Fertilizer Application Method Affects Growth, Nutrient, and Water Use Efficiency of Container-Grown Shade Tree Whips

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Abstract. The mineral nutrition requirements and fertilizer application methods for container-grown shade tree whips are not well understood. This experiment was conducted to determine the effects of fertility method (water soluble vs. controlled release) on growth, water, and N use efficiency of four taxa [*Acer × freemanii* ‘Jeffersred’ (Autumn Blaze® maple), *Cercis canadensis* L. (Eastern redbud), *Malus* (Mill.), ‘Prairifire’ (Prairifire crabapple), and *Quercus rubra* L. (red oak)] in two production environments [outdoor gravel pad vs. a retractable roof structure (RRS)]. No single fertilizer method consistently resulted in the greatest growth. In the RRS, maple and crabapple heights, and crabapple and redbud caliper were larger when whips were fertilized with controlled-release fertilizer (CRF); outdoors, CRF resulted in taller maples and larger caliper crabapples. However, in the RRS, maple whips fertilized with water-soluble fertilizer had higher production water use efficiency than those fertilized with CRF, whereas crabapple whips had higher N use efficiency when fertilized with CRF. Nitrogen use efficiency was higher for redbud and crabapple whips fertilized with CRF than with CRF. Outside, crabapple whips fertilized with CRF had higher production water use efficiency than those fertilized with water-soluble fertilizer. There were no differences in N use efficiency attributed to fertilizer method. When averaged over fertilizer application methods, height, caliper, water, and N use efficiency were greater when whips were grown in RRS than outdoors. There were two exceptions: Maple caliper and production water use efficiency were marginally higher when whips were grown outdoors. The greater growth for whips produced in the RRS was attributed to reduced ambient and substrate temperature stress.

A tree whip is a small tree with limited branching, 1.2 to 2.4 m in height, with a caliper size of 12.7 to 19.1 mm. Traditionally, whips are field grown and sold bareroot. There are challenges associated with bareroot whip production: Trees may be dug in fall

before they are fully dormant and stored for long periods (up to 5 months) before shipping. Furthermore, whips designated for field production may not be transplanted until late spring, causing increased transplant shock compared with those transplanted earlier in the season. Recovery can take up to 2 to 3 years and can cause death (Mathers et al., 2002). Transplant mortality is high enough that it prevents production of some taxa (Struve et al., 1987). Thus, container whip production systems were developed to minimize transplant shock and allow difficult-to-transplant species to be produced profitably (Struve, 1996; Struve et al., 1987).

One concern with containerized whip production is low mineral nutrient use efficiency (Struve, 1995, 2002; Struve and Rose, 1998). Low mineral nutrient use efficiency has many causes: inefficient application methods (overhead fertigation), nutrient addition rates, or controlled-release fertilizer (CRF) release profiles that do not match plant uptake potential. Also, container-grown plants may experience elevated root temperatures. Black containers on light-colored production surfaces absorb radiant heat.

Elevated substrate temperatures cause root death (Johnson and Ingram, 1984), reducing water and mineral nutrient-absorbing surface area (Handreck and Bunker 1996), resulting in water stress and low nutrient use efficiency. Furthermore, elevated substrate temperatures alter nutrient release rates and nutrient release profiles of CRFs (Huett and Gogel, 2000; Kochba et al., 1990; Oertli and Lunt, 1962).

Retractable roof structures (RRS), or other environmental modification methods, could reduce plant stress and increase growth (Nelkin and Schuch, 2004; Schuch, 2004; Svenson, 1999, 2000; Svenson and Johnston, 1991; Svenson et al., 2000). This research was conducted to determine the effects of two fertilizer application methods (CRFs vs. water soluble) on the growth, water, and N use efficiency (NUE) of container-grown whips in two production environments (outdoor container pad vs. RRS).

Materials and Methods

Red oak (*Quercus rubra* L.) acorns were received in Sept. 2002 (Lawyer Nursery, Plains, Mont.). The acorns were placed in water for 1 hour and the floating (damaged) acorns were removed. The seeds that sank were drained and placed in unsealed plastic storage bags in a 3 to 5 °C cooler (Bally Case and Cooler, Bally, Pa.) for a 10-week cold stratification period. The experiment was conducted from Jan. to Oct. 2003. It was begun on 16 Jan. when four Spinout®-painted flats (26 × 52 × 10-cm deep; Kadon Corp., Dayton, Ohio) were filled with soilless substrate (510 MetroMix; O.M. Scott and Sons Co., Marysville, Ohio). Germinated acorns were placed end-to-end on top of the substrate with the root tip facing down, and the flats watered and returned to the cooler. The flats were removed from the cooler on 11 Feb. and placed on a greenhouse bench at The Ohio State University, Columbus, to complete germination. A single layer of milky polyethylene (70% light transmission), with holes punched for ventilation, was placed on top of the flats to speed germination. The polyethylene was removed when the shoots emerged. Greenhouse conditions were natural photoperiods and 21 °C day/18 °C (± 6 °C) night temperature. Water temperature averaged 18 °C (± 4 °C) and relative humidity averaged 33% (± 3.8%).

