

# Fertilizer Composition, Concentration, and Irrigation Method Affect Growth and Development of *Oxalis regnellii* and *O. triangularis*

Chad T. Miller<sup>1</sup>, Neil S. Mattson, and William B. Miller

Department of Horticulture, Cornell University, 159 Plant Science Building, Ithaca, NY 14853

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**Abstract.** *Oxalis regnellii*, the shamrock plant, and *O. triangularis* are niche ornamental greenhouse crops produced and marketed primarily for their foliage; thus, it is imperative to produce the fullest, most colorful, and blemish-free plants as possible. An experiment was conducted using *O. regnellii*, comparing two irrigation methods, overhead (drip) irrigation versus subirrigation, in addition to varying 20N–2.2P–16.6K fertilizer concentrations, 50, 100, 200, 300, and 500 mg·L<sup>-1</sup> nitrogen (N). Overhead irrigation produced larger plants with increased root mass as compared with subirrigation. Low or high fertilizer concentration (50 mg·L<sup>-1</sup> N and 500 mg·L<sup>-1</sup> N, respectively) led to reductions in the fresh and dry weight of overhead-irrigated plants compared with intermediate fertilizer rates. At the highest fertilizer treatment, plant height was decreased. Chlorophyll index (based on SPAD readings) increased linearly and quadratically for subirrigated and overhead-irrigated plants, respectively. A second study analyzed the effects of seven different fertilizer formulations on growth of *O. regnellii* and *O. triangularis*. The fertilizers used in this study were Jack's LX All Purpose (21N–2.2P–16.6K), Peter's Professional (20N–8.8P–16.6K), Jacks Poinsettia FeED Ca-Mg (15N–1.7P–12.5K), Jack's Petunia FeED Mg (20N–1.3P–15.7K), Peter's Professional Peat-Lite Dark Weather Feed (15N–0P–12.5K), Peter's Excel Cal-Mag (15N–2.2P–12.5K), and the slow-release fertilizer Osmocote® (14N–4.2P–11.6K). Growth of both species was significantly reduced by fertilizers that contained little or no phosphorus (P). Current water-soluble fertilizer recommendations of 21N–2.2P–16.6K or slow-release granule fertilizer of 14N–4.2P–11.6K (Osmocote®) produced acceptable, marketable plants, whereas the best *O. regnellii* and *O. triangularis* plants were produced using 15N–2.2P–12.5K and 20N–1.3P–15.7K formulations, likely as a result of the additional calcium (Ca), magnesium (Mg), and iron (Fe) in the mixtures.

*Oxalis regnellii*, the shamrock plant, is a niche crop produced primarily for the St. Patrick's Day holiday (De Hertogh and Le Nard, 1993; Dole and Wilkins, 2005). Fertilization recommendations for oxalis are limited. De Hertogh and Le Nard (1993) recommend using 14N–4.2P–11.6K Osmocote® (no rate specified) after visible growth or a weekly liquid application of 200 mg·L<sup>-1</sup> N of 20N–8.8P–16.6K in the irrigation water. Leaf chlorosis has been reported during greenhouse production and has been hypothesized to be Fe deficiency (De Hertogh, 1996; De Hertogh and Le Nard, 1993; Dole and Wilkins, 2005; Hammer, 2006). Iron deficiency is a common disorder that affects many plant species and is often the first micronutrient that becomes limiting in greenhouse media as pH rises (Nelson, 1994). In addition to high substrate pH, another potential cause of Fe deficiency is poor root system growth attributable to

disease, poor substrate aeration, and excessive watering (Nelson, 1994).

Many oxalis species are found in nature in the understory (Brickell and Zuk, 1996). Under high light conditions, leaves fold downward, a response similar to water stress. In *O. montana*, Comerro and Briggs (2000) suggest this leaf folding is a hydropassive response as the plant reorients its leaves as a result of lower water potential from increased transpiration. If greenhouse growers do not assess the cause of wilted leaf appearance, they may unwittingly overwater oxalis, causing root damage and subsequent induced nutrient deficiencies, including Fe. Therefore, a better understanding of a more efficient watering practice would be beneficial.

There are a vast number of species and cultivars produced in the floriculture sector, and often times, cultural guidelines are lacking for specialty niche crops. A major drawback to developing cultural guidelines is that species and even cultivars do not all respond similarly to nutrition and irrigation rates and practices. Overhead irrigation (e.g., hand, boom, drip) and subirrigation (e.g., ebb and flow) are two irrigation methods commonly

used in the greenhouse industry and each system has advantages and limitations. A major advantage to overhead irrigation compared with subirrigation is the ability to control soluble salt levels through leaching. Overhead drip irrigation and boom watering systems, as compared with hand watering, can also reduce labor costs and can improve efficiency of water delivery (Hall, 1980; Harbaugh et al., 1986). Major drawbacks to overhead irrigation, particularly hand irrigation, include labor costs and the potential for poor water use efficiency. Another drawback to overhead irrigation is the potential for unsightly mineral residue on foliage from fertilizer applications, compromising crops marketed primarily for their foliage characteristics such as oxalis. Other drawbacks to overhead irrigation include potential for clogged emitters, increased susceptibility for foliar diseases, and foliage deflecting water, reducing penetration to the media.

