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Winter irrigation increased yield of 'Washington' navel orange (*Citrus sinensis* L. Osbeck)

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SUMMARY

The present study aimed to quantify the effect of withholding irrigation during the winter season in southern California on the productivity of 'Washington' navel orange and to determine whether the additional expense of irrigating navel orange trees during the winter is a cost-effective production management strategy. Yield and fruit size were quantified for 30 year old 'Washington' navel orange scions on Troyer citrange rootstock which were rain-fed from October 1 to March 1 in each of three successive years and for another set of trees which were irrigated during the winter. Supplementing winter rainfall with irrigation significantly increased the weight of fruit per tree in all three years of the study (45 ± 17 kg fruit tree^{-1}, n = 3 years) and number of fruit per tree in the two years in which the rain-fed, −winter irrigation trees had significantly lower predawn water potentials than the +winter irrigation trees. Despite the yield increases which resulted from supplementing winter rain with irrigation in each year of the study, there was no reduction in the number of commercially valuable fruit with tranverse diameters between 7.0 to 8.0 cm in any year ($P \leq 0.05$). Trees receiving winter irrigation to supplement rainfall were less affected by a preharvest freeze: compare a 50% reduction in yield from the previous year for the +winter irrigation treatment to a 93% reduction for the −winter irrigation trees. Irrigation treatment did not affect tree nitrogen status. Even in the year when the lowest net increase in yield was obtained with the greatest amount of irrigation water, valued at a high cost for California, winter irrigation was a cost-effective management strategy for the production of 'Washington' navel orange.

HIGH quality water at an affordable price is becoming increasingly limited in many crop production areas of the world, including California (Takele *et al.*, 1995). Where surface water is available, it is often contaminated with salt. Many growers rely on underground aquifers, but these are being depleted more rapidly than they can be recharged (Kingsolver, 1986). Worldwide, shortages in water available to agriculture are likely to become chronic due to increased urban and environmental demands. For example, due to years of drought, increased competition for available water, and regulatory restrictions on water supplied to agriculture, the cost of water to citrus growers in San Diego County, California, averages $4,942 per ha per year (Dr Gary Bender, Farm Advisor San Diego County, pers. comm.). As water costs associated with citrus production have increased, growers worldwide have sought ways to save water while minimizing or eliminating negative effects on yield and revenue. Researchers have attempted to identify specific times in the phenology of the citrus tree during which water deficits can be imposed without adversely affecting fruit number, size or quality to enable growers to reduce consumption of irrigation water (Hilgeman and Sharp, 1970; Du Plessis and Du Plessis, 1987; Cohen and Goell, 1989; Goell, 1993).

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Regulated-deficit irrigation is an irrigation scheduling strategy designed to save water while having a minimum impact on tree productivity. This is accomplished by imposing water-deficit stress during phenological periods or seasons when the tree is relatively tolerant to stress (Goldhamer and Beede, 1995). Identification of phenological stages that are tolerant or less sensitive to water deficits is required for growers to make irrigation management decisions based on cost-to-benefit analysis of yield and fruit quality versus water saved. The technique of regulated deficit irrigation has been investigated with deciduous tree crops (Chalmers *et al.*, 1984; 1986; Mitchell *et al.*, 1984, 1989; Li *et al.*, 1989; Boland *et al.*, 1993; Lampinen *et al.*, 1995), but to our knowledge, not with citrus. In the absence of the basic information required to utilize regulated deficit irrigation in citrus production, growers in Mediterranean climates have opted to save water and money by withholding irrigation during the winter when citrus grown in such climates is typically dormant, the crop has achieved near maximum size, evaporative demand is low, and there is the greatest likelihood of rain.

The present study was undertaken: (i) to quantify the effect on tree productivity of withholding irrigation during the winter season, a time when the 'Washington' navel orange tree is relatively tolerant to stress; and (ii) to determine whether the additional cost of irrigating during the winter is cost-effective as a management strategy for the production of the navel orange. Yield and fruit size were quantified for 30 year old 'Washington' navel orange scions on Troyer citrange rootstock which were rain-fed from 1 October to 1 March in each of three successive years and for another set of trees which were irrigated during the winter to supplement the rain. In year two of the experiment, there was a freeze in December prior to harvest. Thus, the results of this research also provide data on the effect of the two irrigation management strategies on the yield loss caused by the freeze and on the return yield the following year.

MATERIALS AND METHODS

Plant material

Thirty year old 'Washington' navel orange trees on Troyer citrange rootstock at the Citrus Research Center and Agricultural Experiment Station of the University of California, Riverside, were used. Tree density was 237 trees ha^{-1}. In previous years, the trees produced yields similar to the average annual production for southern California navel orange trees, i.e., 30 t ha^{-1} (California Agricultural Statistics Service, 1986-1991).