On 13 Feb. dormant bareroot *Cercis canadensis* (Eastern redbud) seedlings and *Acer × freemanii* ‘Jeffersred’ (Autumn Blaze® maple) and *Malus* ‘Prairifire’ (Prairifire crabapple) rooted cuttings (12–15 cm tall) were received (John Holmlund Nursery, LLC, Gresham, Ore.), graded for uniformity, root pruned to 4 cm in length, and placed in the cooler to maintain dormancy until planting. Plants were transplanted into Spinout®-treated (Griffin Corp., Valdosta, Ga.) square containers (250-XL; Nursery Supplies, Inc., Fairless Hills, Pa.) filled with 510 MetroMix substrate, and placed pot-to-pot on greenhouse benches that had been watered for

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several days before transplanting. Greenhouse conditions were the same as those described to germinate red oak acorns. Plants were watered as needed to avoid moisture stress. On 27 Feb., one-flush red oak seedlings were lifted from the flats, root pruned to 4 cm in length, and transplanted into the 250-XL containers. All plants remained in the greenhouse until 20 Mar., when half the plants in each taxa were randomly selected and moved to an RRS (Cravo Equipment, Ltd., Brantford, Ontario, Canada). Plants in the RRS were protected from freezing by solar radiation, and bottom heat was supplied by electrical propagation mats (A.M. Leonard, Inc., Piqua, Ohio) at 21 °C. Plants were placed pot-to-pot on the propagation mats and watered to avoid moisture stress. Water temperature averaged 13 °C (± 7.2 °C). The 30 $\times$ 9.3-m peaked-roof RRS was oriented on a north-south axis. The side walls were 3.2 m tall and the peak was 6 m. A control panel (Micro-Grow Systems, Temecula, Calif.) was programmed to close the roof when the air temperature dropped below 13 °C or rose above 30 °C. The sidewalls opened when outdoor temperatures exceeded 21 °C. The RRS was covered with a clear woven-polyethylene covering (RC02; Cravo Equipment).

Starting 28 Mar., all the plants in the RRS and greenhouse were fertilized once per week with 21N-3.1P-5.9K (21-7-7) Peter's water-soluble fertilizer (O.M. Scott and Sons Co.) at a rate of 100 mg-L⁻¹N using a fertilizer injector (Dosatron, Clearwater, Fla.).

On 12 May, 15 plants from each taxa and environment were harvested to obtain initial growth measurements. Caliper, height, and leaf area were determined with a model Li-3100 leaf area meter (LI-COR, Inc., Lincoln, Neb.). The substrate was washed from the root system and the seedlings pruned at the root collar. The plant parts from individual plants were placed in separate paper bags. Root, shoot, and leaf tissues were oven dried for one week at 54 °C (Blue M Electric Forced-Air Drying Ovens, Williamsport, Va.). Total plant dry weights were calculated by summing root, shoot, and leaf dry weights from individual plants.

From the initial harvest, three plants per taxa and environment were randomly selected. The oven-dried root, shoot, and leaf tissues were ground to pass through a 20-mesh screen and were analyzed for total N by the Service Testing and Research Laboratory (Ohio Agricultural Research and Development Center, Wooster (www.oardc.ohio-state.edu/starlab/references.asp#plant_tissuefeed)). Total N contents of roots, shoots, and leaves were calculated by multiplying root and shoot dry weights by their respective tissue N concentrations. Total seedling N content was calculated by summing individual seedling root, shoot, and leaf N contents.

