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Citrus Yield and Fruit Size Can Be Sustained for Trees Irrigated with 25% or 50% Less Water by Supplementing Tree Nutrition with Foliar Fertilization—

Comparison of Conventional Irrigation and Partial Root Zone Drying at the Same Reduced Irrigation Rates Supplemented with Equal Foliar Fertilization

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INTRODUCTION

For California citrus growers, the cost of irrigation water is a major expense associated with citrus production. Irrigation water is nearing $200/acre-foot in the San Joaquin Valley. 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.

Regulated deficit irrigation (RDI) and partial root zone drying (PRD) were developed to further improve water-use efficiency in perennial fruit tree crops to further reduce water use and expense (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. It is important to note that reducing vegetative shoot growth 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 is being used over RDI 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, size or quality, with the exception that the ratio of solids to acid in the juice was lower than that of the control in the first year of the experiment (Loveys et al., 1999).

Our research goal is to meet the challenge of California's water shortage crisis by demonstrating that yield of commercially valuable large-size navel orange fruit (transverse diameter 69-88 mm; 2.7-3.5 inches) can be sustained despite irrigating citrus trees with 25% or 50% less water. The proposed research will test the feasibility of using partial root zone drying (PRD) to reduce the amount of water and soil (irrigation-applied) fertilizer used in citrus production combined with foliar fertilization to sustain the yield of commercially valuable large fruit (Boman, 2002; Lovatt, 1999) and, thus, increase grower net profit. Our approach increases water- and nutrient-use efficiency (WUE and NUE). Our research goal of testing PRD to reduce water use in citrus production and to increase grower net income is not only timely, it might be critical to the sustainability of California's citrus industry.

OBJECTIVES

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 using irrigation rates, which are 25% and 50% less than the well-watered control under conventional irrigation (CI).
2. To compare the PRD treatments with CI at the reduced rates (CI-RR) of 25% and 50% less 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, and on return bloom for two crop-years compared to well-watered control trees receiving soil fertilization.
4. To provide a cost:benefit analysis of the results to the growers.

DESCRIPTION

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 using irrigation rates that are 25% and 50% less than the well-watered control under conventional irrigation (CI). To determine if it is necessary to alternately wet and dry the two sides of the tree to reduce water use without reducing yield, the PRD treatment is compared with CI at the reduced rates (CI-RR) of 25% and 50% less than the well-watered control. The irrigation treatments imposed follow:

1. Well-watered control (based on evaporative demand) – trees have an emitter on each side of the five trees within the row so that both sides of the tree are wet. Evaporative demand based on CIMIS is used to set the amount of water to be applied to the well-watered control. We are using historical and real time weather data (CIMIS) to predict the amount of water the trees will need in the up-coming 4-day period. Treated trees receive 25% or 50% less than this amount. All treatments are irrigated when soil moisture content is –30 cb at a depth of 30 cm for the well-watered control trees, which may occur before the end of 4 days.
2. 25% PRD – 25% less water than well-watered control – trees have an emitter on each side of the five trees within the row, which alternate in delivery of the tree and then the other.
3. 50% PRD – 50% less water than well-watered control – trees have an emitter on each side of the five trees within the row that alternate in delivery to one side of the tree and then the other.
4. 25% CI-RR – 25% less water than well-watered control – trees have an emitter on each side of the fives trees within the row so that both sides of the tree are wet.
5. 50% CI-RR – 50% less water than well-watered control – trees have an emitter on each side of the five trees within the row so that both sides of the tree are wet.

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, and on return bloom for two crop-years compared to the well-watered control trees receiving soil fertilization. The foliar fertilization treatments applied are the following:

1. A winter prebloom foliar application of low-biuret urea (46% N, 0.25% biuret, 26 kg N/ hectare; 23 lb N/acre) in mid-January to increase floral intensity to sustain yield (Albrigo, 1999; Ali and Lovatt, 1992, 1994; Lovatt et al., 1988).
2. Foliar-applied potassium nitrate (28 kg KNO_3/ hectare; 25 lb KNO_3/acre) applied at dormancy (February) and post bloom (~April) to increase the yield of commercially valuable large size fruit (Boman, 2002); the second potassium nitrate application post-bloom (~April) will target 75% petal fall in the northeast quadrant of the tree, which typically occurs at the end of April or beginning of May.
3. Application of low-biuret urea (46% N, 0.25% biuret, 26 kg N/hectare; 23 lb N/acre) at maximum peel thickness (early to mid-July) to increase yield of commercially valuable large size fruit (transverse diameters of 69-88 mm, 2.7-3.5 inches, respectively) (Lovatt, 1999).

