Effects of Applying Less Water by Partial Root Zone Drying versus Conventional Irrigation on Navel Orange Yield

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Abstract

California produces "picture perfect" navel orange fruit for the fresh fruit market on 50,339 irrigated ha. Irrigation water is a major expense. Partial root zone drying (PRD), the practice of alternately irrigating and drying the root zone on each side of the tree, was developed for year-round use to reduce water use in vine and tree fruit production. Prior California research suggested that PRD increased nutrient-use efficiency and reduced *Phytophthora* root-rot. For grape, benefits obtained with reduced water use were the same for PRD and conventional irrigation (CI), raising the question of whether PRD was critical to achieving water savings and yield benefits in citrus production. Our research objective was to compare effects on total yield, fruit size and quality of reducing annual water use in a commercial navel orange orchard using PRD versus CI at 25% and 40% less water (CI-RR) than the well-watered control. In Year 1, control trees were irrigated when soil moisture reached -30 cb at 30 cm; PRD and CI-RR trees were watered when soil moisture reached -60 cb. All reduced irrigation treatments reduced yield and fruit size. In Year 2, the lowest irrigation rate was 50% less water than the well-watered control, but all trees were irrigated when control tree soil moisture reached -30 cb at 30 cm. All PRD and CI-RR treatments reduced total fruit number and number of commercially valuable fruit (diameter 6.9-8.8 cm) per tree, except CI-RR-25% trees, which produced more marketable small fruit than control trees. Grower income was markedly reduced by the loss of valuable large fruit when irrigation was reduced and was not offset by the value of water saved.

INTRODUCTION

Partial root zone drying (PRD), the practice of alternately wetting and drying the root zone on two sides of the tree, was developed to improve water-use efficiency in perennial vine and tree crops to further reduce water use and expense (Kriedemann and Goodwin, 2003). The method limits the vigor of vegetative shoot growth in favor of fruit development with the goal that neither the current nor return yield is negatively affected. With PRD, timing is flexible in relation to vine or tree phenology. Thus, PRD can be used year-round.

In a 4-year field study with commercial *Citrus sinensis* in Australia, 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, size or quality, with the exception that the ratio of solids to acid (TSS:acid) in the juice was lower than that of the control in the first year of the experiment (Loveys et al., 1999). Soil moisture content was a good indicator of when the dry side of the tree needed to be irrigated (Loveys et al., 1999; Mingo et al., 2003).

Successful implementation of PRD in citrus orchards in California would provide considerable financial savings to growers. PRD has been shown to have the added benefits of increasing nutrient-use efficiency by increasing root biomass, reducing root infection by *Phytophthora*, increasing fruit size and reducing puff in commercial citrus orchards in California (Lutz et al., 1988) and reducing crease of sweet orange fruit produced in Australia (Treeby et al., 2003). Whether conventional irrigation (CI) at equally reduced rates would provide these benefits to navel orange production is unknown.

Researchers in Australia reported significant internal movement of water from the irrigated side of the tree to the dry side of the tree in their experiment in a commercial orchard (Loveys et al., 1999). Taken together, the literature suggests that physiological changes occur in tree crops under PRD that either do not occur or do not occur to the same degree when they receive the same reduced rate of irrigation on both sides of the tree by CI. However, a recent study with *Vitis vinifera* challenges this interpretation by providing evidence that the benefits obtained by reduced water use were independent of whether irrigation was by PRD or CI (Gu et al., 2004). This raises the question of whether it is critical to alternate wet and dry sides of the tree to alter tree physiology and to save water, and whether the extra irrigation lines required for PRD are really necessary, or whether irrigation rate can simply be reduced with CI to achieve the same water savings and yield benefits in citrus production as PRD.

The research goal was to test the feasibility of using PRD as a means to reduce the amount of water used in citrus production in order to increase grower net income. The 2-year experiment tested the efficacy of PRD in navel orange production, determined its effects on total yield, fruit size, fruit quality, and water savings, and provided a cost: benefit analysis relative to well-watered control trees and trees receiving the same reduced irrigation rates by conventional irrigation (CI-RR).

