence development and bud break; April to June is the period of flower opening and fruit set; July to September is the period of exponential fruit growth; and October to harvest in November is the period of fruit maturation.

Year 1

From 1 January through harvest on 30 November, trees in the CI-RR-25% and PRD-25% treatments received only 16% less water than the well-watered control trees (Table 1). The greatest reduction in irrigation water applied to CI-RR-25% and PRD-25% trees was 22% from July through harvest. This level of stress and its timing had no effect on the total number of fruit per tree, but significantly reduced the number of commercially marketable fruit (packing carton sizes 56-138, fruit diameters 8.8-6.0 cm), indicating that the effect of 22% less water from July to harvest was on fruit growth not fruit retention (Table 2). These data also confirmed that the 10% reduction in irrigation from January through June for the trees in these treatments had no effect on fruit set. From January through March, trees in the CI-RR-50% and PRD-50% treatments received just 20% less water than the well-watered control. From April through June, the CI-RR-50% and PRD-50% trees received 27% and 20% less water than the well-watered control trees, respectively. From July through harvest, CI-RR-50% and PRD-50% trees received 49% and 44% less water than the well-watered control trees, respectively. For these trees, both the total number of fruit and number of commercially marketable fruit (packing carton sizes 56-138) per tree were significantly less than the well-watered control trees (Table 2). Reducing the irrigation rate 44% to 49% reduced the total number of fruit and number fruit of packing carton sizes 113 and 138 per tree compared to trees receiving 22% (CI-RR-25% and PRD-25%) less water than the well-watered control, but did not further reduce the yield of large size fruit (packing carton sizes 56, 88 and 72), demonstrating that reducing irrigation rate 44% to 49% impacted fruit retention as well as fruit size.

As irrigation rate decreased, juice mass (g) and juice volume per fruit decreased below the values for the well-watered control (P <0.0001) (Data not shown).

Interestingly, all fruit due to the lower juice volume had higher TSS and percent acidity than fruit from the well-watered control trees ($P < 0.0001$). Since both TSS and acidity changed in parallel, there was no effect of irrigation rate on TSS: acid. Fruit were legally mature despite the low TSS: acid (8.4-9.2; legal maturity is 8.0) at harvest in November.

Foliar-applied fertilizers did not offset the negative effects of reduced irrigation, which significantly reduced the number of fruit in all commercially marketable fruit size categories, especially fruit of packing carton sizes 56, 88 and 72. This dramatically reduced the value of the crop and grower total income, even when the irrigation rate was reduced only 22% (CI-RR-25% and PRD-25%) from July to harvest (Table 2).

Year 2

From January through March, CI-RR-25%, PRD-25%, CI-RR-50% and PRD-50% trees received 24%, 21.5%, 48%, and 45% less water than the well-watered control trees (Table 1). Given the failure of the foliar fertilizer treatments to mitigate the effects of even a 22% reduction in irrigation (CI-RR-25% and PRD-25%) on fruit size in Year 1, in Year 2 the efficacy of applying the cytokinin 6-BA in combination with foliar-applied fertilizer was tested. All trees in reduced irrigation treatments received 25% less water than well-watered control trees starting in April. From April through June, trees in the CI-RR 25%, CI-RR-25% + 6-BA, PRD-25% and PRD-25% + 6-BA treatments received 26%, 28%, 22% and 3.5% (faulty Bermad flow meter) less water than the well-watered control trees, respectively (Table 1). From July through September, CI-RR-25%, CI-RR-25% + 6-BA, PRD-25% and PRD-25% + 6-BA trees received 26%, 27%, 22% and 19% less water than the well-watered control trees, respectively (Table 1). On-tree fruit diameter measured on 1 August indicated no significant differences in fruit size among treatments (Data not shown). 6-Benzyladenine (6-BA) was applied with the two irrigation events per week from 1 August through 31 October, for a total of 4 g 6-BA per tree. From 1 October through harvest 8 November, CI-RR-25%, CI-RR-25% + 6-BA, PRD-25% and PRD-25% + 6-BA trees received 22%, 22%, 23% and 19% less water than the well-watered control trees, respectively, with the differences for the entire year 25%, 30%, 22% and 17% less water than the well-watered control trees, respectively (Table 1). These differences in irrigation rates had no significant effect on the total number of fruit per tree compared to well-watered control trees (Table 3). Trees treated with 6-BA tended to have more fruit per tree compared to trees in the same irrigation treatment not receiving 6-BA. However, all trees in the reduced irrigation treatments (with or without 6-BA) yielded significantly fewer commercially valuable large fruit (packing carton sizes 56, 88 and 72) and significantly more fruit smaller than packing carton size 138 compared to well-watered control trees (Table 3). However, unlike Year 1, the reduced irrigation treatments did not cause a significant reduction in the yield of packing carton sizes 113 or 138. Consistent with Year 1, juice mass and juice volume deceased below that of the well-watered control for trees in all reduced irrigation treatments except trees in the PRD-25% + 6-BA treatment ($P = 0.002$ and $P = 0.003$, respectively) (Data not shown). In Year 2, there was also an increase in TSS and percent acidity for trees in all reduced irrigation treatments except trees in the CI-RR-25% + 6-BA treatment. Since both TSS and acidity changed in parallel, there was no effect of irrigation rate on TSS: acid. All fruit were legally mature (TSS: acid 8.7-9.3).