On 13 May, all the remaining plants were transplanted into 11.4-L classic Spinout® treated containers (Nursery Supplies, Inc.), filled with a 60% pine bark, 25% peat moss, 7% composed sludge (composed municipal sewage sludge from the city of Akron, Ohio),

7% haydite, and 1% sand substrate (Willoway Nurseries, Inc., Avon, Ohio). After transplanting, plants in the RRS were placed on a trellis system in the RRS. The trellis system used two 3.5-m long, 10-cm square wood posts, set 1.5 m in the ground. A board was mounted between the posts, and four high-tensile wires, 80 cm apart, were attached. Within a row, pots were placed on 30-cm centers. A split-plot experimental design was used, with fertility method as the main plot and taxa as the subplots. For each species, there were five replications with three individual plants per replication—a total of 15 plants per species and fertilizer method. The same experimental design was used for the plants from the greenhouse, but they were placed on an outdoor gravel pad after transplanting. All plants were trained to 2-m tall bamboo stakes (A.M. Leonard, Inc.), attached to the wire. On 30 June, all containers were treated with surface-applied imidacloprid 75 WSP (Marathon, Olympic Horticultural Products) at 6.1 g/pot.

The two fertilizer application methods used were a 9-month formulation of a CRF (20N-2.2P-6.6K; 20-5-8 Osmocote®; O.M. Scott and Sons Co.), surface applied on 16 May at 45 g per pot (or 9 g N per pot), or daily fertigation with 1.14 L day⁻¹ [applied during two 15-min periods each day via in-line emitters (LD-06-12 Rainbird Dripline; Rainbird Irrigation, Azusa, Calif.)] of 21N-3.1P-5.9K (21-7-7 Peter's, O.M. Scott and Sons Co.) of water-soluble fertilizer applied at 100 mg N-L⁻¹ (or 12.9 g N per pot for the season). Fertigation began on 13 May and was ended 3 Sept., after which the plants received water at 1.14 L per day. The water-soluble fertilizer was injected into the irrigation water with model DI-16 Dosatron. Plants fertilized with CRF also received 1.14 L of water day⁻¹ during two, 15-minute irrigation events, but without fertilizer—a total of 163 L pot⁻¹ for the season.

Ambient and substrate temperatures were recorded between May and Oct. with two WatchDog Data Shuttle units (model 425), each fitted with external soil and ambient temperature sensors (model 3667) and a quantum light sensor (model 3668; all from Spectrum Technology, Inc., Plainfield, Ill.), in each production environment. Hourly temperatures were averaged to obtain daily temperatures, and daily temperatures were averaged to obtain monthly averages. Substrate temperature probes were placed 5-cm deep and 4 cm from the west side of the containers in two randomly selected pots in each environment. We chose 30 °C as the stress temperature threshold, and totaled the number of hours ambient or substrate temperature exceeded 30 °C. Similarly, hourly quantum light levels (400–700 nm) were converted to monthly averages.

Starting on 9 July, and biweekly until 18 Sept., leachate electroconductivity and nitrate-N (NO₃⁻) concentrations were measured using the pour-through method (Wright, 1986) as modified by Bilderback (2001). Three randomly selected containers per species and fertilizer type in each pro-

duction environment were monitored throughout the experiment. Electroconductivity and NO₃⁻ concentrations were measured with digital meters (Compact Conductivity Meter, model B-173 and Cardy Plant Nutrient Meter, model 2300, Horiba Laboratory Products, Irvine, Calif. respectively). The NO₃⁻ leachate readings were converted to elemental N by multiplying by 0.226.

On 1 Oct., trunk caliper (at 15 cm above substrate surface) and height were measured on all trees. Leaf area and leaf dry weights were determined for one randomly selected tree per replication and taxa. Leaf, stem, and root tissues from three randomly selected plants from each fertilizer, taxa, and production environment were ground and analyzed for N as described earlier. Root, shoot, leaf, and total plant N contents were calculated as before.

For each taxa, fertilizer application method, and production environment, plant N uptake between 13 May and 1 Oct. was calculated by subtracting total plant N content in May from that in Oct. The plants selected for tissue analysis were used for estimating N uptake. To obtain the May and Oct. pairings, plants within a harvest date and treatment combination were ranked by total plant dry weight, and the smallest to largest plants in May were paired with the smallest to largest plant in Oct. NUE was calculated as [(N_O - N_M)/N_T], where N_O is the Oct. N content, N_M is the May content, and N_T is the total N applied from either CRF or water-soluble fertilizer.

October root-to-shoot ratios were calculated by summing shoot and leaf dry weights and dividing by the total root dry weight. Production water use efficiency (WUE) was calculated as the ratio between total plant net dry weight and the total volume of water applied between the harvest dates.

$$WUE = (DW_R + DW_S + DW_L)/(H_2O_T)$$

where DW_R, DW_S, and DW_L are plant dry weights of roots, shoots, and leaves respectively; and H₂O_T was the total irrigation volume (163.02 L-season⁻¹) applied to individual containers between 13 May to 1 Oct.

