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Effects of Fertilizer on Media Chemistry and Red-flowering Currant Seedling Growth Using a Subirrigation System

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Abstract. **Water conservation in nursery systems is an ever-increasing focus, yet there is relatively little guidance for growers producing seedlings intended for restoration regarding how practices such as subirrigation influence plant growth in the nursery and after outplanting. Our study investigated red-flowering currant (*Ribes sanguineum* Pursh) seedling development and early field performance using different fertilizer treatments under a subirrigation regime. Plants were fertilized with 1) incorporated organic fertilizer, 2) incorporated controlled-release fertilizer, 3) top-dressed controlled-release fertilizer, or 4) water-soluble fertilizer. We found that seedlings grown with organic fertilizer used significantly less water than all other treatments. Media electrical conductivity (EC) levels were significantly greater in the organic fertilizer treatment, and EC values in the top portion of the media were significantly greater than the middle or bottom portions for all fertilizer treatments. The remaining subirrigation water at the end of 22 weeks held 17% of applied nitrogen (N) from the water-soluble fertilizer treatment and less than 1% of applied N from the other fertilizer treatments. We observed no differences in plant morphology among fertilizer treatments. Seedlings were subsequently out-planted into low- and high-competition treatments, where myriad factors indicated reduced growth among high-competition compared with low-competition plots, highlighting that competition for soil water limited seedling performance. These results indicate that a variety of fertilizers can be used to grow red-flowering currant under subirrigation and that postplanting growth is enhanced with control of competing vegetation.**

Throughout the restoration industry seedling growers are making more environmentally conscious decisions, particularly with regard to water conservation practices (Dennis et al., 2010). As water conservation measures and wastewater runoff issues gain more attention in native plant nurseries, the "ebb-n-flow" closed subirrigation watering systems are of interest in this pursuit. In a closed subirrigation system, water can be moved from a reservoir tank into an application basin where the plants are located; capillary action of the media draws the water necessary to irrigate the plants. After irrigation, water can be returned to the reservoir tank to be recycled through the system again at a later time. This practice can lead to decreased water use, particularly for broadleaf species (Ahmed et al., 2000; Davis et al., 2011; Dumroese et al., 2006); increased uniformity of crops resulting from uniform water application (Neal, 1989); and recycling of unused water and reduced fertilizer use because of the closed-loop nature of the system (Landis and Wilkinson, 2004).

Despite growing interest in subirrigation system use for native plant production, little guidance exists regarding how to adapt fertilization practices to this method (Klock-Moore et al., 2001; Morvant et al., 2001). Several fertilizer options exist, from water soluble to media incorporated. For those aiming to maximize conservation values, organic fertilizer use is attractive, particularly as market niches expand for organic nurseries, and organic waste by-product availability increases (Carpio et al., 2005). A U.S. survey of 120 nursery and greenhouse growers in 2009 revealed that 42% of those surveyed were currently using organic fertilizer (Dennis et al., 2010). Like traditional fertilizers, organic fertilizer is available in liquid, water-soluble, and controlled-release forms.

Production nurseries often use water-soluble inorganic fertilizers or controlled-release fertilizer to grow crops for restoration. Although water-soluble fertilizer has been used with subirrigation systems, it is recommended that these fertilizer concentrations be reduced to obtain quality plants (Dole et al., 1994; Klock-Moore et al., 2001). This helps ensure that nutrient delivery is consistent with plant needs and the growth phase during nursery production. Conversely, controlled-release fertilizer can provide balanced nutrition throughout the growing season at a release rate that is potentially less likely to leach into groundwater. In an open subirrigation system, in which the water is not recycled, the use of water-soluble fertilizer can result in a greater percentage of nutrients leaching because a portion of the fertilizer is being released immediately as runoff after moving through the media (Morvant et al., 2001). As a result of the increased residual fertilizer in subirrigation water from water-soluble fertilizer, controlled-release fertilizer may be a better choice to use in such systems. In an open subirrigation system used to grow geraniums (*Pelargonium* ×*hortorum* 'Pinto Red'), Morvant et al. (2001) found that controlled-release fertilizer increased nutrient-use efficiency whereas water-soluble fertilizer led to greater concentrations of nutrient leaching and no increase in plant quality or growth. When incorporated into media, controlled-release fertilizer nutrients are released by moisture in the media for uptake by plants, leading to less fertilizer pollution in leachate and improved fertilizer-use efficiency (FUE) (Landis and Dumroese, 2009).

The placement of controlled-release fertilizer (incorporated in the media vs. top-dressed on the media) may influence the rate of nutrient release. Fertilizer prills dry intermittently between irrigation events when top-dressed and therefore release nutrients more slowly than when incorporated in controlled-release fertilizer (Lunt and Oertli, 1962). Because subirrigation involves the upward movement of water into media, controlled-release fertilizer that is top-dressed may remain dry and therefore may make nutrient release difficult in this system. In a subirrigation experiment growing New Guinea impatiens 'Illusion' (*Impatiens hawkeri* Bull.),

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Richards and Reed (2004) demonstrated that plants grown in containers with controlled-release fertilizer incorporated into the growing media exhibited greater dry mass than those grown in containers that were top-dressed with controlled-release fertilizer, suggesting that nutrient release occurred more slowly in the top-dressed treatment. Klock-Moore et al. (1999) found no growth differences, however, between plants grown in containers with top-dressed vs. incorporated controlled-release fertilizer using subirrigation. These results suggest that it is still unclear whether a top-dressed controlled-release fertilizer used with subirrigation systems can produce high-quality plants.

Different types of irrigation systems may affect media chemical properties, such as EC. Media EC in closed subirrigation systems is typically greater than in overhead-irrigated systems because of the recycling of fertilizer. This increase in media EC implies that not only could fertilizer amounts be reduced in these systems (Davis et al., 2011; Dumroese et al., 2011), but also the residual salts in subirrigation water could act as a nutrient reserve to be used by the plant at a later time (Dumroese et al., 2006). Managing proper EC levels during nursery cultivation is important to sustain plant quality, and it is important to consider how fertilizer type may influence media EC levels depending on nutrient release rates and fertilizer placement.

Although use of subirrigation to propagate horticultural species is well documented, little of this information exists relative to native plant production. Because native plants are often outplanted in harsh environments with little to no postplanting care—compared with horticultural species, which typically receive postplanting care—it is important that high-quality plants are produced during nursery culture to ensure successful establishment. Red-flowering currant is a shrub native to the Pacific Northwest and west coast of the United States and is planted frequently on restoration sites (Hobbs and McGrath, 1998; Houghton and Uhlig, 2004; Vanbianchi, 1994) and ornamental landscapes (Brennan, 1996). Given the breadth of its production and use in restoration, understanding the impacts of the aforementioned alternative propagation methods on seedling growth and field performance could be most beneficial. Specifically, knowing how different fertilizer types influence nursery culture and seedling quality within a subirrigation system will help growers determine which fertilizer is best to use for growing native plants.

This experiment was conducted to compare morphological and physiological characteristics of red-flowering currant (*Ribes sanguineum* Pursh) grown using different fertilizer types in a closed subirrigation system and to examine possible residual effects. We also studied the contribution of fertilizer to potential wastewater in a subirrigation system. We hypothesized that red-flowering currant seedlings would grow successfully under a subirrigation watering regime, and morphological and physiological differences would exist among plants grown using different fertilizer types. Specifically, we hypothesized that controlled-release fertilizers would provide more efficient nutrient delivery and decrease contribution to leachate. We also hypothesized that seedlings from all treatments would be of suitable quality to withstand outplanting under a range of vegetative composition.