Like with overhead irrigation, there are positive and negative implications associated with subirrigation (e.g., ebb and flow, tray, trough, floor flooding). There is the potential to reduce labor costs because many plants can be irrigated at the same time and often with the push of a button. Subirrigation also has the potential to improve water and fertilizer use efficiency (Dole et al., 1994; Holcomb et al., 1992; Uva et al., 1998) because the irrigation water is often collected and recirculated, reducing input costs (i.e., fertilizer) and reducing runoff and nutrient leaching. Currently, with increasing social concerns regarding water use and nutrient runoff, it is imperative to conduct, at minimum, small-scale trials to determine efficient but effective irrigation practices for individual species. Another benefit to subirrigation is reduced susceptibility for foliar diseases with little to no water contacting the foliage. However, there is an increased risk for spread of disease between plants, particularly soilborne pathogens, when using an ebb and flood system with recirculated water. A major production challenge with subirrigation is that soluble salts can accumulate, because leaching does not occur (Kang et al., 2004), which can reduce plant growth and development (Todd and Reed, 1998). The costs associated with installing or retrofitting a greenhouse can also be a limiting factor for implementing subirrigation.

Greenhouse fertilization of floriculture crops typically uses fertilizers dissolved in and delivered through the irrigation water. Selecting the appropriate fertilizer composition is important to ensure adequate and not deficient or toxic amounts of nutrients. An important consideration in selecting a fertilizer is the ratio of ammonium to nitrate-N, because the N source of the fertilizer affects its potential for increasing or decreasing substrate pH (Marschner, 1995; Reed, 1996). Moreover, the N source and growing temperature interaction is important to consider (Barker and Mills, 1980). For example, under cool greenhouse conditions, the propensity for toxic ammonium-N to accumulate in plants is greater. This would be important

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<sup>1</sup>To whom reprint requests should be addressed; e-mail ctmiller@ksu.edu.

with *O. regnellii* production in northern greenhouses, because the crop is primarily forced during the time of year in which growers often try to save energy by using as little heat as possible, which could potentially result in ammonium toxicity. Other important considerations for fertilizer selection include the fertilizer trace element charge, the content of Ca and Mg, and potential acidity or basicity (Bierbaum, 1997; Reed, 1996). Careful fertilizer selection not only aids in optimal plant growth, but can also reduce production costs and nutrient runoff (Elliot, 1990; Uva et al., 1998).

With little information regarding fertilizer recommendations and irrigation practices of greenhouse production of oxalis, two experiments were designed with the following objectives: 1) to determine the effects of fertilizer concentration and irrigation method on growth of *O. regnellii*; and 2) to investigate the effect of fertilizer formulation on growth and development of *O. regnellii* and *O. triangularis*.

## Materials and Methods

*Expt. 1: Irrigation method and fertilization concentration.* *Oxalis regnellii* rhizomes from a commercial Dutch supplier (Leo Berbee Bulb Co., Marysville, OH) were used in this experiment. Five rhizomes ( $\approx 2$  to 3 cm) for each irrigation and fertilizer treatment combination were planted singly (experimental unit) in 10-cm (0.5-L) standard plastic pots on 28 Apr. 2009 using a commercial peat-based media substrate (Metro Mix 360; Sun Gro Horticulture Ltd., Vancouver, Canada). *Oxalis* plants were grown in a greenhouse under ambient light and photoperiod conditions at 42° N latitude at 21 °C  $\pm$  0.02 (mean  $\pm$  SE). Plants were spaced so that plant canopies would not

touch, encompassing  $\approx 1.5$  ft<sup>2</sup> per pot. The treatments were arranged as a split plot with irrigation method as the main plot factor and fertilizer concentration as the subplot factor. The five experimental units for each fertilizer treatment were randomly arranged on each bench.

Pots were irrigated using one of two irrigation treatments: subirrigation or overhead irrigation (drip irrigation). Plants were irrigated daily, or as needed, with one of five fertilizer treatments: 50, 100, 200, 300, or 500 mg·L<sup>-1</sup> N from a commercial water-soluble fertilizer that contained 21N-2.2P-16.6K and micronutrients (Jack's Professional LX Water Soluble Fertilizer 21-5-20 All Purpose; J.R. Peter's Inc., Allentown, PA). Supplemental magnesium (MgSO<sub>4</sub>·7H<sub>2</sub>O) to the final rate of 30 mg·L<sup>-1</sup> Mg was added as a result of low Mg levels in the tap water. The municipal tap water had an electrical conductivity (EC) of 0.4 dS·m<sup>-1</sup> and alkalinity of 111 mg·L<sup>-1</sup> CaCO<sub>3</sub>. Each bench contained its own 525-L reservoir. Fertilizer solutions were mixed directly in each reservoir at the final solution concentration. These were replaced as needed (approximately every 3 weeks) when the reservoir level dropped below 100 L. Submersible pumps connected to a manually operated switch were used to deliver the water to the subirrigation trays or the drip irrigation lines. For the subirrigation treatment, trays were filled to 3 cm, which required  $\approx 5$  min. Once the pumps were turned off, it took 10 min for benches to drain. Pots were irrigated to effective water-holding capacity. Overhead-irrigated plants were irrigated daily by manually turning on a drip irrigation system until water just began to leach out of the bottom of containers, i.e., leaching fraction  $\approx 5\%$ .