Experimental plan

The two irrigation treatments were: (i) rain-fed, no irrigation from 1 October to 1 March (−winter irrigation); and (ii) winter irrigation, rain supplemented with irrigation from 1 October to 1 March (+winter irrigation). Irrigation was by furrow every three weeks for 24 or 48 h (24, 243 l h^{-1} ha^{-1}). There were 12 individual tree replicates per treatment. Trees used in the experiment were shown by leaf analysis to have sufficient nitrogen at the initiation of the study (2.68%; spring flush leaves from nonfruiting terminals analyzed in September according to Embleton *et al.* 1973). The trees received 0.5 kg N per tree as urea (granules, 0.25% biuret, BP Chemical, Lima, OH) applied to the soil on 18 January, 5 December and 11 November for years 1 to 3, respectively.

For all three years of the study, fruit were harvested between the last week of January and the last week of February. Total fruit weight per tree and total fruit number per tree were determined. Fruit transverse diameter was measured for individual fruit in randomly selected and weighed subsamples representing 5 to 30% of the total number of fruit per tree for the three years of the study, respectively. These data were used to estimate fruit size distribution in the following categories: (i) fruit with a transverse diameter from 7.0 to 8.0 cm (packing carton sizes 88 and 72), (ii) fruit with a diameter with 6.1 to 6.9 cm (packing carton sizes 138 and 113), and (ii) fruit with a diameter from 5.2 to 6.0 cm (packing carton sizes 180 and 163).

Tree predawn water potential was measured with a pressure chamber every third week just

TABLE I
Year 1—Precipitation, irrigation and predawn water potentials of 'Washington' navel orange trees not irrigated and irrigated from 1 October to 1 March

			Tree predawn water potential[y]		
Month	Precipitation (mm)	Irrigation water (l tree^{-1})	−Winter irrigation (MPa)	+Winter irrigation (MPa)	Significance[z]
October	0	9811	—	—	—
November	16	9811	−0.96	−0.67	*
December	70	4906	−1.44	−1.35	n.s.
January	22	9811	−1.43	−1.24	n.s.
February	43	4906	—	—	—

[y]Values represent the means of 12 individual replicate trees per irrigation treatment.
[z]*Represents significance at $P \leq 0.05$, and n.s. = non-significant at $P \leq 0.05$ at Duncan's Multiple Range test.

before irrigation. Two to three water potential measurements were made on 12 trees per irrigation treatment using fully expanded mature leaves. Predawn water potential is presented as the mean ±SE, n = 12.

Leaf total nitrogen concentration was determined for a sample of 40 five month old, spring flush leaves from nonfruiting terminals per tree collected in September of each year as described by Embleton *et al.* (1973). Leaves were washed with soapy water, rinsed thoroughly with distilled water, oven-dried at 60°C, and ground in a Wiley mill to pass through a 40-mesh screen. Total N was determined for a 25 mg sample with 12 replications per treatment using the conventional micro-Kjehldahl method.

Statitical analysis

The data trees were part of a larger experiment and were analyzed as a completely randomized design. Data were subjected to analysis of variance using the SAS general linear model procedure (SAS Institute, 1988). Mean separation was accomplished with Duncan's multiple range test at $P \leq 0.05$.

RESULTS

Effect of irrigation treatment on tree predawn water status

From October to March, total rainfall was between 113 to 150 mm for the three years of the study (Tables I–III). In year 1, there was sufficient rainfall that predawn water potentials for the trees in the two irrigation treatments were not statistically different from December to March (Table I). In years 2 and 3, rainfall through December was only 10 mm and trees that were rain-fed (−winter irrigation) from 1 October to 1 March exhibited significantly lower predawn water potentials through February despite the fact that in January and February total rainfall was 103 and 115 mm each year, respectively (Tables II and III). Predawn water potentials of −2.32 to −2.62 MPa for the trees in the −winter irrigation treatment were indicative of moderate water-deficit stress and no symptoms of stress were observed in any year of the study. With the resumption of irrigation to all trees in March, tree predawn water potentials returned to values between −0.37 and −0.56 each year. Thus, there were no significant differences

TABLE II
Year 2—Precipitation, irrigation and predawn water potentials of 'Washington' navel orange trees not irrigated and irrigated from 1 October to 1 March

			Tree predawn water potential[y]		
Month	Precipitation (mm)	Irrigation water (l tree^{-1})	−Winter irrigation (MPa)	+Winter irrigation (MPa)	Significance[z]
October	7	9811	—	—	—
November	3	4906	—	—	—
December	0	4906	−2.50	−0.81	*
January	42	0	—	—	—
February	61	4906	−2.32	−0.90	*

[y]Values represent the means of 12 individual replicat trees per irrigation treatment.
December measurements were made on 10 individual tree replicates.
[z]*Represents significance at $P \leq 0.05$ by Duncan's Multiple Range test.