Materials and Methods

Nursery culture and fertilization. We transplanted one-season-old, red-flowering currant seedlings grown in 340-mL Styroblock containers (Beaver Plastics Ltd., Edmonton, Alberta, Canada) at the University of Idaho Pitkin Forest Nursery in Moscow, ID, into blow-molded 1-gallon trade nursery containers (2.6 L; #1NC; McConkey & Co., Sumner, WA) on 20 June 2013. We filled pots with Sunshine Mix #4 Aggregate Plus soilless potting media (SunGro Horticulture Inc., Elizabeth City, NC) because this is the standard for nursery production. Fertilizer treatments consisted of controlled-release fertilizer applied as top dressing or incorporated into media, an incorporated organic fertilizer, and a water-soluble fertilizer. Table 1 provides details on fertilizer treatments and application rates. For organic and incorporated controlled-release fertilizers, each treatment replicate was mixed separately. Each fertilizer was applied so that during an 18-week period, each seedling received 1.92 g of plant-available N; for the organic fertilizer, we compensated based on the work of Gale et al. (2006), who found that an average of 60% of the N contained within an organic fertilizer was released during a 70-d growing period (see Table 1). The water-soluble fertilizer treatment was added to subirrigation buckets once per week on the same day for 18 weeks (0.11 g N/week × 18 weeks = 1.92 g N/seedling). The transplanted seedlings were grown with ambient lighting for 22 weeks at Oxbow Farm and Conservation Center in Carnation, WA, under a Retractable Roof Greenhouse (Cravo Equipment Ltd., Brantford, Ontario, Canada).

Subirrigation system. We used a manually operated "ebb-n-flow" system (Fig. 1). Five benches (replicates) were built to hold four cement-mixing trays each (0.61 × 0.91 × 0.20 m; Plasgad Advanced Logistic Solutions, Kibbutz Gadot, Israel), one for each fertilizer treatment. Each tray held 12 seedlings and had a small plastic riser system to encourage air pruning of roots without impeding subirrigation. A 1.9-cm-diameter hole was drilled into the middle of each tray for drainage and was plugged with a rubber stopper. For each subirrigation event, water was added to the trays. After each subirrigation event, plugs were removed to allow any remaining water to drain into a storage bucket assigned specifically to each tray for the duration of the experiment. Lids had a hole for water entry but prevented splashing. Each storage bucket was covered with tulle fabric to filter out large debris. Trays were rotated randomly once every 2 weeks within and among subirrigation benches to minimize microclimate differences.

To protect the subirrigation water from debris, airborne pathogens, and algal growth, a second intact lid was placed on the bucket after watering. Buckets were also covered with a white blackout cloth (Rockland Industries, Baltimore, MD) to discourage algal growth. Buckets were cleaned with a phosphate-free soap (Free & Clear Dish Liquid; Biokleen, Vancouver, WA) once each month.

Subirrigation methods. Irrigation scheduling was determined by gravimetric water content [see "manager technique" in Dumroese et al. (2015)]. One randomly selected seedling per tray was used to monitor gravimetric water content. Seedlings were irrigated when 25% (weeks 1–11), 35% (weeks 12–15), or 50% (weeks 16–22) of the water had left the media via transpiration and evaporation.

After the target water loss was reached, plants in their trays were subirrigated for 1 h. For the first subirrigation event, 16 L water was added to each tray. After 1 h, plugs were removed and water was allowed to drain into the storage buckets for 15 min. For subsequent subirrigation events, the water volume in the storage buckets was brought up to a total of 16 L using tap water and was reapplied to the trays. When the water-soluble fertilizer fertilization ended at 18 weeks, subirrigation continued for all treatments an additional 4 weeks. Subsequently, three random plants from each tray (n = 60) were harvested. Seedlings were separated into roots, stems, and leaves that were dried for 72 h at 60 °C. Before drying, root volumes were obtained following the methods of Harrington et al. (1994). Dried samples were sent to A&L Great Lakes Laboratories, Inc. (Fort Wayne, IN) for nutrient analysis.

Measurements. Water-use efficiency (WUE) was the quotient of total plant mass (measured in grams) and total amount of water used (measured in liters) throughout the experiment. We weighed the storage buckets after each subirrigation event; the difference in water mass applied each time (16 kg) and the residual collected in the storage bucket equaled water use. The EC and pH of the subirrigation storage bucket effluent were measured after each irrigation using a FieldScout EC probe (Spectrum Technologies, Plainfield, IL) and an IQ 150 pH Meter (Spectrum Technologies), respectively. Water samples were taken during weeks 3, 9, 14–18, and 22 from all 20 storage buckets directly after irrigation and were immediately sent to JR Peters Laboratory (Allentown, PA) for nutrient analysis. Media EC and pH levels were monitored weekly with the FieldScout EC probe and the IQ 150 pH meter. Measurements were taken from three containers in each tray at three different depths: 2 cm below the media surface, 8 cm below the media surface (the middle of the pot), and 2 cm above the bottom of the pot (14 cm below the media surface).

Height and root-collar diameter (RCD) measurements were taken weekly (n = 240).

Table 1. Fertilizer treatments, application rates, and application methods used to grow *Ribes sanguineum* during a 22-week period. All treatments supplied each seedling with 1.92 g nitrogen (N).

Fertilizer type	Application method	Fertilizer	Rate
Organic fertilizer	Incorporated into media	NutriRich Organic 8–2–4 (8N–0.9P–3.3K)[z,y]	40 g/plant
Controlled-release fertilizer	Incorporated into media	Osmocote Pro 17–5–11 (17N–2.2P–9.1K)[x]	11.29 g/plant
Controlled-release fertilizer	Top dressed	Osmocote Pro 17–5–11 (17N–2.2P–9.1K)[x]	11.29 g/plant
Water-soluble fertilizer	Applied weekly via water	Peter's Professional 24–8–16 (24N–3.5P–13.3K)[w]	5.33 g/tray[v]

[z] Gale et al. (2006) estimated that only 60% of N is plant available; therefore, additional fertilizer was added to this treatment to ensure equal target plant-available N among treatments (1.92 g N/plant).

[y] Stutzman Environmental Products, Inc., Canby, OR.

[x] Three- to 4-month release rate. Everris NA, Inc., Charleston, SC.

[w] Everris NA, Inc., Charleston, SC.

[v] Each tray contained 12 seedlings.

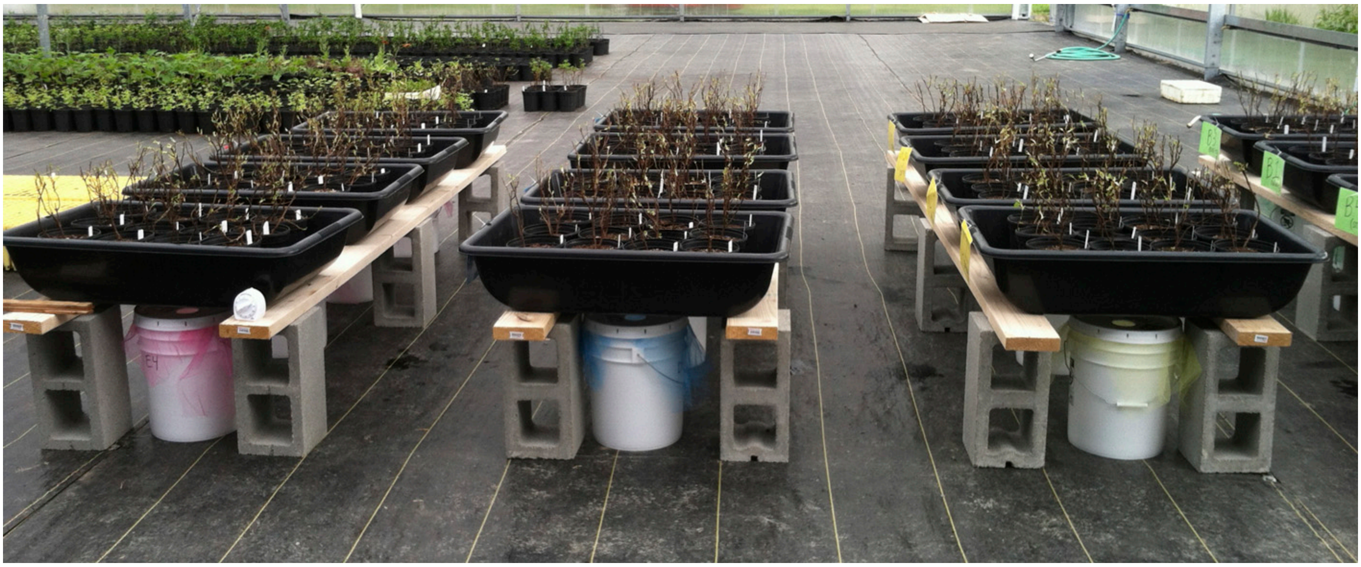

Fig. 1. Subirrigation construction design used during the nursery production phase.

