Effect of RDI on Quality and Economic Yield of Navel Oranges

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Abstract. *Growing oranges under drought conditions is a challenging task which can result in the adoption of regulated deficit irrigation (RDI). This research was conducted at two locations in California using five irrigation regimes, during the months of July and August, to assess the effect of limited water application on the quality and economic yield of navel oranges. The partial budget modelling approach was used to assess the economic impact of reduced water application on the price of the oranges sold in the U.S. and exported to Japan. At both locations there was a significant difference in fruit Brix index and yield at lower RDI treatments compared to fruit receiving higher doses of water. The implementation of RDI in navel oranges can increase crop quality, yet severe RDI levels can decrease yield. Generally, the price of "free-watered" citrus in the U.S. was lower than citrus in the Japanese market. More importantly, the economic analysis adopted in this study showed the Japanese market was an incentive to: (1) manage water to benefit from that niche market, and (2) produce fruits of lower weight that would ultimately be compensated through higher prices.*

Keywords: RDI, Navel oranges Brix, partial budget modelling, micro-sprinkler fertigation system

Introduction

Citrus crops are a highly profitable commodity in the United States (U.S.) with California and Florida being the two leading States (USDA, 2012). In 2012, the U.S. citrus production totaled 11.2 million tons with a value of $3.2 million of which $2 million was produced in California. The contribution of California citrus crops was 30% of the total U.S. citrus fruit production and 42% of the national value (CDFA. 2014). Citrus crops are one of California's most profitable and essential products to the State economy bringing in over $2 billion annually (California Citrus Mutual, 2013). A vast number of citrus crops are currently in production in California, such as: navels, valencia, minneola tangelos, grapefruit, lemons, and mandarins which are produced across the state and have a large portion based in the central San Joaquin Valley (SJV). The importance of the citrus industry for the sustainability of the local economy is fundamental, yet there are issues that can potentially decrease overall productivity of citrus in the SJV. For example, the recent identification of Asian Citrus Psyllid (ACP) and Huanglongbing (HLB) Disease has become a major problem for citrus growers throughout the State because the potential transmission of citrus greening disease which can destroy the citrus industry having detrimental consequence on the economy (Citrus Research Board, 2010; Grafton-Cardwell and Daugherty, 2013). The yearly potential of frost damage is also an issue growers try to overcome and reduce the severity of the harvest impact they will endure.

Currently, the drought situation in California is probably the issue of most concern to farmers, as the availability of water, or lack thereof, can ultimately affect pestilence and frost management.

Regulated Deficit Irrigation (RDI) is an optimization strategy in which irrigation is applied during drought-sensitive growth stages of a crop (Kriedemann and Goodwin, 2003). Basically, water application is limited to drought-tolerant phenological stages of the crop, often during the vegetative stages and the late ripening period. Total irrigation application throughout the crop cycle is therefore below the crop's evapotranspiration (ETc) requirements (Fereres and Soriano, 2007). While this inevitably results in plant drought stress, overall productivity is maximized by the water supplied through RDI, which is generally the main limiting resource (English, 1990).

RDI has also been used to increase the Brix index and soluble solid levels in various crops (Johnstone et al., 2005). For consumer preference, increasing the Brix index- which is an indicator of the sweetness of the fruit, and reducing the size is essential as consumers tend to prefer a sweet orange with an average size. These two fruit attributes increase the desirability of the product and, thus, RDI can be utilized to potentially impact plant physiological stress in an effort to obtain these desired fruit qualities.

One approach by California citrus growers in dealing with the lack of water allocation in recent years has been the adoption of RDI in many crops, such as: grapes, almonds, pistachios, and citrus throughout the State (Goldhamer and Fereres. 2005). While the implementation of RDI practices in various cropping systems has shown to have beneficial effects, it is vitally important to examine the effects of RDI on the various species of citrus production, plant physiology, fruit quality and economic yield.

Objectives

As part of our ongoing research aimed at optimizing water use efficiency (WUE) for various crops grown in the San Joaquin Valley (SJV), for this study the focus was on navel oranges (*Citrus Sinensis* (L.) Osbeck, cv. Washington 'frost nucellar'). The overall objective was to quantify the effects of RDI on fruit quality and economic yield of navel oranges grown in the central region of the SJV, California. For this presentation, a specific objective was to review the fertigation protocol adopted to ensure that the citrus crop received the equivalent of 50%, 75%, 100% (growers practice/control), 125%, and 150% of the reference evapotranspiration (ET), along with adequate plant nutrition needs.