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 40-year-old *Citrus sinensis* cv. 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. 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. 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. Irrigation volumes were based on the amount of water used by the control trees over prior 3 or 4 days, respectively, calculated using measurements available from the California Irrigation Management Information System (CIMIS) and the crop coefficient for citrus. 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. Year 1 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) 40% PRD – 40% less water than well-watered control; (4) 25% CI-RR – 25% less water than well-watered control; and (5) 40% CI-RR – 40% less water than well-watered control. In Year 1, control trees were irrigated when soil moisture content reached −30 cb at 30 cm, and PRD and CI-RR trees when soil moisture content reached −60 cb at 30 cm. In Year 2, all treatments were irrigated when soil moisture content was −30 cb at a depth of 30 cm for the well-watered control trees, but the trees in the PRD and CI-RR treatments receiving 40% less water than the well-watered control now received 50% less water.

At harvest in January, 12 months after treatment initiation each year, total fruit number and fruit size distribution (pack out) per tree were determined. A 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:acid by the UC Lindcove Analytical Laboratory. Fruit were mechanically juiced with a commercial juicer. TSS concentration was determined by refractometry. 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). Cost:benefit was estimated from crop value. Fisher's Protected LSD Test at $P \leq 0.05$ was used to test for treatment effects using the SAS statistical program (SAS Institute, Cary, N.C.).

RESULTS AND DISCUSSION

The liters of water applied per treatment per quarter from January to harvest 12 months later for Years 1 and 2 are given in Table 1. The quarters correspond to the following stages of tree phenology: January to March – inflorescence development and bud break; April to June – flower opening and fruit set; July to September – exponential fruit growth; and October to harvest - fruit maturation.

Year 1

Problems were encountered in applying the correct amount of irrigation water to the CI-RR and PRD trees in Year 1. During the first quarter, January through March, trees in all reduced irrigation treatments received from 44% (25% CI-RR) to 83% (40% CI-RR) less water than the well-watered control trees rather than the prescribed 25% or 40% less water (Table 1). From April through June, irrigation rates were only 22% (25% CI-RR) to 59% (40% PRD) less than the well-watered control. In July to September, trees in reduced irrigation treatments received from 6% more water (25% PRD) to 65% less water (40% PRD) than the well-watered control trees. Irrigation rates decreased from October through harvest at 41% (25% CI-RR) to 71% (40% PRD) less water than the control trees. As a result by the end of Year 1, trees in the 25% and 40% CI-RR treatments received 29% and 52% less water than the well-watered control trees, respectively, whereas trees in the 25% and 40% PRD treatments received 36% and 65% less water than the control, respectively.

Trees in the 25% CI-RR treatment receiving 29% less water than the well-watered control trees for the year suffered a 29% reduction in total number of fruit per tree. Reducing the amount of irrigation water applied an additional 7% to 36% resulted in a loss of ≥ 90% of the total fruit per tree. Trees in all reduced irrigation treatments produced significantly fewer fruit in all fruit size categories, with the exception that trees in the 25% CI-RR treatment produced an equal number of small fruit of low commercial value (packing carton size 138, 6.0-6.3 cm in diameter) as the well-watered control trees (Table 2). All reduced irrigation rates had a dramatic effect on fruit size and crop value. For trees in the 25% CI-RR treatment, which received only 29% less water than the well-watered control trees, there was a 66% reduction in yield of commercially valuable large fruit (packing carton sizes 88+72+56, diameters 6.9-8.8 cm), which resulted in a 44% reduction in crop value compared to well-watered control trees. Reducing the irrigation rate to 36% (25% PRD), 52% (40% CI-RR) or 65% (40% PRD) less than the well-watered control reduced the yield of commercially valuable large fruit ≥ 95% ($P < 0.0001$) and reduced the value of the crop ≥ 90% ($P < 0.0001$) (Table 2).