Foliar samples (5 g, fresh weight) were taken for nutrient analysis (A&L Great Lakes Laboratories; Fort Wayne, IN) from one plant in each tray (n = 20). Before shipping, sampled leaves were agitated in deionized water and phosphate-free soap for 10 s to remove any surface residue or deposits, and then towel-dried and placed in paper bags. FUE was calculated by dividing total seedling N (measured in grams) by total N applied (measured in grams). Seedling N concentrations (measured as a percentage) were determined by dividing total seedling N (measured in grams) by total seedling mass (measured in grams). Nitrogen-use efficiency (NUE) was calculated by dividing total seedling mass (measured in grams) by total seedling N (measured in grams).

During weeks 8, 11, and 14–16, gas exchange measurements were taken on the uppermost, fully expanded leaves of three randomly selected plants from each tray using the LI-6400XT (LI-COR, Lincoln, NE) equipped with a standard leaf chamber (model 6400–02B) with an LED light source. Depending on the weather, measurements were made 3 to 6 h after sunrise. Three light response curves were averaged to determine photosynthetic photon flux (*PAR*) settings for the study. Settings on the LI-6400 for all sampling periods were as follows: *PAR* of 1100 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, reference carbon dioxide concentration of 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, flow rate of 400 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, leaf temperature at 22 °C, and relative humidity of 50% to 75%.

Pest control. Aphids (*Aphis* spp.) were detected on the plants about 6 weeks after transplanting and were controlled using Safer® Brand Insect Killing Soap (Lititz, PA) or Neem oil (Bonide Products Inc., Oriskany, NY) per label instructions on a weekly basis for 6 weeks.

Water content analysis. A post hoc analysis was performed to examine the available water content of our media with and without organic fertilizer because results indicated seedlings treated with organic fertilizer had a significantly greater WUE. A high-range pressure system and ceramic plates at –0.033 MPa (field capacity) and –1.5 MPa (wilting point) were used to determine the water-holding capacity of the two media (Klute, 1986). Five samples of each media type were analyzed for field capacity and wilting point. Bulk density and the gravimetric water content of each sample were obtained, and media water content was calculated as

$$\text{Media water content} = \frac{D_b \times \theta_m}{D_w},$$

where D_b is the bulk density of media, θ_m is the gravimetric water content, and D_w is the density of water ($D_w = 1\ \text{g}\cdot\text{cm}^{-3}$). After media water content was determined at the field capacity and wilting point of each media sample, plant-available water (P_w) was calculated as

$$P_w = \text{Field capacity} - \text{Wilting point}.$$

Out-planting experiment. The outplanting site was located on a floodplain in the Snoqualmie Valley near Carnation, WA. Annual average rainfall is 1581 mm. Soil consisted of deep, moderately well-drained Nooksack silt loam formed in alluvium on floodplains and low river terraces (Soil Survey Staff, Natrula Resources Conservation Service, U.S. Department of Agriculture, 2018). Grazing occurred at the site more than 50 years ago, and the predominant vegetation present was common velvetgrass (*Holcus lanatus*) and bentgrass (*Agrostis* spp.), which are often used for grazing (Esser, 1994; Gucker, 2008).

We used a split-plot design with two competing vegetation treatments (whole plots) × four nursery fertilizer treatments (split plots) × five replications. In April 2014, ten 5 × 5-m plots were arranged in a grid, with a 3-m mowed perimeter around each plot, with five plots assigned randomly to each competition treatment. For the low-competition treatment, plots were covered with landscape fabric (Dewitt Co., Sikeston, MO) to eliminate vegetation. Vegetation in the high-competition treatment was allowed to grow unchecked after an initial mowing to facilitate outplanting. In May 2014, after the vegetation under the landscape fabric in the low-competition plots had died, the high-competition plots and borders were mowed. In mid May, 16 seedlings were planted into each plot, spaced 1 m apart (n = 160). The growing season lasted 20 weeks. Because the use of landscape fabric has been shown to increase soil temperatures (Clarkson, 1960), grass cuttings were placed over the landscape fabric in the low-competition plots to limit temperature differences between high- and low-competition soils. Throughout the field season, the low-competition plots were weeded to minimize competition and the 3-m perimeters around the plots were mowed. To quantify aboveground biomass, a 0.5-m^2 area was chosen randomly in each high-competition plot and vegetation was clipped at ground level during June and August in the same sample areas. Clippings from each plot were bulked, dried 96 h at 60 °C, and weighed.

Weather and soil measurements. A weather station (model 2900ET; Spectrum Technologies) and data loggers were used to collect weather and soil moisture data, including hourly air temperature (measured in degrees Celsius), relative humidity (measured as a percentage), and rainfall (measured in millimeters). Vapor pressure deficit (VPD) was calculated from ambient temperature (measured in degrees Celsius) and relative humidity (measured as a percentage) using

$$\mathrm{VPD} = \left(a e^{\left(\frac{bT}{T+c}\right)}\right)(1 - h_r),$$

where a, b, and c are constants (a = 0.611 kPa, b = 17.502, and c = 240.97 °C), T is temperature, e is the exponential constant, and h_r is relative humidity [measured as a percentage per 100 (Campbell and Norman, 1998)]. Volumetric soil moisture (θ, $m^3 \cdot m^{-3}$) and soil temperature (measured in degrees Celsius) measurements were collected hourly in each plot at 10 cm and 40 cm below the soil surface using ECH_2O-TE soil moisture probes and Em50 data loggers (Decagon Devices, Inc., Pullman, WA). Three each of high- and low-competition plots were chosen randomly to collect soil samples in weeks 5 and 16 to determine any differences between competition treatments in nutrient concentrations resulting from decomposition of biomass under the landscape fabric. Samples were sent to A&L Great Lakes Laboratories, Inc., for extractable inorganic N analysis. Soil cores were taken from the same plots and dried 48 h at 100 °C to obtain soil bulk density (Soil Quality Institute, 1999).

Gas exchange and leaf water potential. Field gas exchange was measured 6 Oct. 2014, between 0830 and 1200 HR using the same LI-6400XT system. Two seedlings from each fertilizer split plot were chosen randomly from each replication for gas exchange measurements (n = 80). LI-6400 leaf chamber settings were the same as the nursery experiment.

Two weeks after seedlings were outplanted, leaf water potential measurements began and continued at 4- to 5-week intervals (2 June; 3 July; 6, 7 Aug.; 28, 29 Aug. 2014) to assess competition effects on plant moisture stress. Leaf water potential measurements were taken using a pressure chamber (PMS Instrument Co., Albany, OR). Predawn (Ψ_{pd}) measurements were conducted between 2430 and 0400 HR, and midday (Ψ_{md}) measurements occurred in the afternoon between 1300 and 1600 HR on the same day. Two seedlings from each fertilizer split plot were chosen randomly from each replication for water potential measurements (n = 80).

Seedling growth. Height (measured in centimeters) and RCD (measured in millimeters) measurements were taken on each seedling during weeks 1 and 20 (n = 160). During week 20, the aboveground biomass of two seedlings from each fertilizer split plot was collected in each competition whole plot and dried 72 h at 60 °C to assess any differences in growth between fertilizer treatments and competition levels (n = 80).

Statistical analysis. All statistical analyses were completed using R [version 3.1.1 (R Core Team, 2013)]. The nursery study was a randomized complete block design with four fertilizer treatments replicated five times. We used analysis of variance (ANOVA) to identify differences in water use, subirrigation water EC, pH, nutrient concentration, foliar nutrition, and seedling morphology among fertilizer treatments. When ANOVA indicated significant differences ($P < 0.05$) among fertilizer treatments, multiple comparisons were calculated using Tukey's mean separation test (α = 0.05). ANOVA was completed to determine differences across media water content as well. A repeated-measures ANOVA was used to assess any differences among media EC and pH variables, and net carbon assimilation. When repeated-measures ANOVA indicated significant differences ($P < 0.05$) among fertilizer treatments, Tukey's test was performed (α = 0.05).