Materials and Methods

The study was conducted at two separate locations in the city of Woodlake, California (Figure 1). Both locations had similar soil types, rootstock, scion, fertilization, irrigation, and age of crop. Irrigation and fertilizer was applied through a micro-sprinkler fertigation system (fanjet). There were five irrigation levels relative to evapotraspiration (ET) which meant that the crop evapotranspiration (ET_c) requirements were met at 50%, 75%, 100% (growers practice/control), 125%, and 150% of ET.

The fields consisted of mature navel oranges planted in 1964. The citrus crop consisted of propagated cultivars Washington 'Frost Nucellar' scion grafted on Troyer citrange (*Poncirus trifoliata)* rootstock. Troyer rootstock has the characteristics to be reasonably vigorous and resistant to *Phytophthora parasitica*, nematodes, and tristeza virus as well as cold tolerance. The tree spacing was 22ft by 22ft. The research sites, referred to as the North and South locations, were each 43,560ft^2 (i.e. 1 acre) (Figure 1).

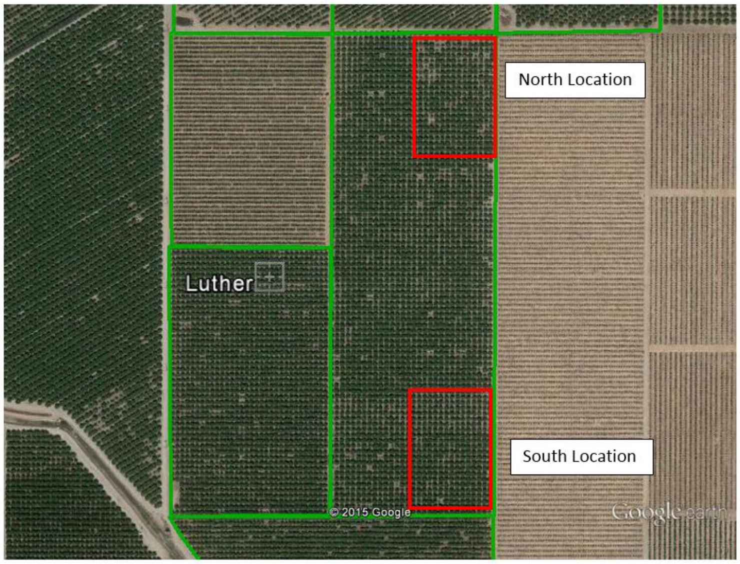


Figure 1**:** Google Earth® imagery of the North and South locations.

The study was conducted from spring 2014 to spring 2015 (traditional citrus growing season) in a commercial citrus farm in Woodlake, California. Both North and South locations contained identical soil, irrigation, crop age and fertilizer programs. Moreover, both fields had a soil type of consisting of a sandy loam with an electrical conductivity of 3.6 dS/m, predominantly calcium driven. The experimental design consisted of 3 blocks and 4 herbicide treatments within each block (0%, 50%, 75%, and 100% (growers practice) of Matrix (PRE) herbicide (main plots) with the five different RDI treatments. Each block was replicated three times and consisted of four rows with one row in between each herbicide treatment as a buffer.

Sampling plots were represented by two trees with a one tree buffer between each sub-treatments. During the active growing season (late-March to November), this citrus block was provided with 25-32 hours of irrigation per week, approximately 0.1-0.15 acre-inches per irrigation event. Irrigation events occurred in two weekly application of 10-15 hours per irrigation event dependent on crop evapotranspiration (ETc). The RDI treatments were calculated in relation to the traditional irrigation practices in place by the farmer. In order to ensure irrigation accuracy, all RDI treatments in all blocks were subjected to a flow and pressure test to ensure irrigation uniformity. Moreover, irrigation was calculated by implementing an irrigation schedule that was crop specific by taking into account: evapotranspiration (ETo), crop coefficient (Kc), and a 95% irrigation efficiency factor (University of California Cooperative Extension. 2015). Climatic data from at the nearby Lindcove, California Irrigation Management Information Systems (CIMIS) station was used to develop the irrigation schedule for conventional treatment (1.00 RDI). Irrigation treatments (RDI) were confirmed by using collection cans to determine the efficacy and distribution of the micro-sprinklers.