RESULTS AND DISCUSSION

Irrigation was twice a week on Tuesday and Friday. Irrigation amounts were based on UCR campus-based CIMIS ET calculations using current and historic weather data to project the irrigation needs for the well-watered control trees for the up-coming three or four days, respectively. This approach was an improvement over simply replacing the water the trees used in the past three or four days – an approach that only by coincidence meets the actual water needs of the trees. All treatments were irrigated when soil moisture content of the well-watered control trees was –30 cb at a depth of 30 cm. Throughout the experiment, well-watered control trees received 100% of ET. Low-biuret urea-N and KNO_3 fertilizers were applied to the foliage as described above.

In Year 1, from April through May 24, trees in all reduced irrigation treatments received more water than was supposed to be applied. Trees in the 75% PRD and 75% CI-RR treatments received only 15% less water than well-watered control trees and those in the 50% PRD and 50% CI-RR treatments received 30% and 36% less water than well-watered control trees, respectively. From May 24 through November, trees scheduled to receive 75% of this rate (i.e., 25% less water) by conventional irrigation (CI-RR-75%) or by partial root zone drying (PRD-75%) actually received only 22% less water than the well-watered control trees (Note that the difference in the amount of irrigation water applied to trees in the CI-RR-75% and PRD-75% treatments was 0.5%). Trees in the CI-RR-50% and PRD-50% treatments scheduled to receive half as much water as the well-watered control trees actually received 50% and 43% less water than the well-watered control trees, respectively, from May 24 through harvest in November.

By the end of August, average fruit diameter (measured on tree) was significantly reduced for trees in all reduced irrigation treatments compared to the well-watered control (Table 1). Average fruit size was significantly smaller for trees in the 50% CI-RR treatment, which received 6% less water than trees in the 50% PRD treatment. Thus, it is of interest that there was no significant difference in fruit size for trees in the 75% PRD treatment compared to the 50% PRD treatment, despite the fact that the trees in the 50% PRD treatment received 16% less water. It is noteworthy that the smallest fruit (50% CI-RR) were only 10 mm (0.4 inches) smaller than fruit of well-watered control trees, despite receiving 36% less water.

The 22% reduction in irrigation imposed in the 75% PRD and 75% CI-RR treatments for six months resulted in a highly statistically significant reduction in total yield in kilograms of fruit per tree (Table 2). It is worth noting that imposing a reduction of 22% in applied water after May 24 through November did not significantly reduce the total number of fruit per tree (Table 3). Thus, the major effect of the 22% reduction in irrigation rate from May 24 through harvest in November by either conventional irrigation or PRD was an effect on fruit weight and packout (fruit size distribution). The 22% reduction in irrigation translated into a significant reduction in kilograms and number of fruit in all commercially marketable fruit size categories and especially in commercially valuable large size fruit of packing carton sizes 88, 72, and 56 compared to well-watered control trees (Tables 2 and 3). Six months of 22% less water significantly reduced the average weight of individual fruit and both juice weight and juice volume per fruit (Table 4). The reduced juice content of the fruit significantly increased both the total soluble solids (TSS, ºbrix) and percent acidity of the fruit (Table 4). Since both these quality parameters were increased, there was no significant effect of irrigation rate on the solids to

Table 1: Effect of reducing irrigation rate 25% or 50% by conventional irrigation (75% CI-RR and 50% CI-RR, respectively) or partial root zone drying (75% PRD and 50% PRD, respectively) on average fruit size of the 'Washington' navel orange compared to well-watered control trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside. Fruit transverse diameter was measured in August 2010.

Treatment [z]	Whole Tree	Tree Quadrant			
		North	East	South	West
	fruit diameter (mm) [y]				
Control	49.97 a [x]	50.76 a	51.29 a	49.15 a	48.69 a
75% CI-RR	46.47 b	46.41 b	45.94 b	47.40 ab	46.14 ab
50% CI-RR	39.96 c	40.90 c	40.05 c	40.16 d	38.71 c
75% PRD	45.34 b	45.54 b	46.28 b	45.65 bc	43.98 b
50% PRD	43.81 b	43.58 bc	44.22 bc	42.83 cd	44.62 b
P-value	<0.0001	<0.0001	0.0002	<0.0001	<0.0001

[z] Compared to the well-watered control trees, trees in the 75% CI-RR and 75% PRD treatments received 15% less water from April through May 24 and 22% less water from May 24 through harvest in November; trees in the 50% CI-RR and 50% PRD treatments received 36% and 30% less water from April through May 24, respectively, and 50% and 43% less water from May 24 through harvest in November, respectively. Well-watered control trees received 100% ET over the entire year.