TABLE III
Year 3—Precipitation, irrigation and predawn water potentials of 'Washington' navel orange trees not irrigated and irrigated from 1 October to 1 March

Month	Precipitation (mm)	Irrigation water (l tree^{-1})	Tree predawn water potential[y] −Winter irrigation (MPa)	+Winter irrigation (MPa)	Significance[z]
October	1	9811	—	—	—
November	8	9811	−1.83	−1.34	*
December	0	4906	−2.47	−1.52	*
January	40	0	—	—	—
February	75	2543	−2.62	−1.49	*

[y]Values represent the means of 12 individual replicate trees per irrigation treatment.
[z]*Represents significance at $P \leq 0.05$ by Duncan's Multiple Range test.

between predawn water potentials for trees in the two treatments in March of any year.

Effect of irrigation treatment on yield

In all three years of the study, supplementing winter rainfall with irrigation significantly increased the kg of fruit per tree (Table IV). The yield increases due to winter irrigation were more dramatic with regard to both kg and number of fruit per tree for years 2 and 3, the years in which the rain-fed, −winter irrigation trees had significantly lower predawn water potentials in both December and February than the +winter irrigation trees (Tables II, III, IV and V). In year 3, all trees in the study were irrigated during the period from 1 October until harvest, in the last week of February. Thus, the 1.7-fold increase in kg fruit per tree and the 2.2-fold greater number of fruit per tree for the +winter irrigation treatment were likely due to treatment effects prior to or during initiation of the floral apex and inflorescence development.

Effect of irrigation treatment on fruit size

Despite the increased yields (kg fruit tree^{-1}) which resulted from supplementing winter rain with irrigation in each year of the study, there was no reduction in the number of fruit of commercially valuable sizes, i.e. those with transverse diameters between 7 to 8 cm, in any year ($P \leq 0.05$). The correlation coefficients (r^2) for the number of fruit in each size category versus yield averaged for all three years of the study were 0.54 for fruit with transverse diameters between 7 to 8 cm (Figure 1); 0.88 for fruit 6.1 to 6.9 cm in diameter (Figure 2); and 0.38 for small, less commercially desirable fruit with transverse diameters of 5.2 to 6 cm (Figure 3) ($P \leq 0.001$).

TABLE IV
Average yield (kg per tree) of the 'Washington' navel orange trees not irrigated or irrigated from 1 October to 1 March[y]

Year of the experiment	−Winter irrigation	+Winter irrigation	Significance[z]
1	95	122	**
2	7	56	***
3	86	146	***

[y]Values represent the means of 12 individual replicate trees per irrigation treatment.
[z]*** and **Represent significance at $P \leq 0.05$ and 0.01, respectively, by Duncan's Multiple Range test.

Interaction between irrigation treatment and preharvest freeze

Trees receiving winter irrigation to supplement rainfall exhibited significantly less yield loss in response to the preharvest freeze in December of year 2 (Tables IV and V). Yield was 50% less in year 2 compared with year 1 for the +winter irrigation treatment. In contrast, trees in the −winter irrigation treatment lost virtually all their fruit in response to the freeze (yield in year 2 was only 7% of year 1).

Trees supplemented with winter irrigation also produced a greater return crop in the year following the freeze than unirrigated trees (Tables IV and V). Yield in the year after the freeze was 20% greater in terms of kg per tree and 70% greater in terms of number of fruit per tree than yield in the year prior to the freeze for the +winter irrigation treatment. The increase in yield in the return crop after the freeze was due to a 30% increase in commercially valuable fruit with diameters from 6.1 to 8 cm and a greater than ten-fold increase in small, less commercially desirable fruit with transverse diameters between 5.2

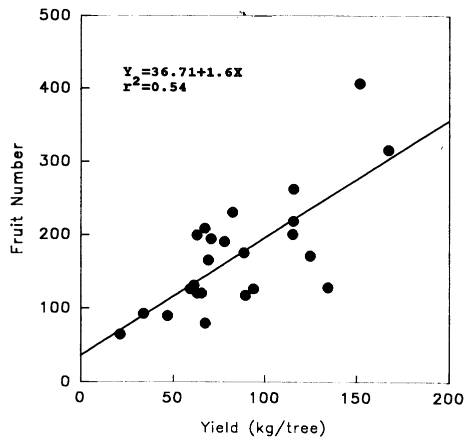

FIG. 1
Number of fruit with diameters of 7.0 to 8.0 cm tree^{-1} vs. yield (kg tree^{-1}) for trees in the +winter irrigation treatment averaged over the three years of the study for each replicate (n = 12).

and 6 cm. For rain-fed (−winter irrigation) trees, the return crop following the freeze was 10% lower in terms of both kg and number of fruit per tree than the year before the freeze. The relative number of fruit in each size category was the same for the return crop as for the year prior to the freeze.