From the dry weight and leaf area data, relative growth rate (RGR) was calculated according to Harper (1977) for the three plants per taxa, fertilizer, and production environment that were selected for nutrient analysis. RGR g-g⁻¹·day⁻¹) was calculated as

$$RGR = (\log_e W_O - \log_e W_M) (t_O - t_M)$$

where W_O and W_M are 1 Oct. and 13 May dry weights respectively, and t_O and t_M are the Oct. and May times (in days) respectively. NUE was obtained similarly to WUE and was calculated as the ratio between total plant N uptake and the total N applied between 13 May and 1 Oct.

Data were subjected to analysis of variance using the GLM procedure within SAS® (SAS Institute, Inc., 2000) as a fixed-effect model. Data were analyzed as a split-plot design with a separate analysis run for each

environment; the main plot was fertilizer and the subplots were taxa (Steele and Torrie, 1980). The effect of fertilizer application method on height, caliper, and dry weight analyses was tested using the means from three individual plants from each of five replications per harvest and species. The effect of fertilizer on NUE, total plant dry weight, and tissue N concentration used three randomly selected individuals from each harvest, taxa, and fertilizer application method, and was analyzed as three single plant replications. WUE, total leaf area, and RGR analyses used five randomly selected individuals from each harvest, taxa, and fertilizer application method, and were analyzed as five single plant replications.

Results and Discussion

Production environments were not replicated, so statistical comparisons were not made between environments, although the relative difference between the production environments are made later. Average environmental conditions for each environment were calculated. Container substrate temperatures inside the RRS averaged 27.6 °C (range, 21.1–31.1 °C; Fig. 1A). Those in containers on the outdoor gravel pad averaged 31.6 °C (range, 22.3–36.9 °C; Fig. 1B). Air temperatures averaged 27.1 °C (range, 20.7–30.3 °C in the RRS; Fig. 1A). Those outside averaged 27.0 °C (range, 22.7–30.3 °C; Fig. 1B). The difference between season-long average air and substrate temperatures in the RRS was 0.9 °C; outside the difference was 8.4 °C. Favorable temperatures for root growth of northern temperate plants range from 20 to 30 °C (Larcher, 1995), temperatures above 30 °C inhibit root growth (Mathers, 2003), and temperatures above 39 °C injure roots (Johnson and Ingram, 1984). Thus, whips grown outside on the gravel pad experienced more stressful substrate temperatures than whips grown in the RRS. Other researchers have found that any production structure that partially reduced light also reduced substrate temperatures (Schuch, 2004; Svenson, 2000).

Average photosynthetically active radiation (PAR) levels in the RRS were lower than outside—740.9 and 1139.2 molQm⁻²Qs⁻¹ respectively (Fig. 1A and B). The decreased PAR in the RRS resulted from closing the fabric roof when ambient temperatures exceeded 30 °C. Typical light saturation levels for sun leaves of woody plants is between 25 to 50 klx (Larcher, 1995), or 475 to 950 molQm⁻²Qs⁻¹ (Langhans and Tibbitts, 1997). We assumed levels more than 1000 molQm⁻²Qs⁻¹ would not result in increased net photosynthesis, and may be inhibitory to plant growth. Outside PAR levels exceeded 1000 molQm⁻²Qs⁻¹ 72% of the time during the growing season (data not presented); inside they never exceeded 1000 molQm⁻²Qs⁻¹. Although PAR levels were

lower in the RRS than outside, levels were not low enough to reduce net photosynthesis, as evidenced by the dry weight data (presented later in Table 1).

Leachate electroconductivity values in the RRS for CRF and water-soluble fertilizers had similar patterns (Fig. 2). Both fertilizers had the highest electroconductivity levels between 9 and 24 July and then gradually declined through the season. The pattern of leachate electroconductivity levels from the containers grown outdoors was similar to those from the RRS, except that the highest readings were obtained on 9 July (Fig. 2). The pattern of NO₃ readings for both fertilizers and both environments was similar: It peaked between 9 and 24 July and declined through the growing season (Fig. 3).

Fig. 2. Leachate electroconductivity (EC) readings for plants fertilized with either 20N–2.2P–6.6K controlled-release fertilizer (CRF) or fertigated with water-soluble (WS) fertilizer (21N–3.1P–5.9K) in a retractable roof structure (RRS) and on an outdoor (OD) production environments and electroconductivity readings from irrigation water with WS fertilizer or without. Each value is the mean of three replications.