Data collected after 5 weeks included pH and EC, leaf fresh weight (FW) and dry weight (DW), root dry weight (RDW), plant height and diameter with diameter being calculated as the average of two perpendicular measurements, and SPAD meter readings (Minolta Chlorophyll Meter SPAD-502; Spectrum Technologies, Plainfield, IL) of five randomly selected leaves, one per experimental unit (plant), to determine chlorophyll index. All statistical analyses were conducted using JMP Version 8 (SAS Institute, Cary, NC). Two-way analysis of variance (ANOVA) tests were conducted to identify differences in the measured parameters in response to irrigation or fertilizer treatment. General linear, quadratic, or cubic regression lines were applied as appropriate based on *r*<sup>2</sup> values to determine patterns of the measured parameters in response to fertilizer concentration.

*Expt. 2: Fertilizer formulation.* *Oxalis regnellii* and *O. triangularis* rhizomes (Leo Berbee Bulb Co., Marysville, OH) that were stored at 3 °C for several months were planted on 5 Feb. 2010. Eight rhizomes ( $\approx 2$  to 3 cm) of each species for each fertilizer treatment were individually planted in 10-cm (0.5-L) pots using a commercial peat-based substrate (pH  $\approx 5.6$ ) (LC1; Sun Gro Horticulture Ltd.) and grown in a greenhouse at 21 °C  $\pm$  0.02 (mean  $\pm$  SE) with ambient light and photoperiod at 42° N latitude. Plants were spaced on 30-cm centers to reduce competition effects and arranged as a completely randomized design. Plants were fertigated, overhead by hand, typically twice per week or as needed at the initial signs of wilting with one of seven fertilizer treatments (Table 1) at 250 mg·L<sup>-1</sup> N. Osmocote® was incorporated in the media mix at the recommended rate of 5 g·L<sup>-1</sup> (2.5 g per pot) and watered with clear

Table 1. Fertilizers used to evaluate growth and development of *Oxalis regnellii* and *O. triangularis*.

Fertilizer	Analysis (%)									CCE <sup>2</sup> (lbs)	Acidity/ basicity	Percent of total NO <sub>3</sub> <sup>-</sup> :NH <sub>4</sub> <sup>+</sup> :(NH <sub>2</sub> ) <sub>2</sub> CO	Media pH <sup>3</sup> /EC
	(N-P-K)	Ca	Mg	B	Fe <sup>4</sup>	Mn	Cu	Zn	Mo				
21-5-20 All Purpose <sup>5</sup>	21-2.2-16.6	—	0.15	0.0210	0.0105	0.1050	0.0525	0.0105	0.0525	407	A	13.08: 7.92: 0.00	6.6/1.90
20-20-20 General Purpose <sup>6</sup>	20-8.8-16.6	—	0.05	0.0068	0.0036	0.0500	0.0250	0.0009	0.0025	555	A	6.07: 3.83: 10.10	5.8/2.10
15-4-15 FeED + Ca + Mg <sup>7</sup>	15-1.8-12.5	4.00	2.00	0.0068	0.0112*	0.1125	0.0563	0.0750	0.0675	77	B	12.12: 2.88: 0.00	6.7/2.17
15-0-15 Dark Weather Peat-Lite <sup>8</sup>	15-0-12.5	10.69	0.00	0.0150	0.0075	0.0750	0.0375	0.0075	0.0375	344	B	13.50: 1.50: 0.00	6.9/2.18
15-5-15 + Ca + Mg <sup>9</sup>	15-2.2-12.5	5.00	2.00	0.0187	0.0187	0.075	0.0325	0.0075	0.0325	131	B	12.00: 3.00: 0.00	6.8/2.40
20-3-19 Petunia FeED + Mg <sup>7</sup>	20-1.3-15.8	—	1.34	0.0200	0.0100*	0.2000	0.0500	0.0100	0.5000	420	A	11.96: 8.04: 0.00	6.6/2.01
14-14-14 Osmocote <sup>8</sup>	14-4.2-11.6	—	—	—	—	—	—	—	—	—	—	5.80: 8.20: 0.00	4.7/3.80

<sup>2</sup>Calcium carbonate equivalent (per ton).

<sup>3</sup>Products of Jr. Peters, Inc., Allentown, PA.

<sup>4</sup>Products of Scotts Company, LLC.; Marysville, OH. No micronutrients supplied.

<sup>5</sup>Values were obtained at the end of the experiment. pH values determined using the pour-through method. pH and EC values for the two species, *O. regnellii* (n = 5) and *O. triangularis* (n = 4), were not significantly different; thus, data were pooled (n = 9).

<sup>6</sup>Iron source was supplied as Fe-EDTA, except those marked with an asterisk, which also included Fe-DTPA and Fe-EDDHA sources.