The outplanting study was a two-factor, split-plot design, with competition treated as the whole-plot factor and fertilizer treated as the split-plot factor (two competition types × four fertilizer treatments × five replications). ANOVA was used to detect competition and fertilizer treatment differences, as well as competition type × fertilizer treatment interactions for seedling height, RCD, and photosynthesis. When ANOVA indicated significant differences ($P < 0.05$) among fertilizer treatments, Tukey's significant difference test was used to identify significant mean differences at α = 0.05. Differences in θ, soil nutrient concentrations, Ψ_{pd}, and Ψ_{md} between competition types were examined using repeated-measures ANOVA.

Results

Water use and plant-available water. Seedlings in the organic fertilizer treatment used an average of 100.0 ± 5.66 L water, whereas those treated with controlled-release fertilizer or water-soluble fertilizer used an average of 149.1 ± 3.77 L water during the 22-week experiment (Table 2). This contributed to a significantly greater WUE among seedlings in the organic fertilizer treatment (P = 0.0090), averaging 5.6 ± 0.43 $g \cdot L^{-1}$. Overall, seedlings in the organic fertilizer treatment used 33% less water than seedlings in the other treatments. Media water content at field capacity was greater in the peat-based media with organic fertilizer than in unamended media (P = 0.0114). There was no difference in media water content at the wilting point (P = 0.3280) or the amount of plant-available water (P = 0.1520) between the two (Table 3).

Subirrigation effluent, media EC, and pH. Subirrigation effluent of the water-soluble fertilizer treatment, which received weekly fertilizer applications, had significantly greater EC levels and N concentrations than other treatments ($P < 0.0001$ and $P < 0.0001$ for EC and N concentration, respectively; Table 2 and Fig. 2). The pH of subirrigation water was significantly lower in the water-soluble

Table 2. Mean (SE) water-use efficiency (WUE), subirrigation water used, electrical conductivity (EC), and pH of leachate. EC (n = 26) and pH (n = 17) data are averaged across the entire growing season. Different letters indicate significant differences at α = 0.05.

		Subirrigation		
Treatment^z	WUE ($g \cdot L^{-1}$)^y	Amount used (L)	EC ($dS \cdot m^{-1}$)	pH
Organic fertilizer	5.6 (0.4) b	100.0 (5.7) b	0.28 (0.1) a	6.5 (0.1) ab
CRF, incorporated	4.2 (0.2) a	145.3 (13.0) a	0.17 (0.1) a	6.7 (0.1) a
CRF, top dressed	4.1 (0.2) a	156.6 (6.7) a	0.14 (0.1) a	6.8 (0.1) a
Water-soluble fertilizer	4.1 (0.4) a	145.3 (14.0) a	0.88 (0.1) b	6.5 (0.1) b

^{z}See Table 1 for treatment descriptions.

^{y}WUE = total seedling mass (measured in grams)/total amount of water applied (measured in liters) during the growing season.

CRF = controlled-release fertilizer.

Table 3. Mean (SE) of media water content at field capacity (0.33 MPa) and wilting point (–1.5 MPa), and plant-available water for the medium amended with or without organic fertilizer (OF). Different letters indicate significant differences at α= 0.05 (n = 5).

Treatment	Field capacity ($cm^3 \cdot cm^{-3}$)	Wilting point ($cm^3 \cdot cm^{-3}$)	Plant available water ($cm^3 \cdot cm^{-3}$)^z
With OF	0.36 (0.02) b	0.19 (0.01) a	0.17 (0.03) a
Without OF	0.27 (0.01) a	0.17 (0.02) a	0.11 (0.03) a

^{z}Plant-available water = field capacity media water content – wilting point media water content.

fertilizer than either controlled-release fertilizer treatment ($P = 0.0190$; Table 2).

For media EC, time interacted with both treatment and layer. During weeks 1 and 10, organic fertilizer-amended media had greater EC values than the other treatments ($P < 0.0001$ and $P = 0.0363$ for weeks 1 and 10, respectively; Fig. 3). On week 21, media in the water-soluble fertilizer treatment had significantly greater EC values than the incorporated controlled-release fertilizer treatment ($P = 0.0122$; Fig. 3). Media EC levels decreased in the bottom layer as salts continued to rise to the top layer of media over the 21-week time period. The bottom media layer had greater EC levels than the top layer during week 1 ($P = 0.0207$; Fig. 4). On week 10, the top media layer had significantly greater EC levels than the other layers ($P < 0.0001$), and EC levels were significantly greater in the top layer than the middle layer at week 21 ($P = 0.0157$; Fig. 4).

There were no differences in pH among media layers ($P = 0.0600$), but pH differed among treatments ($P = 0.0020$) such that values were significantly greater in the organic fertilizer treatment than either the top-dressed or water-soluble fertilizer treatments (data not shown). Media pH ranged between 5.6 and 5.8, which is the optimal range for growing plants.

Seedling morphological and physiological parameters. Analyses of seedling N and FUE revealed no differences among treatments (Table 4). NUE of seedlings within the water-soluble fertilizer treatment was significantly lower than that within the incorporated controlled-release fertilizer treatment ($P = 0.0008$; Table 4). Seedlings treated with water-soluble fertilizer had significantly greater N concentrations than those treated with the other fertilizers ($P = 0.0009$; Table 4). Net photosynthetic rates were comparable among treatments at each of the three measurement times (average = 7.91 ± 0.43 $\mu mol \cdot m^{-2} \cdot s^{-1}$; $P = 0.1365$). Seedling morphological characteristics revealed no differences among fertilizer treatments (Table 4). Total seedling mass was similar among all fertilizer treatments and averaged 50.21 ± 1.40 g. Plant height and RCD were similar among all treatments (Table 4), and seedlings in all treatments displayed similar growth patterns.

Site conditions. At the time of outplanting, air temperature was 21.2 °C and VPD was 0.21 kPa. Maximum air temperature was reached on 11 Aug. (33.9 °C); maximum VPD was reached on 4 Aug. (3.6 kPa). During the 20-week study period (20 May to 6 Oct.), overall air temperature averaged 16.9 °C and VPD averaged 0.59 kPa. Mean maximum daily air temperature for the season was 22.8 °C, with a mean maximum VPD of 1.28 kPa (Fig. 5). Total precipitation between 20 May and 6 Oct. was 88 mm, and rainfall occurred each month of the study (Fig. 6). Soils in the low-competition plots had greater temperatures at both depths (20.1 °C at 10 cm and 20.6 °C at 40 cm), with seasonal maxima of 24.7 and 25.2 °C (at 10 and 40 cm, respectively). Soil temperatures in the high-competition plots averaged 17.2 °C and 17.1 °C (at 10 and 40 cm, respectively), with seasonal maxima of 20.9 °C at the 10-cm depth and 20.0 °C at the 40-cm depth.

Volumetric soil moisture differed significantly between the high- and low-competition plots, and at the two different soil depths over the growing season ($P = 0.0400$ and 0.0170, respectively) with no significant interactions between competition treatments and depth ($P = 0.9130$) (Fig. 6). In May, there were no differences in θ between competition treatments or depths (Fig. 6). Significant differences in θ occurred between high- and low-competition plots in June and July, but not between soil depths (Fig. 6). Throughout August and September, significant differences in θ occurred between high- and low-competition plots at both soil depths (Fig. 6). On 6 Oct., θ was significantly different between soil depths, but not between competition treatments (Fig. 6).

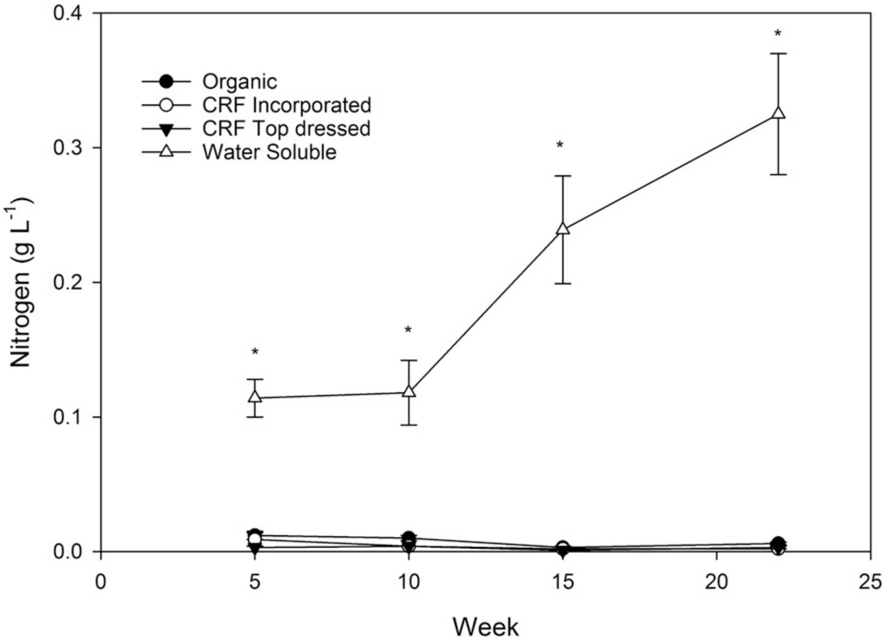

Fig. 2. Mean nitrogen concentration in subirrigation effluent during the 22-week fertilizer application period. Error bars represent SEM (n = 5). Asterisks indicate significant differences among treatments at α = 0.05. See Table 1 for treatment descriptions. CRF = controlled-release fertilizer.