[y] 25.4 mm = 1 inch.

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

Table 2: Effect of reducing irrigation 25% or 50% by conventional irrigation (75% CI-RR and 50% CI-RR, respectively) or partial root zone drying (75% PRD and 50% PRD, respectively) on yield and fruit size (kg/tree) of 'Washington' navel orange trees compared to well-watered control trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside. Harvest was in November 2010.

Treatment [z]	Total	Packing Carton Size					
		56	72	88	113	138	56+72+88
		81-88 mm	75-80 mm	69-74.9 mm	63.5-68.9 mm	60-63.4 mm	69-88 mm
	kg per tree [y]						
Control	259.2 a [x]	2.8 a	5.9 a	33.4 a	71.7 a	86.1 a	42.1 a
CI-RR-75%	220.0 b	0.1 b	0.7 b	3.2 b	14.8 bc	58.0 b	4.0 b
CI-RR-50%	135.3 c	0.0 b	0.0 b	0.0 b	1.0 c	7.9 c	0.0 b
PRD-75%	200.2 b	0.1 b	0.4 b	5.6 b	23.5 b	46.2 b	6.1 b
PRD-50%	154.4 c	0.1 b	0.5 b	2.9 b	6.7 bc	23.5 c	2.7 b
P-value	<0.0001	0.0811	<0.0001	<0.0001	<00001	<0.0001	<0.0001

[z] Compared to the well-watered control trees, trees in the 75% CI-RR and 75% PRD treatments received 15% less water from April through May 24 and 22% less water from May 24 through harvest in November; trees in the 50% CI-RR and 50% PRD treatments received 36% and 30% less water from April through May 24, respectively, and 50% and 43% less water from May 24 through harvest in November, respectively. Well-watered control trees received 100% ET over the entire year.

[y] 25.4 mm = 1 inch; 1 kg = 2.2046 lbs.

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

Table 3: Effect of reducing irrigation rate 25% or 50% by conventional irrigation (75% CI-RR and 50% CI-RR, respectively) or partial root zone drying (75% PRD and 50% PRD, respectively) on yield and fruit size (number of fruit/tree) of 'Washington' navel orange trees compared to well watered control trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside. Harvest was in November 2010.

Treatment [z]	Total	Packing Carton Size					
		56	72	88	113	138	56+72+88
		81-88 mm	75-80 mm	69-74.9 mm	63.5-68.9 mm	60-63.4 mm	69-88 mm
	------ no. of fruit per tree ------						
Control	2335 a[y]	10 a	26 a	192 a	497 a	809 a	228 a
CI-RR-75%	2624 a	0 b	3 b	18 b	103 bc	545 b	22 b
CI-RR-50%	1805 b	0 b	0 b	0 b	7 c	74 c	0 b
PRD-75%	2328 a	0 b	2 b	32 b	163 b	434 b	34 b
PRD-50%	1939 b	0 b	2 b	13 b	46 bc	221 c	15 b
P-value	<0.0001	0.0811	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z] Compared to the well-watered control trees, trees in the 75% CI-RR and 75% PRD treatments received 15% less water from April through May 24 and 22% less water from May 24 through harvest in November; trees in the 50% CI-RR and 50% PRD treatments received 36% and 30% less water from April through May 24, respectively, and 50% and 43% less water from May 24 through harvest in November, respectively. Well-watered control trees received 100% ET over the entire year.

[y] 25.4 mm = 1 inch.

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

Table 4: Effect of reducing irrigation 25% or 50% by conventional irrigation (7% CI-RR and 50% CI-RR, respectively) or partial root zone drying (75% PRD and 50% PRD, respectively) on fruit quality of 'Washington' navel orange trees located at the Citrus Research Center and Agricultural Experiment Station of the University of California-Riverside. Harvest was in November 2010.

Treatment	Fruit Weight (g)	Juice Weight (g)	Juice Volume (ml)	TSS (°brix)	Acid (%)	TSS:acid
Control	123.9 a[z]	42.8 a	14.9 a	12.9 d	1.4 c	9.2
CI-RR-75%	89.6 b	28.4 b	9.1 b	14.6 c	1.7 b	8.8
CI-RR-50%	70.8 c	16.7 d	4.1 d	16.9 a	2.1 a	8.4
PRD-75%	95.7 b	28.6 b	8.7 bc	14.9 c	1.7 b	8.8
PRD-50%	84.1 b	23.1 c	6.5 c	16.0 b	1.8 b	9.2
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1332

[z] Compared to the well-watered control trees, trees in the 75% CI-RR and 75% PRD treatments received 15% less water from April through May 24 and 22% less water from May 24 through harvest in November; trees in the 50% CI-RR and 50% PRD treatments received 36% and 30% less water from April through May 24, respectively, and 50% and 43% less water from May 24 through harvest in November, respectively. Well-watered control trees received 100% ET over the entire year.