Ca = calcium; Mg = magnesium; B = boron; Fe = iron; Mn = manganese; Cu = copper; Zn = zinc; Mo = molybdenum; EC = electrical conductivity.

water for each irrigation. The fertilizers chosen are typical greenhouse formulations representing a range of different nitrate: ammonium:urea ratios, varying potential acidity/basicity, nutrient ratios, and Fe form(s) supplied. Some fertilizers provided additional macro- and/or micronutrients such as Fe, Ca, and Mg to enhance plant growth in a greenhouse situation (Table 1).

After 10 weeks, plant height and width (calculated as described previously), FWs and DWs, SPAD meter readings (as described previously), and pH and EC readings (n = 9) were obtained. pH and EC values for the two species, *O. regnellii* (n = 5) and *O. triangularis* (n = 4), were not significantly different; thus, data were pooled (Table 2). Leaf chlorosis ratings were taken. Ratings were determined using a rating scale from 0 to 5: 0 = no chlorosis; 1 = minimal chlorosis, slight yellowing; 2 = general leaf yellowing; 3 = progressed leaf yellowing with initial stages of green veins; 4 = distinct interveinal chlorosis; and 5 = severe chlorosis, often exhibiting bleaching. Dried leaf tissue samples were analyzed at a commercial laboratory to determine tissue nutrient concentrations. For each individual species, one-way ANOVA tests were conducted to identify differences in the measured parameters in response to fertilizer formulation and Tukey's honestly significant difference method was used to conduct pairwise comparisons.

## Results and Discussion

### Expt. 1: Irrigation method and fertilization concentration.

Table 2. pH and electroconductivity (EC) means ( $\pm$  SE) of *Oxalis regnellii* plants grown using either overhead or subirrigation at different fertilizer concentrations after 5 weeks.

Irrigation method	Fertilizer concn (mg·L <sup>-1</sup> N)		
	50	100	200
Overhead	50	7.26 (0.22)	1.30 (0.19)
	100	6.67 (0.22)	1.55 (0.19)
	200	5.12 (0.22)	1.09 (0.19)
	300	4.99 (0.22)	4.89 (0.25)
	500	4.90 (0.22)	3.36 (0.21)
Subirrigation	50	7.38 (0.22)	1.85 (0.34)
	100	6.26 (0.25)	2.67 (0.38)
	200	4.93 (0.22)	7.32 (0.34)
	300	5.24 (0.22)	9.46 (0.34)
	500	5.73 (0.22)	13.23 (0.34)

Table 3. Two-way analysis of variance for the effect of irrigation type (Irr; overhead and subirrigation), fertilizer concentration Conc; 50, 100, 200, 300, and 500 mg·L<sup>-1</sup> N; and the interaction (Irr × Conc) on *Oxalis regnellii* growth parameters.

Main effects and interactions	df	Shoot FW			Shoot DW			Root DW		
		MSE	P value		MSE	P		MSE	P	
Irr	1	3,412	<0.0001		16	0.0008		0.32	<0.0001	
Conc	4	164,485	<0.0001		43	0.0362		0.27	0.0027	
Irr × Conc	4	1,238	0.0148		1	0.6460		0.04	0.2466	
		SPAD			Height			Diameter		
Irr	1	220	<0.0001		34	0.0003		103	0.0003	
Conc	4	176	0.0028		34	0.0134		238	0.0006	
Irr × Conc	4	41	0.0696		7	0.2269		20	0.3197	

MSE = mean square error; FW = fresh weight; DW = dry weight.

concentration and irrigation type were significant for all growth parameters (Table 3). The only significant interaction of fertilizer and irrigation was for shoot FW. For overhead irrigation, the greatest FW occurred between 50 mg·L<sup>-1</sup> N and 300 mg·L<sup>-1</sup> N, whereas no optimal fertility for FW was observed between treatments for subirrigated plants. Fresh weight in overhead-irrigated plants was significantly decreased at 500 mg·L<sup>-1</sup> compared with all other fertilization concentrations (Fig. 1A). Overhead-irrigated plants had greater DW compared with subirrigated plants. Significantly increased DWs occurred at 100 mg·L<sup>-1</sup> compared with 500 mg·L<sup>-1</sup> for both irrigation methods (Fig. 1B). Frett et al. (1985) observed significant reduction of petunia shoot DW with higher N concentrations (400 mg·L<sup>-1</sup>). In both irrigation systems, a cubic response was observed for RDW, for which we do not have a clear explanation. Overhead irrigation and subirrigation rates of 200 mg·L<sup>-1</sup> and 100 mg·L<sup>-1</sup> significantly reduced RDW compared with 50 and 300 mg·L<sup>-1</sup> treatments. In both irrigation methods, 500 mg·L<sup>-1</sup> reduced root RDW by 75% as compared with 300 mg·L<sup>-1</sup> (Fig. 1C).