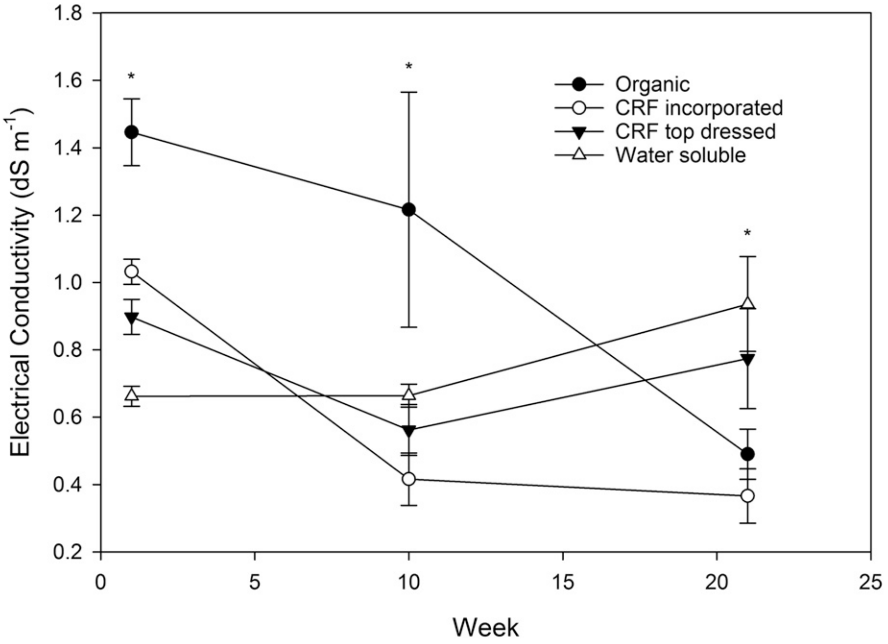

Fig. 3. Mean media electrical conductivity for the four fertilizer treatments at weeks 1, 10, and 21. Error bars represent the SEM (n = 15). Asterisks indicate significant differences among treatments at α = 0.05. See Table 1 for treatment descriptions. CRF = controlled-release fertilizer.

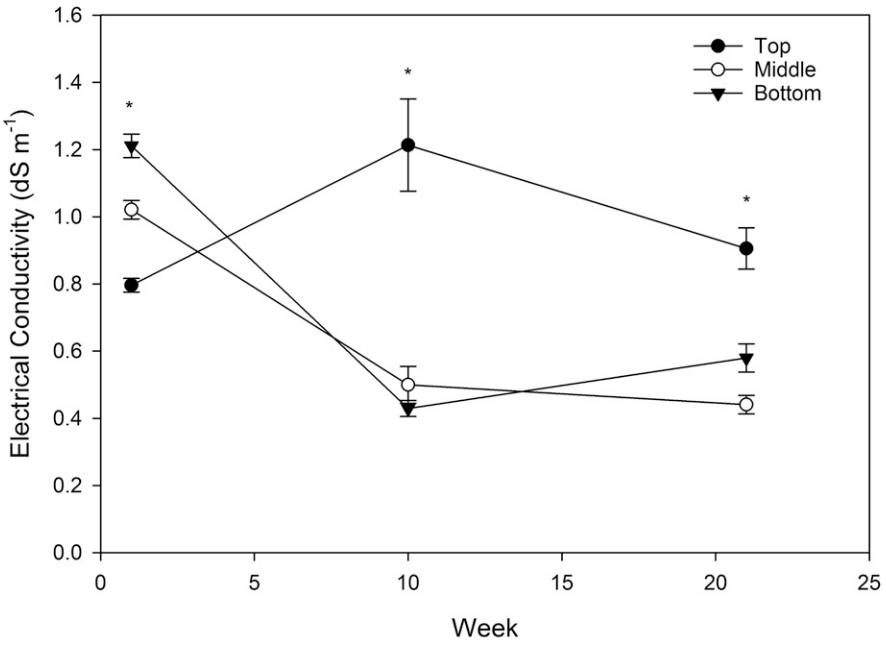

Fig. 4. Mean media electrical conductivity EC at different media layers at weeks 1, 10, and 21. Measurements for top, middle, and bottom were taken 2, 8, and 14 cm below the surface of the media. Error bars represent SEM (n = 20). Asterisks indicate significant differences among treatments at α = 0.05.

Aboveground biomass of competing vegetation averaged 395 $g{\cdot}m^{-2}$. Average soil bulk density for all plots was 1.05 $g{\cdot}cm^{-3}$ and did not differ between competition treatments. No significant differences were detected between high- and low-competition plots in soil nitrate (NO_3^-) or soil ammonia (NH_4^+) concentrations during the two sampling periods (P = 0.1520 and 0.3450, and P = 0.2250 and 0.3740, respectively). For the growing season, NO_3^- concentrations between low-competition (28 ± 11 $g{\cdot}cm^{-3}$) and high-competition (3 ± 1 $g{\cdot}cm^{-3}$) plots were significantly different (P = 0.0471), whereas NH_4^+ concentrations in low-competition (6.7 ± 1.6 $g{\cdot}cm^{-3}$) and high-competition (4.8 ± 0.9 $g{\cdot}cm^{-3}$) plots were not (P = 0.3530).

Gas exchange and leaf water potential. When measured on 6 Oct., plants in the low-competition plots had significantly greater net photosynthetic rates (14.9 ± 0.36 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) than plants in high-competition plots (10.1 ± 0.78 $\mu mol{\cdot}m^{-2}{\cdot}s^{-1}$) ($P < 0.0001$). No differences in net photosynthetic rates were detected among the different fertilizer treatments (P = 0.9000).

During the growing season, there were significant differences in Ψ_{pd} between low- and high-competition plots (P = 0.0482; Fig. 7). No differences in Ψ_{pd} were detected during June and July ($P > 0.0615$), but high-competition plots had significantly lower values for the August dates ($P < 0.0001$ for both dates; Fig. 7). Significant differences occurred during the growing season in Ψ_{md} measurements between high- and low-competition plots (P = 0.0422; Fig. 7). Although there was no difference in Ψ_{md} between treatments during June (P = 0.6040), high-competition plots had significantly lower values for Ψ_{md} in July, August, and October ($P < 0.0150$; Fig. 7). There were no significant differences in Ψ_{pd} among fertilizer treatments throughout the growing season ($P > 0.05$, data not shown).

Seedling survival and growth. In both low- and high-competition plots, only one seedling perished (consumed by a beaver). No differences in height or RCD were found among fertilizer treatments (data not shown). Plants in the low-competition plots had significantly greater heights and RCD than those in the high-competition plots ($P < 0.0001$ for both; Table 5). No interactions between fertilizer and competition treatments for height or RCD were detected ($P > 0.0970$). Aboveground biomass was significantly greater in plots with low rather than high competition ($P < 0.0001$; Table 5). No differences were detected in aboveground biomass among fertilizer treatments (P = 0.5880), or any interaction effects between fertilizer and competition treatments (P = 0.6740).

Discussion

Water use and plant-available water. Seedlings grown with organic fertilizer used considerably less water compared with seedlings grown in other fertilizer treatments. The addition of organic matter has been shown to increase soil water-holding capacity (Hollis et al., 1977). Here, seedlings in the organic fertilizer treatment used ≈33% less water than the other treatments and had the greatest WUE during the growing season. Because there were no differences in plant weight among treatments, the decreased water use may be attributed to the physical properties of media incorporated with organic fertilizer—specifically, media water content.