Effect of irrigation treatment on tree N status

Irrigation treatment had no effect on tree

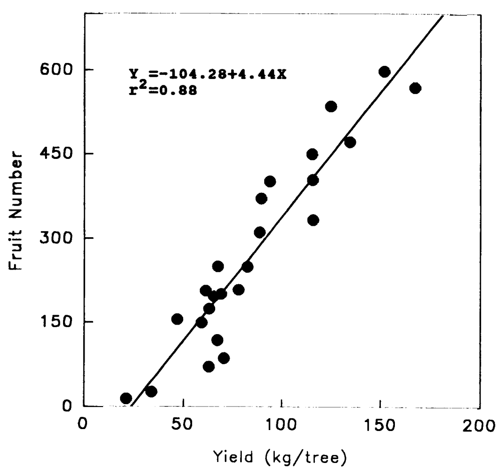

FIG. 2
Number of fruit with diameters of 6.1 to 6.9 cm tree^{-1} vs. yield (kg tree^{-1}) for trees in the +winter irrigation treatment averaged over the three years of the study for each replicate (n = 12).

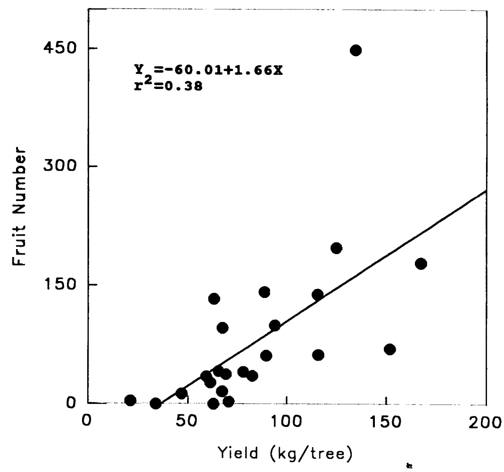

FIG. 3
Number of fruit with diameters of 5.2 to 6.0 cm tree^{-1} vs. yield (kg tree^{-1}) for trees in the +winter irrigation treatment averaged over three years of the study for each replicate (n = 12).

nitrogen status in individual years or cumulatively. Leaf total nitrogen concentrations averaged 2.5% for both irrigated and unirrigated trees in year 3.

DISCUSSION

Water-deficit stress is generally associated with reduced productivity (Bradford and Hsiao, 1982). However, some beneficial effects of water deficits have been reported for a number of fruit tree crops. Withholding irrigation followed by regulated deficit irrigation reduced vegetative shoot growth and pruning costs and increased yield of peach and pear (Mitchell and Chalmers, 1982; Mitchell *et al.*, 1984; Chalmers *et al.*, 1984). For citrus grown in tropical and subtropical areas with distinct

TABLE V
Average number of fruit per tree of the 'Washington' navel orange trees not irrigated or irrigated from October 1 through March 1[y]

Year of the experiment	−Winter irrigation	+Winter irrigation	Significance[z]
	number of fruit tree^{-1}		
1	562	662	NS
2	42	347	***
3	510	1132	***

[y]Values represent the means of 12 individual replicate trees per irrigation treatment.
[z]***Represents significance at $P \leq 0.001$, and NS = non-significant at $P \leq 0.05$ by Duncan's Multiple Range test.

rainy and dry seasons, water-deficit stress substitutes for low temperature in flower induction (Cassin *et al.*, 1969; Reuther and Rios-Castano, 1969; Reuther, 1973). Water-deficit stress is used commercially to induce off-season flowers and fruit in lemons and limes, typically with no negative effects on number, size or quality of the existing crop. However, excessive stress has been documented to cause significant abscission of the new flowers (64%) and reduced development of the current crop (Shalhevet and Levy, 1990). For sweet oranges, water-deficit stress during Stage I of fruit growth (cell division) reduces the number of fruit set but the negative impact of water deficit on fruit size is often off-set by the early decrease in fruit number (Du Plessis and Du Plessis, 1987). Water stress during Stage II of fruit development (cell expansion) strongly affects fruit size. It is during this stage that the greatest rate of fruit growth takes place (Bain, 1957; Holtzhausen, 1972). Cohen and Goell (1989) demonstrated that fruit growth rate was a good indicator of irrigation needs. Water stress during Stage III of fruit development while not as critical, still can affect size and number negatively (Du Plessis and Du Plessis, 1987).