All criteria were included in the development of an effective, crop specific irrigation schedule in which in the conventional treatment (1.00 of ET) received the actual amount of water calculated from the various climactic conditions. Irrigation treatments (RDI) were controlled upon the outputs of micro-sprinklers. This research included the use of FanJet Micro-Sprinklers from Bowsmith. RDI treatments were then quantified into the following 5 irrigation categories: 0.50, 0.75, 1.00, 1.25, and

1.50 of evapotranspiration, having into account the previously mentioned irrigation strategies. By altering the emitter sizes to increase or decrease the water application rate, the amount of water applied for each RDI treatment was attained even though the overall run time was the same. In this approach treatment 1.00 RDI (grower standard) was considered to be the control and based on the hours of application, total emitter output (overall water application) and an efficiency factor, the volume of water applied was determined by the following equation:

$$Gallons\ Applied\ =\ Actual\ Hours\ Applied\ x\ Emitter\ Output\ x\ Efficiency\ Factor$$

All emitters were evaluated throughout the growing season at random evaluation events to maintain high efficiency in water application. The Bowsmith micro-sprinkler emitters used for this research had a pressure differential in which irrigation system psi could be used to alter the rate at which fanjets emitted water. In order to ensure maximum efficiency of the irrigation system, the fanjets were maintained at a minimum pressure of 20 psi. There were three random irrigation system events, at each location, when the efficiency and capacity were evaluated. This evaluation included three fanjet sprinklers in which each was analyzed by performing 15 second flows and the pressure (psi) at each. The following equation was used to evaluate the efficiency of each treatment in accordance to evapotranspiration (ET) demand:

$$Avg.Gallons\ Applied\ per\ Emitter\ =\ Hours\ Applied\ x\ Avg.Gallons\ per\ Flow$$

Fertilizers was applied through a fertigation system in which urea-ammonium nitrate (UAN-32), ammonium polyphosphate (10-34-0), magnesium nitrate, potassium thiosulfate (KTS), and sulfuric acid (H_2SO_4) were injected into the irrigation system. Granular Urea (42-0-0) was also applied via broadcast spreader. Foliar applications of micro-nutrient mixes were conducted twice a year to ensure adequate nutritional levels. Such applications included a mixture of elements such as: zinc (Zn), molybdenum (Mo), manganese (Mn), copper (Cu), and iron (Fe) in EDTA form, nitrogen fertilizer it also included in foliar spray mixes. The addition of sulfuric acid was intended for the purpose of reducing the impact of high carbonates and bicarbonates in the irrigation water. The intended pH level for the irrigation water was of 5±0.5 due to high bicarbonate levels. All the fertilizers were applied via irrigation water through a micro-sprinkler (fanjet) irrigation system. Both North and South locations received the following amounts of fertilizer during the growing season: nitrogen (N) – 90-100 lbs/ac, phosphorus (P) – 45 lbs/ac, potassium (K) – 70 lbs/ac, and micros ranged within the rates of 5 lbs/ac (for Mo and Cu) to 20 lbs/ac (for Zn).

Soil moisture profiles were attained using the Diviner 2000 by Sentek™ Technologies. Volumetric water content measurements (θ) were monitored to assess the degree of moisture reduction within the soil profile. The incorporation of this technology allowed for the proper monitoring during a two-month period in which water application was a critical factor. The instrumentation also facilitated the management of RDI levels to ensure that there were no excessive water reductions, thereby, avoiding further crop stress and physiological damage. Soil moisture readings events were conducted on a weekly basis during the two-month period (July and August) time during which was the growing period of most interest. Diviner access tubes were places at approximately 5 feet in depth to represent the active root zone of navel oranges; readings are recorded for every 10 centimeters (3.94 inches) to a maximum depth of 100 centimeters (39.37 inches).

Fruit circumference (cm) were taken and measured via a digital fruit sizing caliper weekly during the months of July and August 2014 to account for fruit circumference growth. Each RDI treatment, contained 25 marked fruits measured weekly with the fruit size caliper. In addition, fruit size was also measured at harvest, along with percentage Brix indices, percent juice, percent solids, and sugar to acid ratio. Protocol for the measurement of these parameters were in accordance with the