Post hoc analysis revealed no differences in plant-available water between conventional peat-based media used in this study with or without organic fertilizer. The media water content at field capacity was greater in the media amended with organic fertilizer, although the saturation weights of the indicator pots were similar among all fertilizer treatments. Because a complete media water retention curve was not developed for either media type, it is difficult to determine a full understanding of plant water-availability differences among the treatments. Also, physical properties of the fertilizer itself could affect media physical properties as well as media–water relations. In addition to peat-based growing media used in this study, growers have access to a variety of amendments, including composts, coconut coir, rice hulls, and pumice (Landis and Morgan, 2009). With organic fertilizer gaining attention among operational growers, further research needs to be conducted to understand how organic fertilizer affects water use and media physical properties across the range of growing media types used operationally.

Subirrigation water analyses. Subirrigation water with water-soluble fertilizer had the greatest EC and contained 17% of N applied after 22 weeks, whereas subirrigation water of the other treatments contained less than 1% of N applied after 22 weeks. Although there was no difference in seedling weight or total seedling N, seedlings in the water-soluble fertilizer treatment had significantly greater N concentrations. Overall, because there was so much residual N in the leachate (17%) and seedling parameters were relatively similar across fertilizer treatments, in a closed subirrigation system in which nutrients are recycled, water-soluble fertilizer concentrations could likely be reduced without sacrificing seedling quality. Morvant et al. (2001) found similar results when comparing a constant liquid fertilizer to a controlled-release fertilizer to grow geranium (*Pelargonium ×hortorum* 'Pinto Red') seedlings using an open subirrigation system. Not only were EC values greater in the collected constant liquid fertilizer leachate, the percentage of N lost through leaching was 34% in a constant liquid fertilizer treatment, whereas a controlled-release fertilizer treatment leached 1.7% of N applied (Morvant et al., 2001).

Soil EC. Analysis of media EC revealed that organic fertilizer resulted in significantly greater media EC values than the other treatments, suggesting that nutrient availability or release was high in this treatment. Similar results were found when measuring the EC of substrates amended with organic fertilizers while growing hand-watered marigolds (*Tagetes patula* L. 'Janie Deep Orange') (Guihong et al., 2010). Organic fertilizers can be variable in their release rates, depending on moisture and temperature (Agehara and Warncke, 2005). It is likely that nursery cultural conditions aided the early release of nutrients in the organic fertilizer treatment. Conversely, the controlled-release fertilizer treatments maintained a more

Table 4. Mean (SE) final seedling height, root collar diameter (RCD), seedling mass, and total seedling nitrogen (N) for each fertilizer treatment. Mean (SE) fertilizer-use efficiency (FUE), nitrogen-use efficiency (NUE), and N concentration for all treatments. Different letters indicate significant differences at $\alpha = 0.05$.

Treatment^{z}	Ht (cm; n = 60)	RCD (mm; n = 60)	Seedling mass (g; n = 15)	Seedling N (g; n = 5)	FUE (n = 5)^{y}	NUE (n = 5)^{x}	[N] (%; n = 5)^{w}
Organic fertilizer	55.6 (1.8) a	8.4 (0.4) a	46.9 (5.2) a	0.74 (0.06) a	38.3 (2.9) a	62.0 (2.3) ab	1.6 (0.1) b
CRF, incorporated	56.4 (1.2) a	9.1 (0.4) a	50.6 (6.1) a	0.71 (0.05) a	36.9 (2.7) a	70.5 (4.3) a	1.4 (0.1) b
CRF, top dressed	57.9 (1.3) a	9.4 (0.2) a	53.5 (4.0) a	0.85 (0.05) a	44.4 (2.7) a	62.5 (1.2) ab	1.6 (0.1) b
Water-soluble fertilizer	53.4 (1.5) a	8.9 (0.4) a	49.7 (7.7) a	0.94 (0.13) a	48.7 (6.5) a	52.6 (1.3) b	1.9 (0.1) a

^{z}See Table 1 for treatment descriptions.

^{y}FUE = total seedling N (measured in grams)/total N applied (measured in grams).

^{x}NUE = total seedling mass (measured in grams)/total seedling N (measured in grams).

^{w}Seedling N concentration = total seedling N (measured in grams)/total seedling mass (measured in grams).

CRF = controlled-release fertilizer.

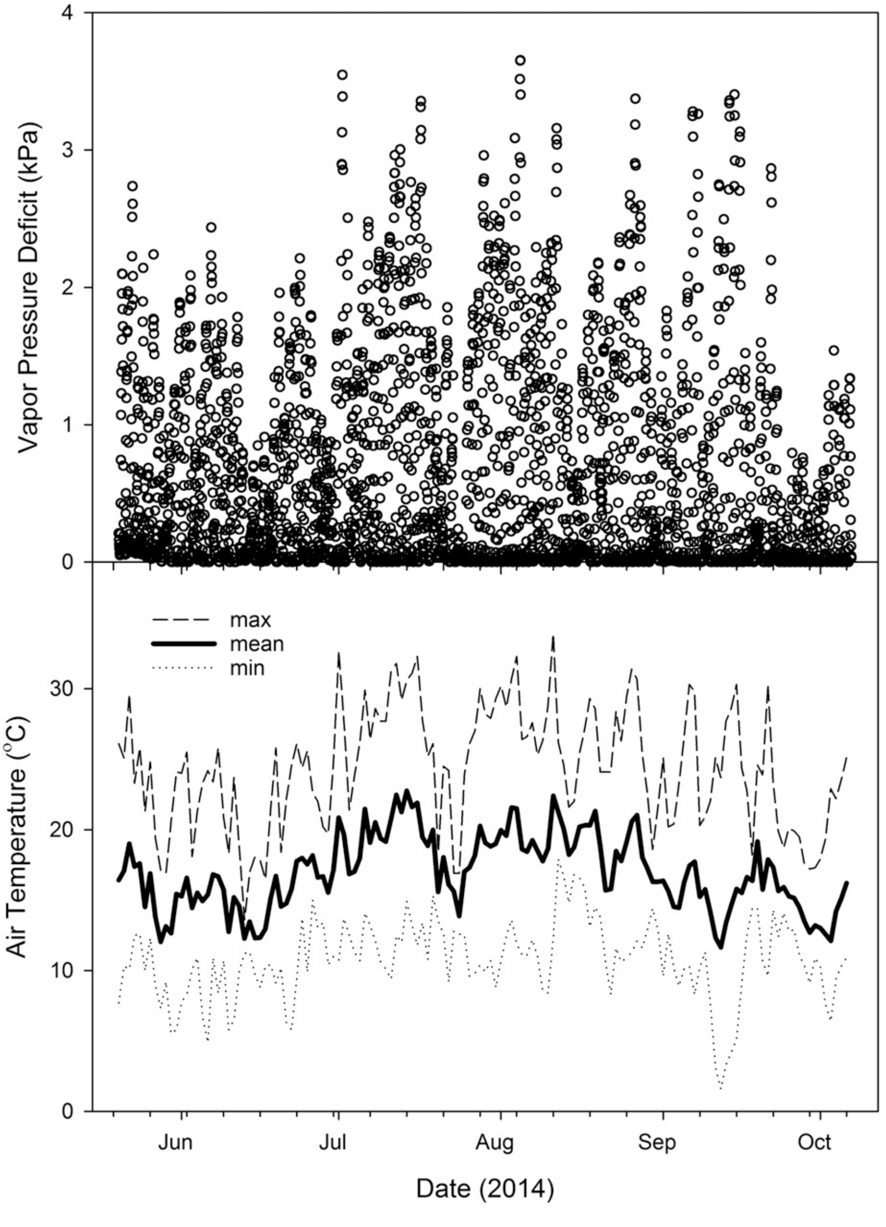

Fig. 5. Hourly vapor pressure deficit (top) and daily average air temperatures (bottom) during the 2014 growing season at the outplanting site near Carnation, WA.

uniform release of fertilizer salts, and media in the water-soluble fertilizer treatment built up nutrients slowly over time.