Fig. 1. (A, B) Average monthly air and substrate temperatures and quantum light levels (PAR) recorded in either a retractable roof structure (A) or on an outdoor production environment (B) from 13 May to 30 Sept. Each value is the mean of two WatchDog temperature and quantum light sensors per environment.

Fig. 3. Leachate $\text{NO}_3\text{-N}$ levels for plants fertilized with either 20N–2.2P–6.6K controlled-release fertilizer (CRF) or fertigated with water-soluble (WS) fertilizer (21N–3.1P–5.9K) grown in either a retractable roof structure (RRS) or on an outdoor (OD) production environments. Nitrate-N readings from irrigation water with WS fertilizer or without are given for comparison. Each value is the mean of three replications.

However, water-soluble fertilizer nitrite- NO_3^- values were higher than those for the CRF plants through 5 Sept. and 30 Aug. in the RRS and outside production environments respectively. Nitrate readings more than 100 mg L^{-1} were attributed to N released by mineralization of the composted sewage sludge. The $\text{NO}_3\text{-N}$ readings less than 100 mg L^{-1} for the irrigation water containing water-soluble fertilizer (Fig. 3) resulted because the majority of the N in the water-soluble fertilizer was in the NH_4^+ form. The season-long average electroconductivity reading for the CRF in the RRS was $0.76 \text{ mMhos}\cdot\text{cm}^{-1}$; outside it was $0.37 \text{ mMhos}\cdot\text{cm}^{-1}$ (estimated by averaging

the monthly readings). Lower CRF electroconductivity leachate readings from the outside production environment were attributed to greater leaching or higher substrate temperatures. Rainfall was nearly 40 cm greater than the 30-year average during the growing season, and outside substrate temperatures were 24% greater than those in the RRS. An irrigation event resulting in a 1× leachate fraction (or an equivalent rain event) can leach up to 90% of available N from the container substrate (Foster et al., 1983). Leaching was reduced in the RRS because the roof closed during rain events.

Assuming total N release from the CRF, the estimated average daily nitrate-N concentration experienced by CRF-fertilized plants was 55.2 mg L^{-1} , which was calculated by dividing the total N applied in the CRF by the total irrigation volume for the growing season ($9000 \text{ mg}/163 \text{ L}$). Season-long average N concentration, calculated from the average leachate readings, were 74.1 mg L^{-1} and 58.9 mg L^{-1} for the RRS and outside production environments respectively. Comtil® (a composted municipal sewage sludge product similar to that produced by the city of Akron) acts as a controlled-release N fertilizer (Falahi-Ardakani et al., 1987), but it may have been responsible for a small (<1%) proportion of the total N taken up by the crop (Struve, 2002); thus, it was not included in calculating the season-long average N concentration.

In the RRS, rebud caliper and root dry weight were larger when plants were grown under the CRF than the water-soluble fertilizer, but shoot-to-root ratios were smaller (Table 1). Autumn Blaze® maples were taller when grown under the CRF, but shoot and total plant dry weight and shoot-to-root ratios were smaller than those grown under water-soluble fertilizer. Prairifire crabapple height, caliper, root, shoot, and total plant dry weights were all greater when plants were grown under CRF. Red oak growth was unaffected by fertility method. Those plants fertilized with CRF were larger than those fertilized with water-soluble fertilizer, with the exception of red maple height and dry weight.

In the outside environment, Autumn Blaze® maple had the greatest height, caliper, root, shoot, and total plant dry weights (Table 2). Red bud had the highest shoot-to-root ratio (Table 2). In the outside environment, plants fertilized with CRF had higher root dry weights than those fertilized with WS (63.4 vs 42.8 g respectively when averaged over all species; Table 2). Orthogonal contrasts for the fertilizer application methods within each species showed that

Table 1. Plant growth, dry weight, and dry weight shoot-to-root ratio of four taxa grown in a retractable roof structure (RRS) environment when fertilized by two methods.

	Species	Fertilizer	Ht (cm)	Caliper (mm)	Dry wt (g)			Shoot-to-root ratio
					Root	Shoot	Total plant	
RRS	Redbud	CRF ^a	225 ^y	15.8^z	70.1	175.2	245.3	2.50
		WS	232	13.5	39.7	169.2	206.9	4.24
	Red oak	CRF	58	8.8	28.3	21.6	49.9	0.74
		WS	79	9.2	26.5	37.0	63.5	1.07
	Autumn Blaze® maple	CRF	222	16.3	100.0	220.4	320.4	2.24
		WS	209	16.7	93.2	270.0	363.2	2.93
	Prairifire crabapple	CRF	190	11.6	41.4	97.1	138.5	2.23
		WS	149	9.4	20.2	58.7	78.9	2.85
Fertilizer × species SE			7.65	0.44	3.65	9.80	11.44	0.19
Source		<i>df</i>			<i>P</i> > F value			
Fertilizer		1	NS	NS	***	NS	NS	**
Block		4	*	NS	NS	**	**	*
Error A (fertilizer × block)		4	NS	NS	NS	NS	NS	NS
Species		3	***	***	***	***	***	***
Species × fertilizer		3	**	**	**	**	**	**
Error B								

^aPairs of means in bold type within a column and taxa are significant at $P = 0.05$, with two-tailed t -test.