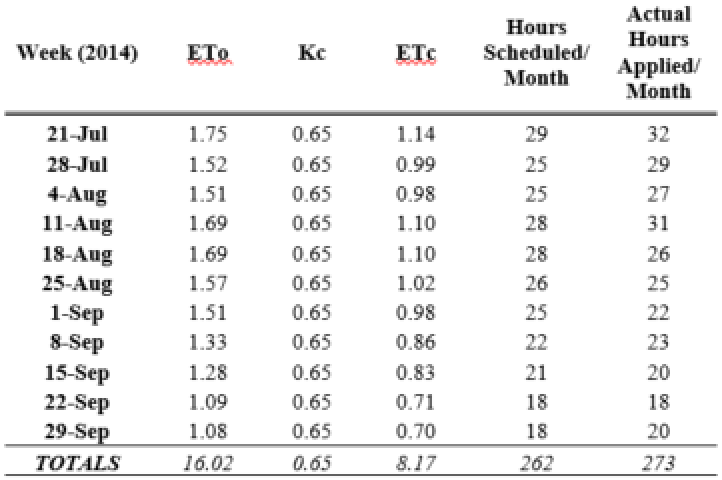
Western Australia Department of Agriculture and Food's methodology for fresh market citrus quality (Western Australia Department of Agriculture and Food, 2014). Briefly, juice extracted from oranges collected from two trees was measured for Brix index using a refractometer. For percent juice and solid, five pieces of fruit were squeezed with a manual press to separate juice (ml) and solid fruit pulp (g). Percent acidity was determined by titration with 0.01N NaOH, and the sugar to acid ratio was calculated. At harvest, data was obtained for total yield (lbs), marketable fruit (fresh market), and non-marketable fruit (culls and juice). Fruit were collected from all sub-plots and subjected to general fruit standards (yield weight (lbs) and fresh market standards) and fruit quality standards (fruit weight (g), fruit solids (g), juice (mL), and sugar to acid ratio). The desired parameters were chosen due to their importance in determining fresh market quality standards and relevance in obtaining high economic yield return (California Citrus Mutual. 2013). The data collected for the growing season was subjected to analysis of variance using univariate general linear model used for split block design using SPSS® software (SPSS, 2013).

In addition to fertigation and crop related data, an assessment of the economic yield was conducted by adopting a partial budget modelling approach. Generally, owners of the citrus farms are often asked to make decisions based on resource constraints and market realities. In many cases, decisions are incremental, such as bringing more land into production, expanding or reducing an enterprise or changing how an enterprise is managed. In this case, climatic factors and plant agronomy were brought together to estimate whether water-saving technology applied to the navel oranges will result in lower yields but higher farm income from better prices.

Results & Discussion

Water Application During Irrigation: Actual run time for water applied during the irrigation of the crop in 2014 is provided in Table 1. Throughout the research, two irrigation uniformity tests were conducted at the beginning and middle end of the study to verify the efficiency of the water application system (Tables 2 and 3).

Table 1: Actual irrigation applied based on ETo and Kc for navel oranges in Woodlake, California from July-September 2014.

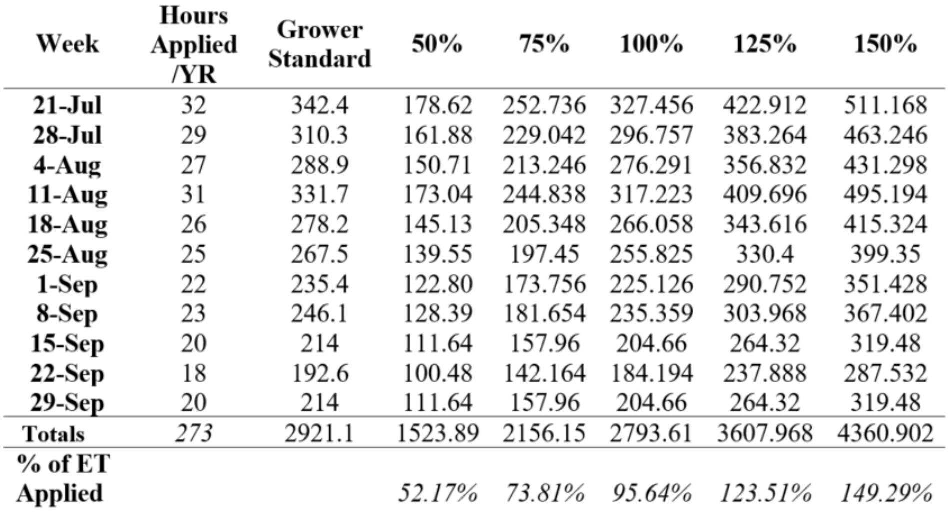


Week (2014)	ETo	Kc	ETc	Hours Scheduled/ Month	Actual Hours Applied/ Month
21-Jul	1.75	0.65	1.14	29	32
28-Jul	1.52	0.65	0.99	25	29
4-Aug	1.51	0.65	0.98	25	27
11-Aug	1.69	0.65	1.10	28	31
18-Aug	1.69	0.65	1.10	28	26
25-Aug	1.57	0.65	1.02	26	25
1-Sep	1.51	0.65	0.98	25	22
8-Sep	1.33	0.65	0.86	22	23
15-Sep	1.28	0.65	0.83	21	20
22-Sep	1.09	0.65	0.71	18	18
29-Sep	1.08	0.65	0.70	18	20
TOTALS	*16.02*	*0.65*	*8.17*	*262*	*273*