All trees receiving foliar-applied fertilizer had leaf concentrations of N, P, K, Ca, S, Mg, B, Mn, Zn, Fe, and Cu equal to or greater than the well-watered control trees, but increased nutrient status did not compensate for the negative effect of reduced irrigation on fruit size, crop value and grower income (Tables 2 and 3). Supplying trees receiving 25% less water than the well-watered control trees by either CI-RR or PRD with a total of 4 g of the cytokinin 6-benzyladenine per tree from 1 August to 31 October in Year 2 also did not offset the negative effect of water deficit on fruit growth, yield of commercially marketable fruit, and crop value.

DISCUSSION

One of the more dramatic results of this research was the documentation of how extremely sensitive 'Washington' navel orange fruit growth is to small differences in irrigation rate during the period of exponential fruit growth. In Year 1, differences of only 20% to 22% from July to harvest (30 November) impacted fruit size, reducing the yield of fruit in all marketable size categories, especially the larger, more commercially valuable fruit of packing carton sizes 56, 88 and 72. Further reductions in irrigation rate exacerbated these problems and reduced the total number of fruit per tree. In Year 2, trees in the CI-RR-50% + 6-BA and PRD-50% + 6-BA treatments received 48% and 45% less water from January through March (prior to 6-BA application) with no negative effect on fruit retention or fruit diameter. The total number of fruit per tree for trees in these treatments was equal to the well-watered control trees. Trees in the PRD-25% + 6-BA treatment received only 3.5% and 19% less water than well-watered control trees (due to a faulty flow meter) from April through June and July through September, respectively, whereas trees in the CI-RR-25% + 6-BA treatment received, 28% and 27% less water than the control during these periods, respectively. These modest reductions in irrigation rate had no effect on total fruit number per tree, but dramatically reduced the number of commercially valuable large fruit (packing carton sizes 56, 88 and 72). Taken together the results of our research indicate that a 20%, or even 40%, reduction in irrigation rate (80% or 60% ET) can be tolerated by trees from January through March and a 20% reduction can be tolerated from April to June, but reducing irrigation 20% or less during the period of exponential fruit growth (July-Sept) had a negative effect on the yield of commercially valuable large fruit (packing carton sizes 56, 88 and 72) and on juice mass and volume. Yield reductions in these fruit size categories significantly reduced crop value and grower income. Savings in the cost of water achieved by reducing irrigation were negated by lost revenue due to the lower yield of commercially valuable large fruit. Treating trees in reduced irrigation treatments with foliar-applied fertilizer and irrigation-applied 6-BA did not mitigate the negative effect of water deficit on fruit size and crop value and added to the cost of fruit production, further reducing grower income. From these data it is clear that attempting to reduce production costs by reducing irrigation rate requires close monitoring and great care in irrigation management.

CONCLUSIONS

The California citrus industry produces "picture perfect" navel orange fruit for the fresh fruit market on 50,339 irrigated ha. The cost of irrigation water is a major expense associated with citrus production. The results of our research provide clear evidence of the negative consequences of reducing irrigation rates for navel orange production below 100% ET on yield, fruit size, quality and grower income. Even modest reductions of only 20% imposed during the critical period of exponential fruit growth reduced the yield of commercially valuable fruit (packing carton sizes 56, 88 and 72) and grower income. In addition, results of our earlier research documented that reducing irrigation more than 25% below 100% ET during flowering and fruit set had a negative effect on fruit set as total number of fruit per tree and on fruit growth, significantly reducing the yield of commercially valuable size fruit, crop value and grower income. In this and the prior experiment, there were no significant differences between reduced conventional irrigation and partial root zone drying. The results of our research indicate that savings in the amount of irrigation water applied could potentially be achieved from January through March, when trees can tolerate a 20%, or even 40%, reduction in irrigation rate (80% or 60% ET). The results illustrate the significant financial consequences to which growers could be subject if, at some point, they were required to produce their crops with less water. The data from this research should be helpful to citrus growers for building the case that a severe restriction should not be imposed and for negotiating critical water allocations.

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Tables

Table 1. Liters of water applied per treatment per quarter from 1 January to harvest 30 November Year 1 and 1 January to harvest 8 November Year 2.