^bEach value is the mean of three single-plant subsamples from five replications.

^cPlants were fertilized with a controlled-release fertilizer (CRF) of Osmocote® 20N–2.2P–6.6K, 9-mo. release, top dressed at $9 \text{ g N}\cdot\text{pot}^{-1}$, or a water-soluble (WS) Peter's, 21N–3.1P–5.9K at $100 \text{ mg}\cdot\text{day}^{-1}$ for a total of 12.9 g N for the season.

NS, *, **, ***Nonsignificant, or significant at $P = 0.05$, 0.01 or 0.001 level respectively.

Table 2. Plant growth, dry weight, and dry weight shoot-to-root ratio of four taxa grown in an outdoor gravel production environment when fertilized by two methods.

Environment	Species	Fertilizer	Ht (cm)	Caliper (mm)	Dry wt (g)			
					Root	Shoot	Total plant	Shoot-to-root ratio
Outside	Redbud	CRF ^x	206 ^y	13.9	56.6^z	144.4	201.0	2.47
		WS	174	11.5	28.1	112.6	140.7	3.90
	Red oak	CRF	49	8.1	36.8	25.6	62.4	0.59
		WS	64	8.0	23.9	28.0	51.9	1.13
	Autumn Blaze® maple	CRF	218	16.9	120.9	220.1	341.0	1.85
		WS	184	17.1	100.3	255.6	355.9	2.57
	Prairifire crabapple	CRF	141	11.2	37.4	66.7	104.1	1.78
		WS	117	8.9	18.8	40.8	59.6	2.19
Fertilizer × species SE			13.12	0.79	4.95	13.17	17.00	0.25
Source			<i>df</i>				<i>P</i> > <i>F</i> value	
Fertilizer			1	NS	*	NS	NS	*
Block			4	NS	NS	NS	NS	NS
Error A (fertilizer × block)			4	NS	NS	NS	NS	NS
Species			3	***	***	***	***	***
Species × fertilizer			3	NS	NS	NS	NS	NS
Error B			24					

^aPairs of means in bold type within a column and taxa are significantly different from each other using orthogonal contrast at $P \leq 0.05$.

^yEach value is the mean of three single-plant subsamples from five replications.

^aPlants were fertilized with a controlled-release fertilizer (CRF) of Osmocote® 20N–2.2P–6.6K, 9-mo. release, top dressed at 9 g N·pot⁻¹, or a water-soluble (WS) Peter's, 21N–3.1P–5.9K at 100 mg·day⁻¹ for a total of 12.9 g N for the season.

NS, *, **, ***Nonsignificant, or significant at $P \leq 0.05$, 0.01 or 0.001 level, respectively.

root dry weight was significantly greater for those plants fertilized with CRF than for those fertilized with water-soluble fertilizer ($P = 0.03$). Shoot-to-root ratios (averaged over all species) were higher when plants were fertilized with water-soluble fertilizer than with CRF (2.45 vs 1.67 g; Table 2) and were higher for all taxa (except Prairifire crabapple) fertilized with water-soluble fertilizer than with CRF.

In the RRS, fertilization method affected Autumn Blaze® maple's RGR; it was higher under water-soluble fertilizer than CRF (Table 3). Fertilization method also affected redbud and Prairifire crabapple NUE; it was higher for both species under CRF than water-soluble fertilizer. Production WUE, defined as the quotient of biomass and total applied irrigation, was lower for Autumn Blaze® maples, but higher for Prairifire crabapples grown under the CRF than under

water-soluble fertilizer. In the RRS, red oak water use, leaf area, and RGR were unaffected by fertility method.

Outside, Autumn Blaze® leaf area and RGR were greater when fertilized with water-soluble fertilizer than with CRF (Table 4). WUE and RGR were greater for Prairifire crabapples in the outside production environment when fertilized with CRF (Table 4).