At the North and South Locations, the amount of water applied as a percentage of the required ET were close to the rates established for the five RDI treatments. This was facilitated by the use of Bowsmith fanjets which allowed for the control of the water delivery by adjusting emitter output in response to pressure (psi) in the irrigation lines. For the North Location, the 0.50 ET treatment was calculated to be 52.17% of the actual ET with an average pressure of 19.8 psi, the 0.75 treatment was at 73.81% with an average psi of 19.7, the 1.00 treatment was at 95.64% with an average psi of 18.9, the 1.25 treatment was at 123.51% with an average psi of 19.6, and the 1.50 treatment was at 149.29% with an average psi of 19.8 (Table 2). This was indicative that the irrigation system in place was at high efficacy and uniformity.

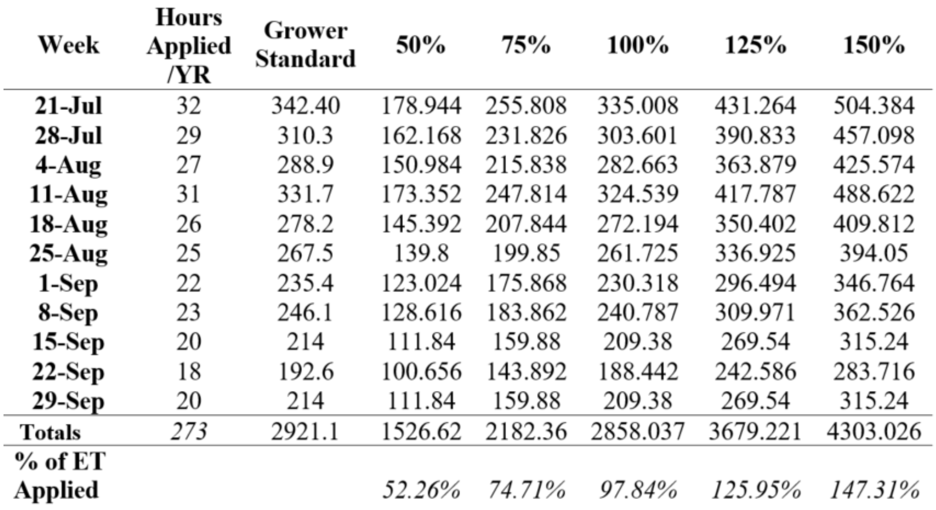
For the South Location, it was established that for the 0.50 treatment the actual amount of the crop ET applied was of 52.26% with an average psi of 20.1, the 0.75 treatment was at 74.71% with an average psi of 19.9, the 1.00 treatment was at 97.84% with an average psi of 19.2, the 1.25 treatment was at 125.95% with an average psi of 20.2, and the 1.50 treatment was at 147.31% with average pressure of 18.9 psi (Table 3).

Table 2: Average emitter output for each treatment throughout the growing season in comparison (%) to evapotranspiration (ET_o) for the North Location.



Week	Hours Applied /YR	Grower Standard	50%	75%	100%	125%	150%
21-Jul	32	342.4	178.62	252.736	327.456	422.912	511.168
28-Jul	29	310.3	161.88	229.042	296.757	383.264	463.246
4-Aug	27	288.9	150.71	213.246	276.291	356.832	431.298
11-Aug	31	331.7	173.04	244.838	317.223	409.696	495.194
18-Aug	26	278.2	145.13	205.348	266.058	343.616	415.324
25-Aug	25	267.5	139.55	197.45	255.825	330.4	399.35
1-Sep	22	235.4	122.80	173.756	225.126	290.752	351.428
8-Sep	23	246.1	128.39	181.654	235.359	303.968	367.402
15-Sep	20	214	111.64	157.96	204.66	264.32	319.48
22-Sep	18	192.6	100.48	142.164	184.194	237.888	287.532
29-Sep	20	214	111.64	157.96	204.66	264.32	319.48
Totals	*273*	2921.1	1523.89	2156.15	2793.61	3607.968	4360.902
% of ET Applied			*52.17%*	*73.81%*	*95.64%*	*123.51%*	*149.29%*

Table 3: Average emitter output for each treatment throughout the growing season in comparison (%) to evapotranspiration (ET_o) for the South Location.