A negative linear relationship occurred between plant height and N concentration in both irrigation practices, although height was only significantly decreased at the 500 mg·L<sup>-1</sup> level for overhead irrigation compared with the 50 and 100 mg·L<sup>-1</sup> rates (Fig. 2A). Using subirrigation, Poole and Conover (1992) found increasing fertilizer rates did not significantly increase or decrease plant height in three different foliage plants. Similar results were

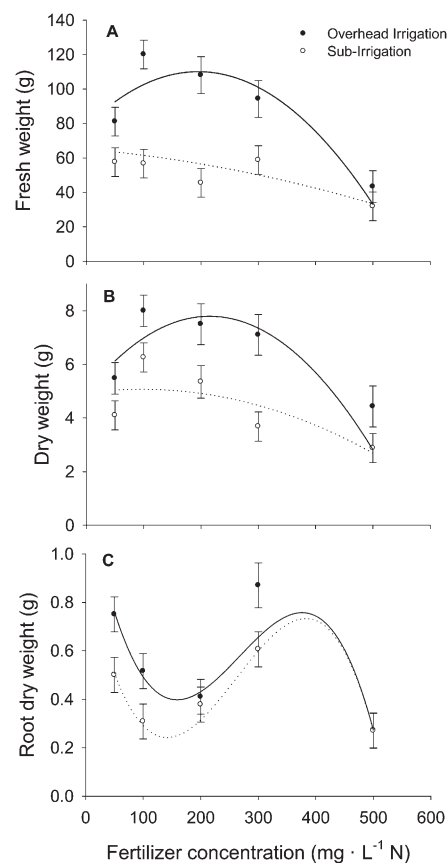


Fig. 1. Effects of irrigation type (overhead and subirrigation) and fertilizer concentration effects on growth parameters of *Oxalis regnellii*. The regression equations, associated *P* values for the associated *F* statistic, and *r*<sup>2</sup> values are as follows: (A) fresh weight: overhead;  $y = -8.28 e^{-4*(x-223.91)^2} - (0.05*x) + 120.04$  ( $P = 0.0021$ ) ( $r^2 = 0.46$ ); subirrigation;  $y = -6.78 e^{-5*(x-243.48)^2} - 0.06*x + 69.09$  ( $P = 0.0060$ ) ( $r^2 = 0.40$ ); (B) dry weight: overhead;  $y = -6.13 e^{-5*(x-223.91)^2} - 0.001*x + 8.04$  ( $P = 0.0045$ ) ( $r^2 = 0.41$ ); subirrigation;  $y = -1.4686 e^{-5*(x-231.25)^2} - (0.004*x) + 5.72$  ( $P = 0.0133$ ) ( $r^2 = 0.34$ ); (C) root dry weight: overhead;  $y = -7.03 e^{-8*(x-227.08)^3} + 8.55 e^{-6*(x-227.08)^2} + 0.002*x - 0.01$  ( $P = 0.0194$ ) ( $r^2 = 0.38$ ); subirrigation;  $y = -7.01 e^{-8*(x-231.25)^3} + 6.49 e^{-6*(x-231.25)^2} + 0.003*x - 0.27$  ( $P < 0.0001$ ) ( $r^2 = 0.68$ ).

observed for both irrigation methods in relation to plant diameter. The smallest plants were observed at 500 mg·L<sup>-1</sup> (Fig. 2B) compared with 100 and 50 mg·L<sup>-1</sup> for overhead and subirrigated plants, respectively.

The greenest plants, or those with the highest SPAD readings, for overhead irrigation were observed at 300 mg·L<sup>-1</sup> and were significantly less green at 50 and 100 mg·L<sup>-1</sup>. In subirrigated plants, SPAD readings increased linearly with increasing N concentration (Fig. 2C). Greener plants were observed at the highest N rates (300 and 500 mg·L<sup>-1</sup>) when compared with the lowest fertilizer rate. Kang and van Iersel (2002) observed chlorophyll content in celosia, dianthus, gomphrena, stock, and zinnia increased as fertilizer solutions increased up to 420 mg·L<sup>-1</sup>.