Fruit harvested from trees in the 25% PRD, 40% CI-RR and 40% PRD treatments had a lower percent juice (juice fresh mass/fruit fresh mass) ($P < 0.0001$) and as a result had higher total soluble solids (TSS) ($P < 0.0058$) and percent acidity than fruit from the well-watered control trees ($P < 0.0001$) (Data not shown). However, TSS:acid ratio was significantly lower than that of well-watered control trees for trees in the 25% and 40% PRD treatments, which received 36% and 65% less water than the control, respectively, but not trees in the 40% CI-RR treatment, despite the fact that they received 52% less water than control trees ($P < 0.0079$). All fruit were legally mature (TSS:acid ≥ 8.0) at harvest, but fruit from the two PRD treatments had slightly inferior eating quality (TSS:acid < 12).

Year 2

Negative effects on total yield, fruit size and crop value associated with all reduced irrigation treatments in Year 1 were attributable not only to the reduced amount of irrigation water applied, but also to drying the soil around these trees to –60 cb at a soil depth of 30 cm before irrigating. In Year 2 trees in all treatments were irrigated when the soil for the well-watered control trees dried to –30 cb at this depth. With the increased frequency of irrigation, the irrigation rate for trees in the 40% CI-RR and PRD treatments was reduced to 50% less water than the well-watered control. From January through March, 25% CI-R, 50% CI-RR, 25% PRD and 50% PRD trees received 35%, 49%, 6% and 47% less water than the well-watered control trees, respectively (Table 1). From April through June, the amount of water applied correctly matched the prescribed amount per treatment. From July through September, 25% CI-RR, 50% CI-RR, 25% PRD and 50% PRD trees received only 16%, 28%, 16% and 27% less water than the well-watered control trees, respectively (Table 1). From 1 October through harvest, 25% CI-RR, 50% CI-RR, 25% PRD and 50% PRD trees received 19%, 36%, 19% and 31% less water than the well-watered control trees, respectively, with the differences for the entire year 21%, 36%, 18% and 36% less water than the well-watered control trees, respectively (Table 1). These differences in irrigation rates affected the total number of fruit per tree compared to well-watered control trees as follows from highest to lowest yield: Control = 25% CI-RR > 25% PRD > 50% CI-RR > 50% PRD ($P < 0.0001$) (Table 3). Reduced irrigation significantly decreased the number of fruit in all fruit size categories compared to the well-watered control trees, with the exception that trees in the 25% CI-RR and PRD treatments produced more small size fruit of low economic value (packing carton size 138, diameter 6.0-6.34 cm) than well-watered control trees (Table 3). All reduced irrigation treatments reduced the number of commercially valuable large fruit (68%-94%) ($P < 0.0001$), resulting in significant losses in crop value (36%-79%) ($P < 0.0001$) compared to the well-watered control.

Interestingly, fruit from trees in the 25% PRD treatment had greater juice mass (g) than trees in all other reduced irrigation treatments ($P < 0.0082$) and greater juice volume (ml) than trees in the 50% CI-RR and 50%PRD treatments ($P < 0.0087$) (Data not shown). Trees in both PRD treatments produced fruit with higher TSS ($P < 0.0001$) and percent acidity ($P < 0.0001$) than trees in all other treatments, including the control, resulting in lower TSS:acid than fruit in all other treatments, except the 50% CI-RR treatment ($P < 0.0004$). All fruit were legally mature and of high eating quality (TSS:acid 13.5-16.8).

CONCLUSION

The results of this research documented that reducing irrigation more than 25% below 100% ETcrop during flowering and fruit set, or 20% per year, has a negative effect on fruit set as total number of fruit per tree and on fruit growth as number of fruit ≥ to packing carton size 113 per tree. Yield reductions in commercially valuable fruit significantly reduced crop value and grower income. Savings in the cost of water achieved by reducing irrigation rate were negated by lost revenue due to the lower yield of commercially valuable fruit. Further reductions in irrigation rate exacerbated these problems, reduced fruit quality, and further reduced grower income. Moreover, at the levels of reduced irrigation imposed in this study, PRD provided no advantage over CI. 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 and emphasize the need for careful irrigation management even when adequate water is available to ensure that irrigation rate not fall below 80% ET during critical stages of tree phenology.