Week	Hours Applied /YR	Grower Standard	50%	75%	100%	125%	150%
21-Jul	32	342.40	178.944	255.808	335.008	431.264	504.384
28-Jul	29	310.3	162.168	231.826	303.601	390.833	457.098
4-Aug	27	288.9	150.984	215.838	282.663	363.879	425.574
11-Aug	31	331.7	173.352	247.814	324.539	417.787	488.622
18-Aug	26	278.2	145.392	207.844	272.194	350.402	409.812
25-Aug	25	267.5	139.8	199.85	261.725	336.925	394.05
1-Sep	22	235.4	123.024	175.868	230.318	296.494	346.764
8-Sep	23	246.1	128.616	183.862	240.787	309.971	362.526
15-Sep	20	214	111.84	159.88	209.38	269.54	315.24
22-Sep	18	192.6	100.656	143.892	188.442	242.586	283.716
29-Sep	20	214	111.84	159.88	209.38	269.54	315.24
Totals	*273*	2921.1	1526.62	2182.36	2858.037	3679.221	4303.026
% of ET Applied			*52.26%*	*74.71%*	*97.84%*	*125.95%*	*147.31%*

The inclusion of the efficiency evaluations during the season was essential in an effort to determine if there were overall inadequacies in the irrigation systems. Overall, the distribution uniformity of the drip irrigation systems was excellent and in accordance with the manufacturer's specifications. More importantly, the experiments at both locations had differences in relative irrigation rates that facilitated the comparison of RDI applied at approximately 0.50, 0.75, 1.00, 1.25 and 1.50 the crop evapo-transpiration (ETc) rates calculated from CIMIS data.

Brix Measurements: RDI on citrus crops has been used to regulate fruit sugar content as explained by Garcia-Tejero et al. (2010) and by Gonzalez-Altozano & Castel (2000) in their research with mandarins (cv. Clementina de Nules) in which RDI was a successful practice to increase Brix content. The desirability for high sugar index in navel oranges has been a primary factor for California citrus growers to develop innovative strategies to increase sugar content. Romero et al. (2006) demonstrated that the introduction of RDI had positive effects in the regulation of sugar level in navel oranges. In the current study the collection of Brix data was conducted monthly on all plots in both the North and South Locations to assess the influence of RDI on fruit sugar levels.

At the North Location, RDI had no significant effect to Brix concentrations for fruits collected during the first month. However, from Months 2 through Harvest there was a significant influence (Month 2: P=0.012, Months 3-Harvest: P=0.000) (Table 5; Figures 1 and 2). The average Brix concentration for oranges subjected to the 0.50 and 0.75 RDI treatments attained the greatest sugar content increase throughout the growing season with Brix indices of 3.67±0.19 in Month 1 and 21.74±0.60 at Harvest for 0.50 RDI; and 3.79±0.17 for Month 1 and 19.59±0.31 at Harvest for the 0.75 RDI treatment. More importantly, at harvest the navel oranges subjected to 0.50 RDI were twice as sweet at those receiving 1.50 RDI. Furthermore, the 1.50 RDI treatment resulted in oranges having the lowest Brix with a mean of 4±0.19 in Month 1 and 12.82±0.45 at Harvest (Figure 3).

Table 4: Significant difference of RDI on Brix in the North Location (α=0.05).

Statistical Significance for Fruit Brix (%) Content: North Location

Month	Irrigation
1	0.857
2	0.012
3	0.000
4	0.000
5	0.000
6	0.000
7	0.000
8	0.000
Harvest	0.008

*Significance (α = 0.05).

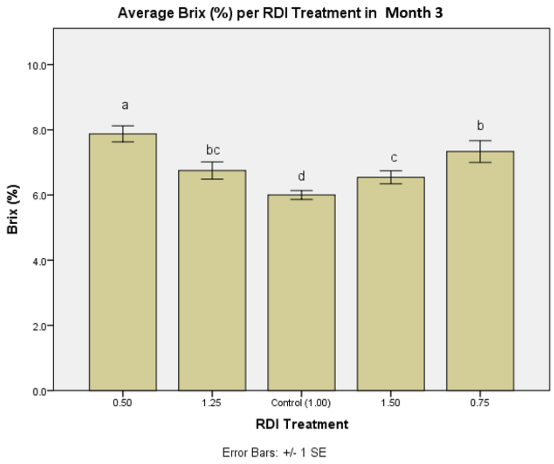


Figure 1: Average Brix index per RDI treatment in the North location in month 3.