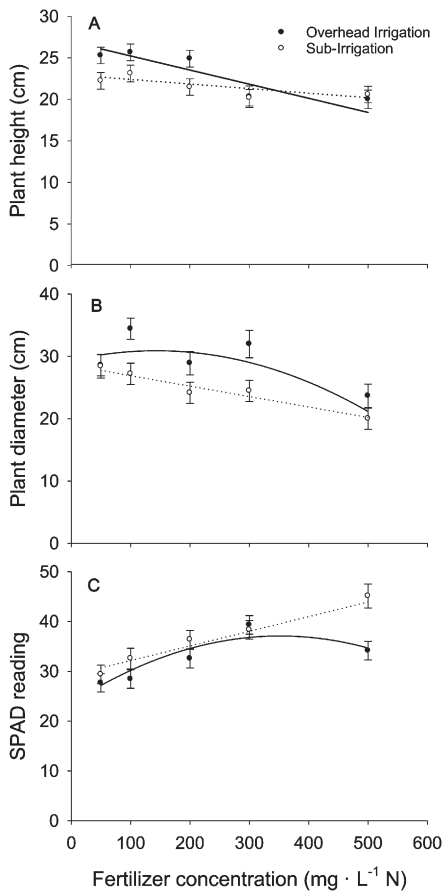


Fig. 2. Effects of irrigation type (overhead and subirrigation) and fertilizer concentration effects on growth parameters of *Oxalis regnellii*. SPAD readings (units) are averages of five readings obtained at destructive harvest per replication. The regression equations, associated *P* values for the associated *F* statistic, and *r*<sup>2</sup> values are as follows: (A) plant height: overhead;  $y = -0.02(x) + 26.92$  ( $P = 0.0004$ ) ( $r^2 = 0.43$ ); subirrigation;  $y = -0.0056(x) + 22.94$  ( $P = 0.0346$ ) ( $r^2 = 0.19$ ); (B) plant diameter: overhead;  $y = -7.66e^{-5}(x-223.91)^2 - 0.012x + 33.16$  ( $P = 0.0100$ ) ( $r^2 = 0.37$ ); subirrigation;  $y = -0.017x + 28.55$  ( $P = 0.0021$ ) ( $r^2 = 0.34$ ); (C) SPAD reading: overhead;  $y = -1.091e^{-4}(x-237.50)^2 + 0.025x + 29.73$  ( $P = 0.0060$ ) ( $r^2 = 0.39$ ); subirrigation;  $y = 0.029(x) + 29.19$  ( $P < 0.0001$ ) ( $r^2 = 0.66$ ).

In the present study, overhead irrigation produced higher quality plants in terms of overall plant stature and increased root mass for *O. regnellii*. High N fertilizer rates, above 300 mg·L<sup>-1</sup> N and rates lower than 100 mg·L<sup>-1</sup> N, should be avoided, because growth of *O. regnellii* is negatively affected. Similar to Dole et al. (1994), Kent and Reed (1996), and Yelanich and Biernbaum (1993), optimal fertilization concentrations are slightly lower for subirrigation methods compared with overhead irrigation, because soluble salt accumulation increased with increasing fertilizer rates (Table 2), which could likely be attributed to less water-leaching events. Generally, whiter, brighter root systems were observed in the overhead-irrigated plants as compared with subirrigated plants and for plants with fertilizer treatments of 200 and 300 L N (personal observation).

**Expt. 2: Fertilizer formulation.** Fertilizer type had significant effects on the measured growth parameters of *O. regnellii* and *O. triangularis* (Table 4). *Oxalis regnellii* plants fertilized with 15N–2.2P–12.5K had significantly higher FW, DW, were taller, and produced wider plants than plants fertilized with 20N–8.8P–16.6K and 15N–0P–12.5K compositions. The greenest *O. regnellii* plants, those with the highest SPAD readings, were produced with 14N–4.2P–11.6K treatments but were just as green as plants fertilized with 20N–1.3P–15.8K. The least chlorotic plants (lowest chlorosis rating) were those fertilized with 20N–1.3P–15.8K containing three different Fe chelate forms, which correlated with the highest leaf tissue Fe concentrations (Table 5). Greatest chlorosis incidence (although only significantly more than fertilizer treatments of 20N–1.3P–15.8K and 14N–4.2P–11.6K) and lower leaf tissue Fe concentrations were observed in plants treated with 15N–0P–12.5K with Fe supplied only in the EDTA form.

*Oxalis triangularis* plant FW increased 2.5 and 1.7 times when fertilized with 20N–1.3P–15.8K compared with those treated with 15N–0P–12.5K and 14N–4.2P–11.6K, respectively. Plant DW decreased significantly by half between plants fertilized with 15N–0P–12.5K as compared with the 20N–1.3P–15.8K formulation. Similarly, plant height and width decreased significantly between those fertilizer formulations. SPAD readings were recorded despite *O. triangularis*' purple leaf appearance and little differences were found between "greenness" levels.

Tissue nutrient analysis indicated that for most fertilizers and tissue concentrations for N, potassium (K), Mg, boron, and copper were in the sufficient range (per commercial laboratory guidelines) for both species (Table 5). Phosphorus tissue levels were acceptable for

all fertilizer treatments except for the fertilizer formulation with no P added (15N–0P–12.5K), in which P levels were deficient in *O. regnellii*. In both species, final plant height was significantly shorter for P-free fertilizer treatments. Phosphorus deficiency is known to reduce plant height (Hansen and Nielsen, 2001; Nelson et al., 2002; Rideout and Overstreet, 2003).

Calcium levels were on the low side of the recommendation levels for sufficient plant growth, even with fertilizer formulations providing extra Ca. Iron levels varied between different fertilizer treatments, as expected. Both 20N–1.3P–15.8K and 15N–1.8P–12.5K fertilizer formulations contain three Fe chelates (Fe EDTA, Fe DTPA, and Fe EDDHA) (Table 1) to increase Fe availability in the case of elevated pH levels. One might expect higher leaf tissue Fe concentrations when fertilizing with the aforementioned fertilizers. Plants fertilized with 20N–1.3P–15.8K had the highest leaf tissue Fe concentrations (85.0 mg·kg<sup>-1</sup>) and lower Ca concentrations, whereas plants fertilized with 15N–1.8P–12.5K had significantly lower leaf tissue Fe concentrations (60.2 mg·kg<sup>-1</sup>) and higher Ca concentrations. The reduced Fe concentration in these tissues despite having several Fe sources available for plant uptake could be the result of an interaction between Fe and additional Ca provided in the 15N–1.8P–12.5K formulation. Manganese (Mn) levels for several fertilizer treatments in *O. regnellii* had Mn levels near the lower sufficiency concentration but should not be of concern. In a previous experiment (manuscript in progress) we found that hydroponically grown oxalis plants grown in Mn-free solutions showed no Mn-deficient symptoms at 27 mg·kg<sup>-1</sup>. This could possibly be explained by a low minimum Mn requirement for oxalis or initial Mn levels in rhizome tissue were sufficient. Molybdenum (Mo)