[y] 28.4 g = 1 ounce; 473 ml = 1 pint.

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

acid ratio (TSS:Acid) of individual fruit. The ratio of solids to acid was low due to the fact that November was early for the harvest of 'Washington' navel oranges trees in 2010. However, the November harvest was necessary to prevent differences in crop load that occurred in response to the differences in irrigation rates in Year 1 from impacting floral intensity and thus crop load in year 2. For trees receiving 22% less irrigation water, there were no significant differences in yield, fruit size or fruit quality related to irrigation method, i.e., conventional irrigation or partial root zone drying. Providing extra N and K via foliar fertilization did not mitigate the negative effects of reducing the irrigation rate by as little as 25% on fruit size and yield.

Both the total kilograms and number of fruit per tree were significantly less for trees in the CI-RR-50% and PRD-50% treatments than for trees in the CI-RR-75% and PRD-75% treatments and the well-watered control trees (Tables 2 and 3). Thus, the reduced amount of irrigation water applied to trees in these treatments increased fruit abscission and decreased fruit growth. All trees receiving less irrigation water than the well-watered control trees produced less kilograms and number of fruit of packing carton sizes 56, 72 and 88, but there were no significant differences among trees irrigated with 22%, 43% or 50% less water than the well-watered control trees. These differences in irrigation rate, however, had an impact on the kilograms and number of fruit per tree of packing carton sizes 113 and 138, consistent with an effect of irrigation treatment on fruit retention and fruit size (Tables 2 and 3). There was an obvious positive correlation between irrigation rate and the juice weight and juice volume of individual fruit, i.e., as irrigation rate increased, juice weight and volume per fruit increased (Table 4). Interestingly, fruit with lower juice volume had higher total soluble solids and percent acidity, clearly an effect due to concentration. Because both total soluble solids and acidity changed in parallel, there was no effect of irrigation rate on total soluble solids to acid ratio. Note that the 7% lower rate in irrigation for trees in the CI-RR-50% versus PRD-50% treatment resulted in a significant difference in fruit quality.

Due to the very negative effects on yield that resulted from reducing the amount of irrigation by 43% to 50% in Year 1, and in prior experiments, it seemed illogical to continue to impose a reduction in irrigation rate > 25%. Thus, in a further attempt to meet our goal of reducing the amount of irrigation water used in citrus production without reducing yield, fruit size and grower income, in Year 2, rather than just confirming that the 50% CI-RR and PRD treatments do not work, we increased the irrigation rate in these treatments to just 25% less than the well-watered control trees and applied the cytokinin 6-benzyladenine (6-BA) with each irrigation starting in July. These trees are now referred to as 25% CI-RR + 6-BA and 25% PRD + 6-BA. The treatment is based on the well-known roles of cytokinins in fruit growth and increasing fruit size and on an accumulating body of literature that cytokinins protect plants from water-deficit stress. It rained in January through May, with significant precipitation in February and March. Thus, in Year 2, the reduced irrigation treatments could not be imposed until the end of May. From June 1 through July 7, trees in the 75% CI-RR and 75% PRD received 28% and 21% less water than the well-watered control trees, respectively. Trees in the 75% CI-RR + 6-BA and 75% PRD + 6-BA treatments received 26% less and 5% more water than well-watered control trees, respectively. The latter was due to a malfunction in the flow meter. Measurement of the transverse diameter of 25 fruit in each of the four quadrants of the three data trees in each of the five replications per treatment (15 trees total for a total 7,500 fruit measured) on July 7 and 8 indicated that over this short period of time there were no significant treatment effects on fruit size (Table 5). By September 5, 2011, trees in the 75% CI-RR and 75% PRD received 22% and 21% less water than the well-watered control tree, respectively. Trees in the 75% CI-RR + 6-BA and 75% PRD + 6-BA treatments received 26% and 15% less water than the well-watered control trees, respectively, and also received ~ 0.5 g/tree 6-BA. All trees in the reduced irrigation experiments received the foliar fertilization treatments as described above. Differences in fruit transverse diameter were quantified on September 1 (Table 6). At present, the 6-BA is without effect. We will continue to measure fruit transverse diameter. Each tree will receive 3 g 6-BA/tree by October 13. Harvest for Year 2 will be in November 2011.