Salt accumulation is common in the top portions of growing media when using subirrigation. The cause is likely a result of a combination of water evaporation at the media surface (Argo and Biernbaum, 1995) and lack of roots in the upper portion of the media (Kent and Reed, 1996; Todd and Reed, 1998). In our study, all fertilizer treatments exhibited greater salt accumulation in the top layer of media compared with the middle or bottom layers, which can be attributed to the upward movement of the subirrigation water through the media (Argo and Biernbaum, 1995; Kent and Reed, 1996; Pinto et al., 2008; Todd and Reed, 1998). The EC in the top layer of media in all treatments was 47% greater than the middle or bottom layers, which is similar to results reported by Pinto et al. (2008), who found that EC of the top layer of media was 48% greater than the middle or bottom layers while growing coneflower [*Echinacea pallida* (Nutt.) Nutt.] in a closed subirrigation system.

Nutrient efficiency. Although there were no differences in seedling weight, total seedling N, or FUE among fertilizer treatments, seedlings in the media-incorporated fertilizer treatment had significantly greater NUE than those in the water-soluble fertilizer treatment. It is suspected that because seedlings grown in the water-soluble fertilizer treatment had greater N concentration but were the same size as seedlings in other fertilizer treatments, they were likely in luxury N consumption. Dumroese et al. (2011) found similar results while growing koa trees (*Acacia koa* A. Gray) using subirrigation. However, other subirrigation studies have found that greater concentrations of N can lead to decreased growth while using a water-soluble fertilizer (Kent and Reed, 1996; Klock-Moore et al., 2001). In this case, water-soluble fertilizer may have provided a steady state of readily available nutrients for growth that was more than satisfactory for the needs of the seedlings; excess N was found in the leachate, and tissue N was greater than the other treatments. In some cases, greater N concentration can benefit seedlings after outplanting (van den Driessche, 1988), although no evidence of such a benefit was observed within the timeframe of our study.

Fertilizer treatments. While subirrigation watering regimes have shown to improve seedling quality when compared with overhead irrigation systems (Bumgarner et al., 2008), little is known about the use of different fertilizer types with subirrigation during nursery cultivation and their subsequent outplanting effects. This study attempted to tease out the differences among subirrigation and fertilizer types, but no morphological or physiological differences were detected after outplanting. These results suggest that any variability in seedling

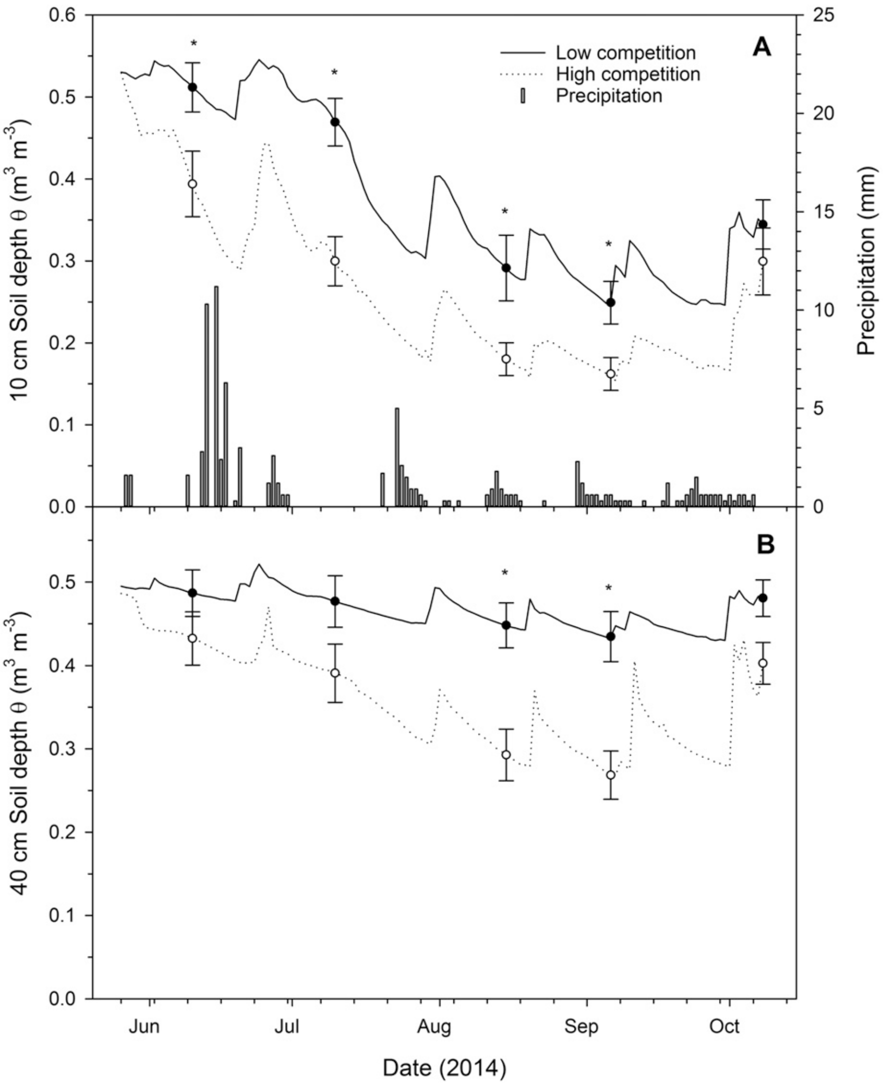

Fig. 6. Volumetric soil moisture content (θ) at (**A**) 10-cm and (**B**) 40-cm soil depths, and daily precipitation totals (**A**, vertical bars) during the 2014 growing season within high- (dotted line) and low- (solid line) competition treatments. Asterisks indicate significant differences at $\alpha = 0.05$ between treatments on dates when seedling physiological measurements were performed.

quality was minimal when considered within the range of outplanting conditions, and that seedlings were of adequate quality to survive. The use of controlled-release fertilizer has been shown to have additional benefits after outplanting including continued fertilization, greater foliar nutrient concentration, height, and RCD (Haase et al., 2006), but our study did not reveal these results. The controlled-release fertilizer used during nursery propagation had a 3–4 month release rate, therefore nitrogen stores of the those treatments may have been depleted once the growing season ended in Dec. 2013, five months after irrigation began. Because the amount of applied N was set equal among the fertilizer treatments and based on the 3–4 month release rate of the controlled-release fertilizer used during nursery propagation, it is possible the nutrients had been completely released by the end of the 2013 growing season. The water-soluble fertilizer treatment had the greatest N concentration at the end of the 2013 nursery phase in a study by Dunlap (2015), suggesting the stored N could aid in further fertilization once in the field. However, due to the morphological and physiological similarities of seedlings among fertilizer treatments in our study, there is no evidence that stored nutrients benefitted plants that received water-soluble fertilizer.

Physiology, soil moisture, and growth. Access to water is essential for stomatal conductance and photosynthesis. In October, net photosynthetic rates were significantly greater in plots with low compared with high competition, indicating that seedlings were able to access water and grow as a result of lower water stress from the lack of competing vegetation. In contrast, water potentials were lower in high-competition plots as a result of competing vegetation and water stress. Predawn water potential values were similar for high- and low-competition plots in June and July, and were significantly lower throughout August. Grass biomass increased in high-competition plots between June and August, indicating that increasing competitive vegetation led to decreased θ and increased water stress as competition for water continued. Eliason and Allen (1997) showed that grass competition reduced California sagebrush (*Artemisia californica* Less.) water potential significantly by outcompeting for available water. Other studies report similar results while growing tree species with competing vegetation (Elliot and White, 1987; Pinto et al., 2012). In contrast, Ψ_{pd} increased throughout the season in low-competition plots. During August and September, θ at the 10-cm depth was at its least value in low-competition plots. However, Ψ_{pd} was increasing during this same time period, indicating that seedlings were able to access soil moisture at the 40-cm depth and therefore increase Ψ_{pd}. In June, Ψ_{md} measurements were comparable between the competition types; but, for the remainder of the season, Ψ_{md} was significantly lower in plots with high competition. The low-competition plots exhibited greater Ψ_{md} values, suggesting that greater θ contributed to less water stress during midday. Although water potential values were substantially different across competition levels in October, Ψ_{md} was increasing in both competition treatments as VPD decreased and temperatures cooled. We would expect the same pattern in Ψ_{pd} values during October for the same reasons, although no measurements were taken to confirm this.