Table 4. Fertilizer effects on growth and development of *Oxalis regnellii* and *O. triangularis*.<sup>z</sup>

Fertilizer analysis (N–P–K)	Fresh wt (g)	Dry wt (g)	Ht (cm)	Width (cm)	SPAD (units)	Chlorosis rating <sup>x</sup>
<i>O. regnellii</i>						
21–2.2–16.6	36.5 ab <sup>y</sup>	2.58 ab	13.3 ab	21.7 ab	29.1 cd	1.20 ab
20–8.8–16.6	28.0 bc	1.94 b	11.4 bc	20.3 b	31.4 bc	1.13 ab
15–1.8–12.5	31.3 abc	2.24 ab	13.8 ab	21.8 ab	28.5 cd	1.63 a
15–0–12.5	18.8 c	1.78 b	9.38 c	21.7 ab	27.5 d	1.88 a
15–2.2–12.5	45.5 a	3.24 a	14.6 a	24.6 a	29.6 cd	1.00 abc
20–1.3–15.8	34.4 abc	2.50 ab	13.1 ab	24.0 ab	33.9 ab	0.08 c
14–4.2–11.6 (Osmocote®)	28.3 bc	2.39 ab	13.3 ab	23.7 ab	35.8 a	0.50 bc
<i>O. triangularis</i>						
21–2.2–16.6	23.1 abc	1.67 ab	12.7 a	19.2 ab	34.5 ab	—
20–8.8–16.6	26.6 ab	1.81 ab	13.9 a	20.1 a	34.4 ab	—
15–1.8–12.5	22.0 abc	1.68 ab	14.1 a	20.7 a	33.1 b	—
15–0–12.5	12.2 c	1.03 b	7.9 b	16.0 b	35.4 ab	—
15–2.2–12.5	21.0 abc	1.49 ab	12.4 a	19.7 ab	35.8 ab	—
20–1.3–15.8	30.6 a	2.14 a	13.7 a	20.8 a	36.1 ab	—
14–4.2–11.6 (Osmocote®)	18.5 bc	1.38 ab	13.5 a	17.9 ab	38.5 a	—

<sup>z</sup>Plants were fertilized with 250 mg·L<sup>-1</sup> N of a water-soluble fertilizer with each watering or with the slow-release fertilizer Osmocote®. Osmocote® was incorporated into media at the rate of 2.5 g per 10-cm pot.

<sup>y</sup>Letters after values in each column for each species represent mean separation using Tukey's honestly significant difference at *P* = 0.05.

<sup>x</sup>leaf chlorosis ratings that were determined from a rating scale from 0 to 5: 0 = no chlorosis; 1 = minimal chlorosis, slight yellowing; 2 = general leaf yellowing; 3 = progressed leaf yellowing with initial stages of green veins; 4 = distinct interveinal chlorosis; 5 = severe chlorosis, often exhibiting bleaching.

Table 5. Fertilizer effects on leaf tissue nutrient concentrations after 10 weeks in *Oxalis regnellii* and *O. triangularis*.