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Tables

Table 1. Liters of water applied per treatment to 'Washington' navel orange trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside (UCR) from 1 January to harvest 12 months later for Years 1 and 2.

	Year 1					Year 2				
Month	Control	CI-RR 25%	CI-RR 40%	PRD 25%	PRD 40%	Control	CI-RR 25%	CI-RR 50%	PRD 25%	PRD 50%
Jan-Mar	86,835	48,225	14,308	33,386	27,368	59,369	38,534	36,036	56,060	31,683
% control	100	55.5	16.5	38.4	31.5	100	64.9	60.7	94.4	53.4
Apr-Jun	253,918	199,069	114,543	116,171	103,604	205,788	155,477	107,889	154,440	104,951
% control	100	78.4	45.1	45.8	40.8	100	75.6	52.4	75.0	51.0
Jul-Sep	273,337	213,529	164,282	290,597	96,449	269,968	225,929	194,708	226,081	197,195
% control	100	78.1	60.1	106.3	35.3	100	83.7	72.1	83.7	73.0
Oct to harvest	184,874	108,222	94,670	73,662	54,092	169,089	136,309	108,411	137,293	116,587
% control	100	58.5	51.2	39.8	29.3	100	80.6	64.1	81.2	69.0
Total	798,963	569,044	387,804	513,817	281,513	704,213	556,250	447,044	573,874	450,417
% control	100	71.2	48.5	64.3	35.2	100	79.0	63.5	81.5	64.0

Table 2. Year 1 – Effect of reducing irrigation 25% or 40% by conventional irrigation (CI-RR) or partial root zone drying (PRD) from 1 January through harvest 12 months later 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). (Control trees were irrigated when soil moisture content reached –30 cb at 30 cm, and PRD and CI-RR trees when soil moisture content reached –60 cb at 30 cm.)

Treatment	Crop value US$ 237 trees/ha	Total	Packing carton size					
			56 8.1-8.8 cm	72 7.5-8.0 cm	88 6.9-7.49 cm	113 6.35-6.89 cm	138 6.00-6.34 cm	56+72+88 6.9-8.8 cm
		---------- *no. of fruit per tree* ----------						
Control	11743.20 a[z]	1143 a	28 a	101 a	263 a	374 a	376 a	392 a
CI-RR-25%	6611.90 b	809 b	8 b	29 b	96 b	226 b	451 a	133 b
CI-RR-40%	851.60 c	108 c	0 b	3 b	14 c	28 c	63 b	18 c
PRD-25%	933.90 c	127 c	0 b	2 b	9 c	36 c	80 b	11 c
PRD-40%	992.60 c	130 c	1 b	2 b	15 c	34 c	79 b	17 c
P-value	<0.0001	0.0003	<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% or 50% by conventional irrigation (CI-RR) or partial root zone drying (PRD) from 1 January through harvest 12 months later 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. (Trees in all treatments were irrigated when soil moisture content reached –30 cb at a depth of 30 cm for the well-watered control trees.)

Treatment	Crop value US$ 237 trees/ha	Total	Packing carton size					
			56 8.1-8.8 cm	72 7.5-8.0 cm	88 6.9-7.49 cm	113 6.35-6.89 cm	138 6.00-6.34 cm	56+72+88 6.9-8.8 cm
		---------- *no. of fruit per tree* ----------						
Control	15668.00 a[z]	1565 a	28 a	95 a	443 a	527 a	472 b	565 a
CI-RR-25%	10128.00 b	1377 a	2 b	19 b	159 b	413 b	784 a	180 b
CI-RR-50%	4469.00 d	731 c	0 b	3 b	29 c	129 c	569 b	32 c
PRD-25%	6692.00 c	1083 b	2 b	5 b	39 c	204 c	834 a	46 c
PRD-50%	3235.00 d	394 d	5 b	15 b	56 c	105 c	212 c	76 c
P-value	<0.0001	<0.0001	<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.