Month	Year 1					Year 2				
	Control	CI-RR 25%	CI-RR 50%	PRD 25%	PRD 50%	Control	CI-RR 25%	CI-RR 25% + 6-BA	PRD 25%	PRD 25% + 6-BA
	Water applied (liters)									
Jan-Mar	64,502	56,955	51,150	60,503	51,253	114,846	87,168	59,697	90,154	63,050
% control	100.0	88.3	79.3	93.8	79.5	100.0	75.9	52.0	78.5	54.9
Apr-Jun	219,699	201,463	159,941	197,949	175,759	278,220	206,717	200,596	216,177	268,482
% control	100.0	91.7	72.8	90.1	80.0	100.0	74.3	72.1	77.7	96.5
Jul-Sep	277,008	215,512	140,443	219,390	155,124	275,835	204,394	200,532	214,048	224,530
% control	100.0	77.8	50.7	79.2	56.2	100.0	74.1	72.7	77.6	81.4
Oct to harvest	64,880	51,190	33,218	51,169	34,841	68,817	53,540	53,540	53,333	55,811
% control	100.0	78.9	51.2	80.1	53.7	100.0	77.8	77.8	77.5	81.8
Total	626,089	525,915	386,923	530,923	420,106	737,718	551,813	514,189	573,945	612,306
% control	100.0	84.0	61.8	84.8	67.1	100.0	74.8	69.7	77.8	83.0

Table 2. Year 1 – Effect of reducing irrigation 25% or 50% by conventional irrigation (CI-RR) or partial root zone drying (PRD) and applying foliar fertilizer from 1 January through harvest 30 November on yield and fruit size (number of fruit/tree) of 'Washington navel orange trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside (UCR).

Treatment	Crop value US$ 237 trees/ha	Total	Packing carton size based on transverse diameter (cm)						
			56 (8.1-8.8)	72 (7.5-8.0)	88 (6.9-7.4)	113 (6.4-6.8)	138 (6.0-6.3)	<138 (<6.0)	56+72+88 (6.9-8.8)
		No. of fruit per tree							
Control	12,815.00 a[z]	2335 a	10 a	26 a	192 a	497 a	809 a	799 b	228 a
CI-RR-25%	4,377.00 b	2624 a	0 b	3 b	18 b	103 bc	545 b	1955 a	22 b
CI-RR-50%	490.00 c	1805 b	0 b	0 b	0 b	7 c	74 c	1724 a	0 b
PRD-25%	4,475.00 b	2328 a	0 b	2 b	32 b	163 b	434 b	1697 a	34 b
PRD-50%	1,916.00 bc	1939 b	0 b	2 b	13 b	46 bc	221 c	1656 a	15 b
P-value	<0.0001	<0.0001	0.0811	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

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

Table 3. Year 2 – Effect of reducing irrigation 25% by conventional irrigation (CI-RR) or partial root zone drying (PRD) and applying foliar fertilizer from 1 January through harvest 8 November, with and without irrigation-applied 6-benzyladenine[z] (6-BA) from 1 August to harvest, on yield and fruit size (number of fruit/tree) of 'Washington' navel orange trees located at the Citrus Research Center and Agricultural Experiment Station, UCR.

Treatment	Crop Value US$ 237 trees/ha	Total	Packing carton size based on transverse diameter (cm)						
			56 (8.1-8.8)	72 (7.5-8.0)	88 (6.9-7.4)	113 (6.4-6.8)	138 (6.0-6.3)	<138 (<6.0)	56+72+88 (6.9-8.8)
		No. of fruit per tree							
Control	15,520.00 a[y]	1662 a	51 a	216 a	198 a	440 a	371 a	382 c	466 a
CI-RR-25%	10,385.00 bc	1785 a	30 ab	65 b	98 bc	351 a	459 a	775 ab	193 bc
CI-RR-25%+ 6-BA	8,180.00 c	2019 a	10 b	37 b	56 c	269 a	570 a	1077 a	102 c
PRD-25%	8,865.00 bc	1874 a	5 b	48 b	96 bc	327 a	503 a	895 ab	149 bc
PRD-25% + 6-BA	11,628.00 b	1914 a	7 b	90 b	155 ab	447 a	488 a	727 b	253 b
P-value	0.0003	0.3683	0.0128	<0.0001	0.0006	0.1555	0.2878	0.0004	<0.0001

[z] 6-Benzyladenine (6-BA) was not applied until 1 August; CI-RR-25% + 6-BA and PRD-25% + 6-BA received 48% and 45% less water than the well-watered control trees from January through March, respectively.
[y] Values in a vertical column followed by different letters are significantly different at *P*-value specified by Fisher's Protected LSD Test.