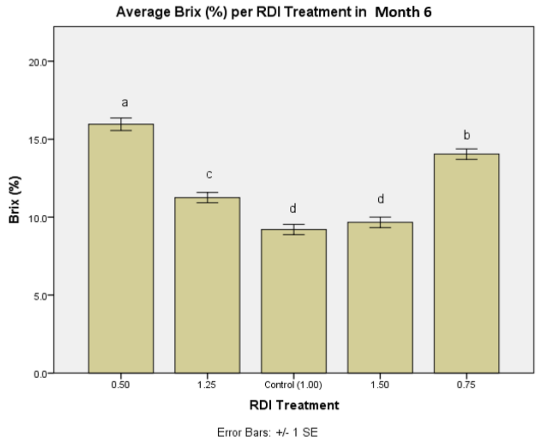


Figure 2: Average Brix index per RDI treatment in the North location in month 6.

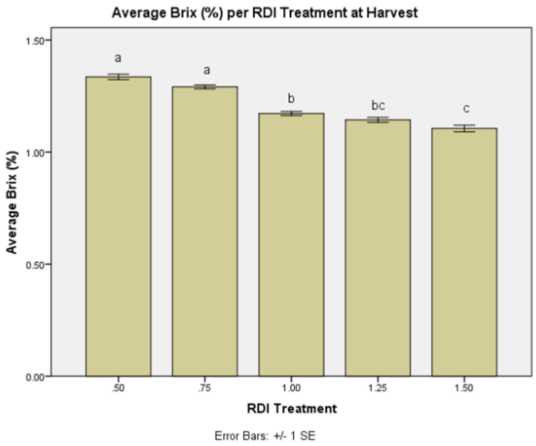


Figure 3: Average Brix index per RDI treatment in the North location in month 6.

As was the case with the North location, there were no significant differences in Brix indices as a function of RDI within the first two sampling events (Table 5; Figures 4 and 5). From Month 3 to Harvest there was a significant effect in Brix levels among the different RDI treatments (Month 3-Harvest all at P=0.000) as the average Brix indices increased from 8.5±0.25 to 20.91±0.45, and from 6.04±0.32 to 12.85±0.39, for oranges receiving 0.50 RDI and 1.50 RDI, respectively. With the exception of Month 4, there was no significant RDI x herbicide interaction effect on Brix levels (Table 5).

Table 5: Significant difference of RDI on Brix in the South Location.

Statistical Significance for Fruit Brix (%)

Content: South Location

Month	**Irrigation**
1	0.513
2	0.503
3	0.000
4	0.000
5	0.000
6	0.000
7	0.000
8	0.000
Harvest	0.000

*Significance (α = 0.05).

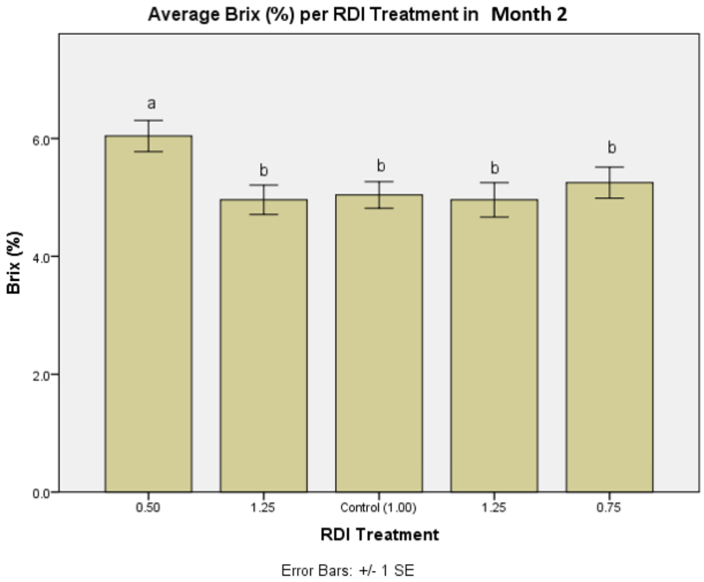


Figure 4: Average Brix index per RDI treatment in the South location in month 2.