Red-flowering currants have fibrous root systems that can reach a minimum soil depth of 40 cm (Hort et al., 2013), whereas grasses at the site had rooting depths of 10 cm (Gucker, 2008). After seedlings in high-competition plots were planted, seedling roots likely responded to competition for water by accessing water at the 40-cm depth. As water stress increased in high-competition plots through August and September, root weight may have continued to increase at the 40-cm depth to access water. This response would be consistent with a model of whole-plant biomass partitioning (Schulze et al., 1983) that predicts that lower water absorption rates will be compensated for by increased biomass partitioning to root growth (Kolb and Steiner, 1990). Chaves et al. (2002) demonstrated that *Lupinus albus* L. increased fine root length under water stress, whereas Kolb and Steiner (1990) found that northern red oak (*Quercus rubra* L.) and yellow-poplar (*Liriodendron tulipifera* L.) responded to competition for soil resources by increasing root weight. In contrast, seedling roots in the low-competition plots were able to establish without competition, and seedlings were able to access water from the 40-cm soil depth as the upper soil layers dried. Despite decreased θ at 10 cm and 40 cm, plant water stress values indicated water was not limited in low-competition plots. Therefore, it is possible these plants were able to allocate more resources to aboveground biomass. Because root excavation was not conducted, it is difficult to speculate whether root biomass differed between the two competition treatments.

Morphological characteristics (height, RCD, and shoot biomass) were significantly

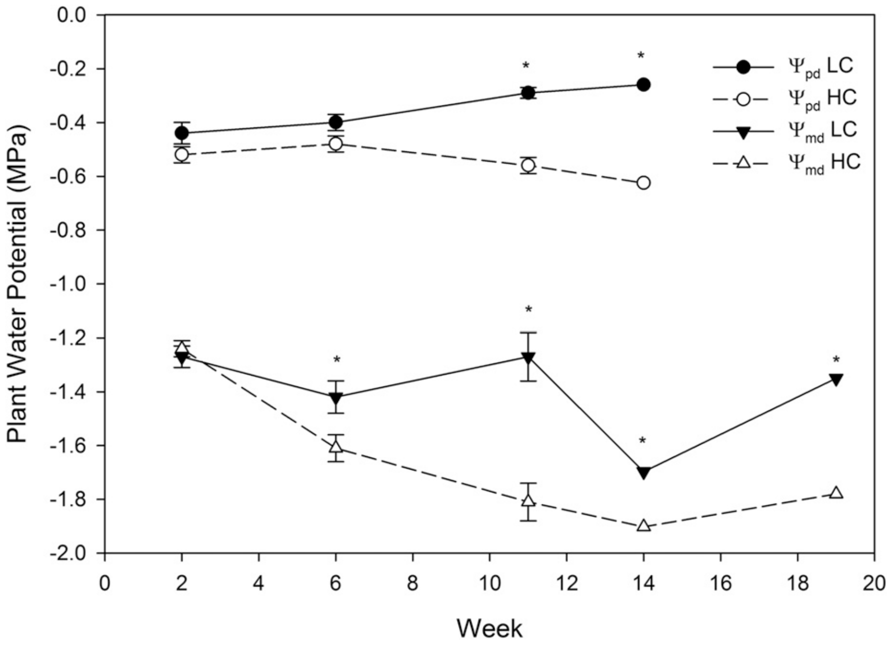

Fig. 7. Predawn (Ψ_{pd}) and midday (Ψ_{md}) water potential of red-flowering currant seedlings during the 2014 field season. Each point represents the mean (n = 40) for all fertilizer treatments within each vegetative treatment: low competition (LC; solid line) and high competition (HC; dotted line). Error bars represent SEM. Asterisks indicate significant differences at $\alpha = 0.05$ between competition treatments at a particular date.

Table 5. Mean (SE) height, root-collar diameter (RCD), and shoot biomass of out-planted red-flowering currant seedlings after one growing season under either low or high vegetative competition levels. Different letters indicate significant differences at $\alpha = 0.05$.

Vegetation treatment^{z}	Ht (cm; n = 80)	RCD (mm; n = 80)	Shoot mass (g; n = 40)
Low competition	97.8 (2.7) a	16.1 (0.6) a	185.8 (18.2) a
High competition	70.5 (1.7) b	13.0 (0.3) b	50.2 (3.5) b

^{z}Low-competition treatment plots were covered with landscape fabric (Dewitt Company; Sikeston, MO) to eliminate vegetation. In high-competition treatment plots, vegetation was allowed to grow unchecked after an initial mowing to facilitate outplanting.

different between the two competition treatments. Seedling height in low-competition plots was 38% greater and RCD was 24% greater, whereas aboveground biomass was 136% greater, suggesting that vegetative competition was the mechanism stunting seedling growth in high-competition plots. Eliason and Allen (1997) found that depletion of soil water by competing vegetation led to reduced growth in *Artemisia californica* plants, whereas Elliot and White (1987) found that competition for moisture led to reduced growth in *Pinus ponderosa* Lawson & C. Lawson seedlings.

In addition to high water availability and lack of competition, other variables may have influenced growth within low-competition plots, including elevated concentrations of NO_3^- and greater soil temperatures. Biomass was not removed before landscape fabric was installed. Throughout the season, vegetation contained under the fabric decomposed and nutrients may have been released. Decreased soil water evaporation and greater temperature under plastic mulch have been shown to favor greater soil microbiological populations, resulting in the accumulation of soil nitrates (Black and Greb, 1962). With limited soil water evaporation and greater soil temperatures in low-competition plots, accumulation of NO_3^- may have occurred and contributed to seedling growth. Despite the grass cuttings placed over the black landscape fabric to mitigate warm soil temperatures, soil temperatures were 3 °C greater in low-competition plots than those with high competition. Warmer soil temperatures are known to increase total plant biomass (Domisch et al., 2001; Peng and Dang, 2003).

It is important to note that all seedlings survived, although seedling growth was lower within high-competition plots. This suggests that, despite competitive effects, plants were able to capture enough resources to grow and survive. In addition, because red-flowering currant flowers from March through June (Gonzalves and Darris, 2008), and grass species at this site flower later [velvetgrass, May–September (Gucker, 2008); bentgrass, June–August (Esser, 1994)], it is possible that currant plants could outcompete grass species for resources the following spring.

Conclusions

As we hypothesized, subirrigation produced plants of similar quality regardless of fertilizer type or application method. Also, as was hypothesized, the leachate from the water-soluble fertilizer treatment had a greater nutrient concentration than the leachate from the controlled-release fertilizer treatments, implying that water-soluble fertilizer concentrations could be reduced to decrease fertilizer waste without sacrificing seedling growth. Management of fertilization regimes could become a strategy to achieve the optimal nutrient concentration when subirrigating with water-soluble fertilizer. Although potentially costlier, the organic fertilizer treatment produced plants comparable to the other fertilizer treatments, demonstrating that environmentally safe slow-release fertilizers can be used effectively in subirrigation systems with minimal nutrient loss. Because organic fertilizers have variable release rates and the potential for increased media salt levels, a greater degree of nursery culture adaptation may be required. Although there were no differences between the controlled-release fertilizer applications in seedling quality, top-dressing with fertilizer offers the additional benefits of increased precision in applying fertilizer amounts (Cox, 1993) and more management control (McNabb and Heser, 1997). Thus, growers would have the ability to select appropriate fertilizing regimes for individual species while using subirrigation. Additional research is needed to examine the effects of various fertilizers in a variety of growing media, particularly organic substrates, in such nursery production systems.

Restoration success depends on nursery cultivation practices to produce seedlings that can establish and survive harsh conditions. As subirrigation is gaining recognition in container nurseries, it is important to understand how plants propagated under this irrigation system will perform in the field. We confirmed our hypothesis that the nutrient delivery method would not have an impact on outplanting performance of red-flowering currant under two contrasting vegetative competition scenarios. This study further supports the management of soil moisture for seedling establishment and growth. Although there were no differences in survival, biomass accumulation and physiological functioning were much improved in plots in which competing vegetation was controlled. When planting species such as red-flowering currant for restoration, effective control of competing vegetation will likely result in better field performance.

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