Fertilizer analysis (N-P-K)	Percent					(mg·kg <sup>-1</sup> )					
	N	P	K	Ca	Mg	B	Fe	Mn	Cu	Zn	Mo
Normal range <sup>2</sup>	3.50–5.50	0.35–1.00	2.00–8.00	0.80–3.00	0.20–1.50	30.0–150.0	60.0–200.0	50.0–200.0	5.00–25.0	30.0–150.0	0.50–5.00
<i>O. regnellii</i>											
21–2.2–16.6	4.35 a <sup>3</sup>	0.44 ab	4.28 a	0.85 bc	0.63 b	54.8 ab	65.5 bcd	57.8 c	13.3 ab	28.5 ab	7.9 b
20–8.8–16.6	4.16 a	0.43 ab	3.98 ab	0.81 c	0.66 ab	39.4 c	74.1 ab	63.6 bc	8.9 cd	22.7 b	3.6 cd
15–1.8–12.5	4.21 a	0.46 a	3.81 bc	1.00 a	0.73 a	36.0 c	60.2 de	82.0 ab	8.9 cd	28.7 ab	8.7 ab
15–0–12.5	3.52 b	0.10 d	2.88 d	0.80 c	0.50 c	48.5 b	49.5 e	67.0 bc	10.4 bc	27.7 ab	7.3 b
15–2.2–12.5	4.04 a	0.44 ab	3.96 b	0.94 ab	0.64 ab	54.3 b	62.7 cd	97.5 a	15.8 a	32.5 a	11.6 a
20–1.3–15.7	4.05 ab	0.27 c	3.93 b	0.88 abc	0.65 ab	57.6 ab	85.0 a	64.0 bc	12.7 ab	27.3 ab	6.3 bc
14–4.2–11.6 (Osmocote <sup>®</sup> )	4.11 a	0.40 b	3.57 c	0.75 c	0.66 ab	63.6 a	72.1 bc	55.2 c	7.04 d	27.7 ab	1.8 d
<i>O. triangularis</i>											
21–2.2–16.6	4.13 a	0.41 a	3.54 a	0.86 ab	0.71 bc	71.5 abc	70.6 bc	70.7 c	10.3 bc	42.7 bc	11.9 b
20–8.8–16.6	3.94 ab	0.42 a	3.53 a	0.83 b	0.71 bc	61.4 bc	78.7 ab	84.1 abc	8.4 d	34.6 de	5.1 c
15–1.8–12.5	3.65 bc	0.39 a	3.15 b	0.92 ab	0.80 a	56.0 c	54.2 d	95.9 ab	9.5 cd	34.5 de	11.8 b
15–0–12.5	3.61 c	0.26 b	3.18 b	0.90 ab	0.68 c	83.4 a	67.0 c	97.1 ab	11.9 b	46.2 ab	20.8 a
15–2.2–12.5	4.25 a	0.43 a	3.58 a	0.95 a	0.74 abc	78.9 a	78.3 ab	101.8 a	15.7 a	49.8 a	18.3 a
20–1.3–15.7	3.98 ab	0.37 a	3.45 ab	0.82 b	0.69 bc	73.5 ab	80.3 ab	71.0 c	8.9 cd	38.2 cd	11.3 b
14–4.2–11.6 (Osmocote <sup>®</sup> )	3.98 ab	0.40 a	3.30 ab	0.83 b	0.77 ab	67.8 abc	88.8 a	73.9 bc	8.3 d	31.0 e	2.8 c

<sup>2</sup>Normal range based on laboratory recommendations.

<sup>3</sup>Letters after values in each column for each species represent mean separation using Tukey's honestly significant difference at  $P = 0.05$ .

N = nitrogen; P = phosphorus; K = potassium; Ca = calcium; Mg = magnesium; B = boron; Fe = iron; Mn = manganese; Cu = copper; Zn = zinc; Mo = molybdenum.

concentrations were significantly higher than the upper sufficiency range, especially for *O. triangularis*. Little information is known for Mo concentration requirements for many plants and Mo toxicities in greenhouse production are not common. In *O. regnellii*, zinc levels were marginally deficient for all fertilizer formulations, with the exception of the 15N–2.2P–12.5K treatment; however, no deficiency symptoms were observed. Zinc deficiencies are uncommon in greenhouse crops (Reed, 1996).

A well-developed, efficient fertilization program requires well-timed and adequate nutrition levels throughout crop production and provides sufficient post-production nutrition in the retail environment for consumers. The controlled-release fertilizer (CRF) (i.e., Osmocote<sup>®</sup>, 14N–4.2P–11.6K) formulation produced marketable plants in our study (although not the largest plants). Oxalis has a short-term production schedule in which CRFs may work well, especially with pre-plant incorporation, which could reduce labor and potential water-soluble fertilizer costs during greenhouse production. Moreover, an added benefit to CRF is greater control over nutrient leaching during greenhouse production based on the interaction of the physical properties of the prill, greenhouse or media temperature, and water application frequency and method (Cabrera, 1997; Haver and Schuch, 1996; Klock-Moore and Broschat, 1999; Lea-Cox, et al., 2001; Medina et al., 2008). Further investigations of CRF application rates and formulations with *Oxalis* forcing are warranted.

Irrigation method, fertilizer concentration, and fertilizer formulation are not the only factors that affect crop production. Other factors include, but are not limited to, temperature (Kang and van Iersel, 2001), light intensity (Masson et al., 1991), growing medium (James and van Iersel, 2001; Poole and Conover, 1992), and specific nutrient proportions (Haley and Reed, 2004). These other

factors should be considered when selecting a specific fertilizer, concentration, and irrigation method to best fit a specific producer's conditions.

Results obtained in these studies provide more information into irrigation and fertilization greenhouse forcing parameters for *O. regnellii* and *O. triangularis*. Because these oxalis plants are marketed mostly for their foliage, it is imperative for oxalis growers to produce the fullest, greenest or reddest, and blemish-free plants as possible.

## Conclusions

Current 21N–2.2P–16.6K and 14N–4.2P–11.6K fertilizer recommendations produced commercially acceptable plants, although larger and potentially more valuable *O. regnellii* and *O. triangularis* plants were produced using the 15N–2.2P–12.5K and 20N–1.3P–15.8K fertilizer formulations, although they were not always significantly different from other fertilizer formulations. Results from the nutrient analysis suggest Ca, Mg, Fe, and Mn have the greatest influence on quality growth and development of *O. regnellii* when using many standard commercial formulations. This is supported by the fact the best performing fertilizers, 15N–2.2P–12.5K and 20N–1.3P–15.8K, both had extra macro- and micronutrients. Fertilizers containing little or no P should be avoided because oxalis leaf growth and plant size were drastically decreased and at the same time, fertilizers with excessive P should be avoided so as to limit any detrimental effects associated with P nutrient leaching and runoff.

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