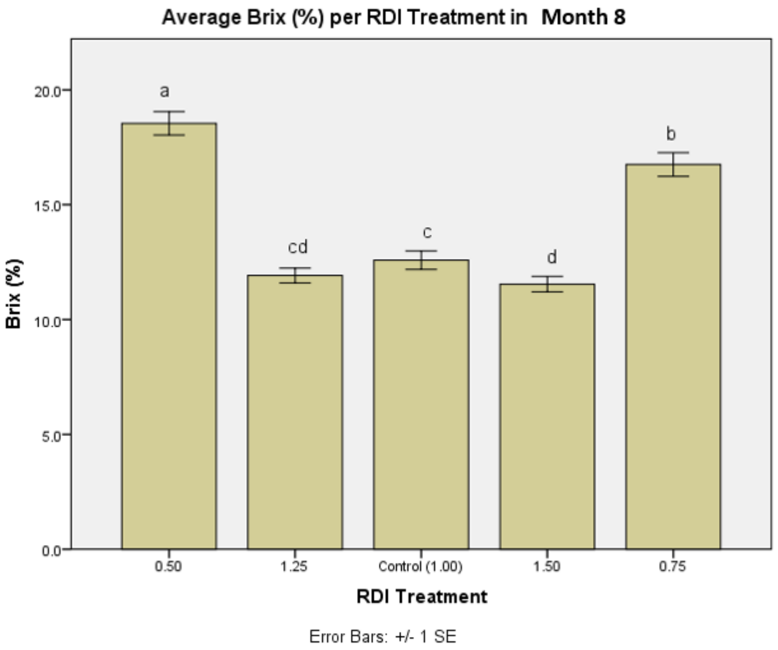


Figure 5: Average Brix index per RDI treatment in the South location in month 8.

These above results are similar to the findings by Romero et al. (2006) in which the sugar content of citrus (cv. Clemenules) increased with a reduction in irrigation. Furthermore, the finding in this study that a reduction in irrigation rates can significantly increase the sugar concentration of navel oranges is consistent with studies conducted on table grapes (Chaves et al., 2007, 2010; Ebel et al., 1993, 1995), pears (Cui et al., 2007), and apples (Ebel et al., 1993). This increase in Brix level in the fruit could be attributed to the induction of enough stress to prevent any further growth but translocation of the photosynthates from the source to the sink (Matthews et al., 1988; Quick et al., 1992). The current study endorses the cultural practice of using RDI to increase Brix levels in the cultivar of navel oranges grown in the Woodlake orchard.

Economic yield: The partial budget modelling was used in this situation given its presentation of incremental changes in the farm operations and how it helps evaluate the financial effect of the intervention. In the current study, the partial budget only included resources that could be changed, such as the reduced water application. Only the change under consideration was evaluated for its potential to vary the farm income. Hence, the partial budgets were based on changes in the following: Increase in income; Reduction or elimination of costs; Increase in costs; and, Reduction or elimination of income. The net impact of the above effects will be the positive financial changes minus the negative financial changes. A positive net indicates that farm income will increase due to the change, while a negative net indicates the change will reduce farm income.

Findings from this study indicate that the price of navel oranges in the Japanese market was an incentive for citrus growers to manage water to benefit from that niche market. In the case of the bulk market, water can be applied up to the point of yield maximization for the bulk market at optimum Brix. There is however, an incentive to reduce water application which can result in a lower yield, measured by fruit weight but a higher brix content. The loss in weight will result in lower revenue using the bulk citrus market model. But, the incentive to produce fruits of lower weight would be compensated through higher prices which more than compensated for the lower yield weight.

Concluding Remarks

- The current study focused on the evaluation of the adoption of RDI as a fertigation strategy for optimizing the sweetness (Brix indices) and economic yield of navel oranges grown in the central SJV, California.
- Firstly, the inclusion of an efficiency assessment of the irrigation system during the season is essential in an effort to determine if there were overall inadequacies in the irrigation systems. Overall, the distribution uniformity of the drip irrigation systems in the current study was excellent and in accordance with the manufacturer's specifications.
- The irrigation system described in the current study comprising micro fertigation sprinklers, commonly referred to as fan jets was suitable comparing the RDI applied at approximately 0.50, 0.75, 1.00, 1.25 and 1.50 the crop evapo-transpiration (ETc) rates calculated from climate data downloadable from California Irrigation Management Information Systems (CIMIS),
- Even though the loss in weight of the navel orange associated with reduced irrigation will result in lower revenue in the local and national bulk citrus market, there is an incentive for growers to produce the navel oranges for international export markets, such as Japan. In the longer term, the lower weight would be compensated through higher prices which can result in a timely return of investment associated with the adoption of the RDI technology.
- The current study endorses the cultural practice of using RDI to increase Brix levels and economic yield for the navel oranges (*Citrus Sinensis* (L.) Osbeck, cv. Washington 'frost nucellar') grown in the Woodlake orchard located in SJV.

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