PRELIMINARY FINDINGS

The results of this research taken together with the results of earlier research provide clear evidence that 'Washington' navel orange trees are highly sensitive to even slight water deficit during the following periods: (i) phase transition, the period when shoot apical

Table 5: Effect of reducing irrigation rate 25% by conventional irrigation (75% CI-RR) or partial root zone drying (75% PRD) on average fruit size compared to well-watered control trees. Fruit transverse diameter was measured in July 2011.

Treatment [z]	Whole Tree	Tree Quadrant			
		North	East	South	West
	fruit diameter (mm) [y]				
Control	39.9 a [x]	38.7 a	38.4 a	43.4 a	39.3 a
75% CI-RR	41.3 a	38.7 a	40.8 a	44.8 a	40.8 a
75% CI-RR + 6-BA	38.3 a	35.7 a	38.8 a	41.9 a	37.8 a
75% PRD	39.9 a	36.9 a	40.3 a	42.8 a	39.7 a
75% PRD + 6-BA	39.7 a	36.8 a	38.9 a	43.3 a	39.7 a
P-value	0.2739	0.1428	0.2511	0.3291	0.3773

[z] From June 1 to July 7, trees in the 75% CI-RR and 75% PRD treatments received 28% and 21% less water than well-watered control trees, respectively; trees in the 75% CI-RR + 6-BA and 75% PRD + 6-BA treatments received 26% less and 5% more water than well-watered control trees, respectively; 6-BA was not applied until after the data reported here were collected. Well-watered control trees received 100% ET over the entire year.

[y] 25.4 mm = 1 inch.

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

Table 6. Effect of reducing irrigation rate 25% by conventional irrigation (75% CI-RR) or partial root zone drying (75% PRD) and supplying 6-benzyladenine via the irrigation (1 g/acre from July -Sept.) on average fruit size compared to well-watered control trees. Fruit transverse diameter was measured in September 2011.

Treatment [z]	Whole Tree	Tree Quadrant			
		North	East	South	West
	fruit diameter (mm) [y]				
Control	57.1 a[x]	55.9 a	55.4 a	59.3 a	57.9 a
75% CI-RR	56.9 a	55.5 a	56.9 a	58.2 ab	56.9 ab
75% CI-RR + 6-BA	52.8 b	51.8 b	52.1 b	54.0 c	53.2 c
75% PRD	54.7 ab	54.3 ab	54.0 ab	56.1 bc	54.5 bc
75% PRD + 6-BA	54.8 ab	53.6 ab	54.4 ab	56.8 abc	54.5 bc
P-value	0.0203	0.069	0.0593	0.0078	0.0298

[z] From June 1 to July 7, trees in the 75% CI-RR and 75% PRD treatments received 28% and 21% less water than well-watered control trees, respectively; trees in the 75% CI-RR + 6-BA and 75% PRD + 6-BA treatments received 26% less and 5% more water than well-watered control trees, respectively. From July 7 to September 5, trees in the 75% PRD and 75% CI-RR treatments received 22% and 21% less water than well-watered control trees, respectively; trees in the 75% PRD + 6-BA and 75% CI-RR + 6-BA treatments received 26% and 15% less water than well watered control trees, respectively, and ~ 0.5 g/tree 6-BA. Well-watered control trees received 100% ET over the entire year

[y] 25.4 mm = 1 inch.

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

buds change from vegetative to floral development (December); (ii) irreversible commitment to floral development, the point in floral development beyond which flowering cannot revert to vegetative growth (the first week of January in Riverside); (iii) flower opening (March-April); and (iv) fruit set (April-May). Further, fruit of the 'Washington' navel orange are very sensitive barometers of irrigation rate. Differences of only 22% for six months from June to harvest in November reduced fruit size (transverse diameter) and fruit weight, reducing both the kilograms and number of fruit per tree in all commercially marketable size categories. In particular, larger, more commercially valuable fruit of packing carton sizes 88, 72 and 56 were fewer, reducing the total kilograms of fruit per tree but not the total number of fruit per tree. Further reductions in irrigation rate exacerbated these problems. Foliar fertilization did not compensate for reduced irrigation rates during Year 1. The results of the first year of this research reinforces the importance of adequately irrigating navel orange citrus trees for maximum yield of commercially valuable large size fruit of packing carton sizes 88, 72, and 56.

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