For the subsample of individual whips selected for nutrient analysis, Autumn Blaze® maples grown in the RRS under water-soluble fertilizer had almost 70% higher total plant N concentration than those grown under CRF, whereas red oaks grown under water-soluble fertilizer had more than twice the N concentration (Table 5). There were no differences in total plant nutrient concentration for any taxa when grown outdoors. Growing these taxa under water-soluble fertilizer caused nutrient loading.

Nutrient loading is defined as an increase in tissue nutrient concentration without an increase in total plant dry weight (Malik and Timmer, 1995). The benefit of mineral nutrient loading during production is greater posttransplant growth (Xu and Timmer, 1999). Possible benefits of nutrient loading to the taxa used in our study are being determined in field transplanting studies. No single fertilizer application method resulted in uniformly greater WHIP growth for all taxa and production environments.

Although lack of replication in environments excluded statistical tests for environmental effects, it is possible to compare relative differences between environments. When averaged over fertilizer methods, all taxa were taller, had greater caliper, and had higher production WUE and NUE than those grown outdoors except for maple, for which caliper and WUE were lower (Table 6). NUE

Table 3. Water use efficiency, leaf area, relative growth rate (RGR), and N use efficiency of four taxa grown in a retractable roof structure (RRS) from 13 May to 1 Oct. when fertilized by two methods.

Environment	Species	Fertilizer	Leaf area (cm ²)	RGR (g·g ⁻¹ day ⁻¹ × 10 ⁻²)	N use efficiency (%)	Water use efficiency (g dry wt L ⁻¹)
RRS	Redbud	CRF ^x	7719 ^y	1.0975	44.8 ^z	1.47
		WS	8654	1.0315	28.8	1.25
	Red oak	CRF	1502	0.5853	4.3	0.27
		WS	2338	1.0625	7.5	0.35
	Autumn Blaze® maple	CRF	9685	1.1067^y	61.7	1.91
		WS	13342	1.3974	73.8	2.17
	Prairifire crabapple	CRF	3557	0.7638	34.2	0.78
		WS	3205	0.5774	18.9	0.41
Fertilizer × species SE			45.9	3.86	9.28	0.0012
Source		<i>df</i>			<i>P</i> > F value	
Fertilizer		1	*	NS	NS	NS
Block		4	NS	NS	NS	***
Error A (fertilizer × block)		4	NS	NS	NS	NS
Species		3	***	**	***	***
Species × fertilizer		3	**	*	NS	**
Error B		24				

^aPairs of means in bold type within a column and taxa are significant at $P \leq 0.05$, with two-tailed t -test.

^yEach value is the mean of five single-plant replications.

^aPlants were fertilized with a controlled-release fertilizer (CRF) of Osmocote® 20N–2.2P–6.6K, 9-mo. release, top dressed at 9 g N·pot⁻¹, or a water soluble (WS) Peter's, 21N–3.1P–5.9K at 100 mg·day⁻¹ for a total of 12.9 g N for the season.

NS, *, **, ***Nonsignificant, or significant at $P \leq 0.05$, 0.01 or 0.001 level, respectively.

Table 4. Water use efficiency, leaf area, relative growth rate (RGR), and N use efficiency of four taxa grown on an outdoor gravel production pad from 13 May to 1 Oct. when fertilized by two methods.

Environment	Species	Fertilizer	Leaf area (cm ²)	RGR (g·g ⁻¹ ·day ⁻¹ × 10 ⁻²)	N use efficiency (%)	Production water use efficiency (g dry wt·L ⁻¹)
Outdoor	Redbud	CRF ^x	6272 ^y	0.9290 ^z	36.3 ^z	1.19 ^y
		WS	8654	0.2344	29.5	0.82
	Red oak	CRF	1765	0.5660	6.2	0.33
		WS	1728	0.5551	3.5	0.28
	Autumn Blaze® maple	CRF	9049^z	0.9816	54.9	2.02
		WS	14340	1.3635	50.8	2.11
	Prairifire crabapple	CRF	1950	0.6210	13.5	0.56
		WS	2347	0.4450	11.6	0.34
Fertilizer × species SE			1114.4	0.0044	6.43	0.084
Source		df	<i>P</i> > <i>F</i> value			
Fertilizer		1	**	NS	NS	*

^zPairs of means in bold type within a column and taxa are significant at *P* 0.05, with two-tailed *t*-test.

^yEach value is the mean of five single-plant replications.

^xPlants were fertilized with a controlled-release fertilizer (CRF) of Osmocote® 20N–2.2P–6.6K, 9-mo. release, top dressed at 9 g N·pot⁻¹, or a water soluble (WS) Peter's, 21N–3.1P–5.9K at 100 mg·day⁻¹ for a total of 12.9 g N for the season.