Comparison of yield results obtained in this study on the basis of weight of fruit, number of fruit, or number of commercially valuable fruit with tranverse diameters between 7 to 8 cm per tree for ±/−winter irrigation treated trees provides no evidence of any benefit from withholding irrigation from 1 October to 1 March. Withholding irrigation resulted in statistically significantly less kg fruit per tree in all three years of the study, even in year 1 when tree predawn water status was not significantly different from that of trees in the + winter irrigation treatment during the period October to March and despite the fact the water deficits in subsequent years were only moderate (approx. 2.5 MPa). Trees in the −winter irrigation treatment were affected more negatively by the preharvest freeze, yielding only 12% of the +winter irrigation trees in terms of both kg and number of fruit per tree and only 60% of the return crop. In all three years of the study, the lower yields of the −winter irrigation trees never resulted in a significant increaase in the number of larger-sized fruit, i.e. 6.1 to 8 cm in diameter.

In contrast, the statistically significant increases in yield were obtained in all three years of the study (an average 45 ± 17 kg per $tree^{-1}$ yr^{-1}, $n = 3$) with an accompanying increase in larger fruit (6.1–8 cm in diameter) by supplementing winter rain with an average of 30,282 ± 7,866 ($n = 3$) litres of water per tree per year. Depending on the value of the crop and cost of irrigation water, this may or may not result in a significant increase in net return to the grower.

Nitrogen is typically applied to the soil in the winter in California to coincide with the rains. While there has been considerable speculation on the amount of this N actually used by the citrus tree, especially in years of drought, supplementing winter rain with irrigation did not elevate the nitrogen status of the navel orange trees in this research. Even for leaf samples collected in September of the third year of the experiment, there was no cumulative effect of withholding winter irrigation in the previous winters on leaf total nitrogen concentration. Trees in both treatments averaged 2.5% N. Thus, the yield differences between the ±/−winter irrigated trees were not due to an effect of irrigation treatment on the uptake of soil applied nitrogen.

The present study is the first to demonstrate the potential benefit of supplementing winter rainfall with irrigation to enhance the yield of the 'Washington' navel orange. Even in years when withholding irrigation from 1 October to 1 March did not significantly change tree predawn water status after November (year 1) and freeze was not a factor (year 1), winter irrigation resulted in a net increase of 27 kg fruit per tree (1.6 packing cartons $tree^{-1}$) with no reduction in fruit size. This year, which had the smallest net increase in yield, but was irrigated with the greatest amount of water from 1 October to 1 March (44151 l $tree^{-1}$) was used to estimate the cost-effectiveness of the treatment. A high value of $81 per 1.0×10^6 l of water resulted in a cost of US$3.58 per tree to yield a net increase of 1.6 packing cartons fruit with a value from approx. US$3.00 to US$6.00 per carton. Thus, supplementing winter rain with irrigation can be a cost-effective management strategy for navel orange production.

During the period December to February, flower initiation and organogenesis take place in southern California. The results of our study provide evidence suggesting that this stage of navel orange phenology is sensitive to water-deficit. The period from October to harvest (the last week of January to the last week of February for the three years of this study), also encompasses the transition from Stage II, the cell expansion phase of fruit growth, which is sensitive to water deficit (Cohen and Goell, 1989), to Stage III of fruit development, which is less sensitive (Hilgeman and Sharp, 1970; Du Plessis and Du Plessis, 1987). The data suggest that water deficit during this phenological period had minimum adverse effect on yield and fruit size of the current crop. This interpretation is based on the fact that in the third and final year of the research, trees in the −winter irrigation treatment were irrigated the same as the +winter irrigation trees from 1 March to harvest but had 40% less kg fruit per tree. This interpretation is consistent with two earlier reports that withholding water from July to December until fruit growth almost stopped (Furr, 1955) or from August to February to create moderate stress (Hilgeman and Sharp, 1970) did not reduce fruit size or yield, respectively.

Further research is required (i) to determine whether there is one, or more, smaller windows within the period 1 October to 1 March that is more sensitive to water deficit or whether it is essential to maintain irrigation for its duration; (ii) to quantify the minimum amount of water required to achieve the tree water status necessary to attain the maximum possible increase in yield and fruit size; and (iii) to identify additional stages in the phenology of the navel orange that are sensitive or tolerant to moderate water-deficit.

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