^{NS}, *, **, ***Nonsignificant, or significant at *P* < 0.05, 0.01 or 0.001 level, respectively.

Table 5. Total plant dry weight and whole plant tissue N concentration of four taxa grown under two fertility treatments in two production environments: a retractable roof structure (RRS) and an outside gravel bed production area.

Environment	Species	Fertilizer	Total plant dry wt (g)	N concn. (%)
RRS	Redbud	CRF ^x	243.4 ^y	2.4
		WS	163.3	2.6
	Red oak	CRF	63.2	0.3
		WS	35.6	0.5
	Autumn Blaze® maple	CRF	351.5	3.5
		WS	367.1	6.2
	Prairifire crabapple	CRF	150.4^z	1.9
		WS	85.4	1.0
Outside	Redbud	CRF	184.5	2.1
		WS	154.5	2.9
	Red oak	CRF	61.3	0.4
		WS	34.6	0.3
	Autumn Blaze® maple	CRF	364.1	2.8
		WS	347.3	3.9
	Prairifire crabapple	CRF	64.5	0.8
		WS	67.8	1.2

^zPairs of means in bold type within a column and a taxa were declared significant if *P* < 0.05.

^yThe total plant dry weight values and the percent N concentration values are the mean of three single-plant replications.

^xPlants were fertilized with a controlled-release fertilizer (CRF) of Osmocote® 20N–2.2P–6.6K, 9-mo. release, top dressed at 9 g N·pot⁻¹, or a water soluble (WS) Peter's, 21N–3.1P–5.9K at 100 mg·day⁻¹ for a total of 12.9 g N for the season.

Table 6. Plant height, caliper, water use, and N use efficiency of four taxa grown in a retractable roof structure relative to those grown on an outdoor gravel bed.

Species	Ht (%)	Caliper (%)	N use efficiency (%)	Water use efficiency (%)
Redbud	1.21 ^z	1.16	1.35	1.38
Red oak	1.21	1.11	1.00	1.07
Autumn Blaze® maple	1.07	0.97	0.99	1.26
Prairifire crabapple	1.32	1.05	1.33	4.00

^zWithin each species, the relative growth difference was derived from the ratio between those plants grown in a retractable roof structure and those grown outdoors. Each value has been averaged over fertilization methods within a production environment. Height and caliper values are the means of 30 plants per taxa whereas water and N use efficiency values are the means of 10 plants and six plants respectively.

was higher for redbud and crabapple whips grown in the RRS than those outdoors, and was similar for red oak and red maple whips (Table 6). The higher water use efficiency of whips grown in RRS was one contributing factor to increased growth found under RRS by several researchers (Nelkin and Schuch, 2004; Schuch, 2004; Svenson, 1998, 1999, 2000; Svenson and Johnston, 1991; Svenson et al., 1992, 2000, 2001). Another contributing factor to greater growth under RRS was reduced temperature stress. How-

ever, the relative growth differences between the two production environments are a result of the specific conditions of this experiment.

The production schedule used in this study should be shortened for all taxa except red oak. Caliper, relative to height, for the other three taxa exceeded ANSI standards in both environments (ANSI, 2004). Excessive height growth (relative to caliper) under both production environments suggest that double cropping may be appropriate. If whips are less

than 1.27 cm in caliper, then height growth in excess of 3.1 m is not beneficial. However, only the RRS can be used for double cropping, because it offers suitable environmental protection for production schedules that exceed the average frost-free time in US Department of Agriculture (USDA) plant hardiness zone 5.

Conclusions

We have demonstrated that under the conditions of this experiment, high-quality whips can be produced in containers in one growing season in USDA plant hardiness zone 5 (156 d frost-free growing season) in an RRS or on an outdoor gravel pad (if the growing season is extended with a 70-d greenhouse production period). The generally greater whip growth in the RRS, relative to the outdoor environment, was attributed to reduced temperature stress, especially to the roots. Increased NUE for two species in the RRS was attributed in part to reduced nutrient leaching during rainstorms; during rain storms, the roof closed. Reduced leaching, combined with greater root dry weight and better root distribution within the containers, increased N uptake. The economic benefits of producing whips in RRSs are difficult to quantify, because they are dependent on the crop type, the local climatic conditions, and specific production practices. However, with proper management, RRSs can increase WUE and NUE without reducing plant growth, and represent a viable alternative to unprotected outdoor production environments.

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