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Optimum Nitrogen Fertilization for Production of Containerized *Raphiolepis × delacourii* 'Snow White'[1]

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Abstract

Rooted stem cuttings of 'Snow White' raphiolepis (*Raphiolepis* × *delacourii* André 'Snow White') were grown in 3.8-liter (#1) black plastic containers containing a pine bark:sand (8:1, by vol) substrate. Plants were fertilized at every irrigation, for 17 weeks, with a 4:1:2 nitrogen (N):phosphorus (P):potassium (K) nutrient solution containing N at 20, 60, 100, 140, 180, 220, or 240 mg·L^{-1} (ppm) supplied as ammonium nitrate (NH_4NO_3). Maximum top and root dry weights were achieved with N at 145 mg·L^{-1}. Substrate solution electrical conductivity increased linearly with increasing nitrogen application rate (NAR) with maximum growth occurring at 1.28 dS·m^{-1}, whereas substrate solution pH decreased linearly with increasing NAR with a pH of 5.3 at 145 mg·L^{-1}. Increasing the N rate beyond 145 mg·L^{-1} had minimal effect on top or root dry weight. Leaf area peaked at a NAR of 171 mg·L^{-1} with a plateau at 524 cm^2. Leaf area increased 275% as the NAR increased from 20 to 171 mg·L^{-1}. Specific leaf area increased linearly with increasing NARs. Carbon allocation between tops and roots was unaffected by NARs from 60 to 280 mg·L^{-1}. Root:top ratio decreased 56% between the pooled NARs (60 to 240 mg·L^{-1}) and N at 20 mg·L^{-1}. Leaf area ratio increased linearly with increasing NARs. Foliar mineral nutrient concentrations of N, P, and sulfur increased linearly with increasing NAR, whereas concentrations of K, calcium, magnesium, and copper responded quadratically to increasing NARs. Top growth increased from inadequate at a NAR of 60 mg·L^{-1} to optimum at 145 mg·L^{-1}, whereas root growth was relatively similar over the same range. At 145 mg·L$^{-1,}$ mineral nutrient concentrations of the top are well within or exceed accepted levels reported, and growers can expect rapid growth of rooted cuttings.

Index words: mineral nutrition, nursery production, woody plant, leaf area ratio.

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Significance to the Nursery Industry

Although 'Snow White' raphiolepis has become a popular cultivar, specific nutritional guidelines for containerized culture of 'Snow White' are unavailable. Results of this study will allow development of a more efficient means of production where growth can be optimized with lower nutrient applications. This would not only decrease fertilizer costs, but help reduce nutrient runoff issues. Increasing fertilizer concentrations of nitrogen (N) beyond 145 mg·L^{-1} (ppm) applied every other day neither improved top growth nor proved detrimental to root growth. Under these conditions, N at 145 mg·L^{-1} provided by a fertilizer having a 4N:1P:2K ratio with a corresponding electrical conductivity of 1.28 dS·m^{-1} was considered optimal for growth of 'Snow White' raphiolepis.

Introduction

Raphiolepis × *delacourii* André is a common hybrid between *R. umbellata* C.K. Schneider (yeddo raphiolepis) and *R. indica* Lindl. (Indian hawthorn) (16). Although the individual species, *R. umbellata* and *R. indica*, are used to some extent in the landscape, most cultivars tend to be of hybrid origin, combining characteristics of both parents. In years past, *Raphiolepis* × *delacourii* was seldom used due to lack of cold hardiness and poor resistance to diseases (7) including entomosporium leaf spot (*Entomosporium maculatum* Lév.) which infects and discolors the foliage and causes leaf drop in shady locations (10). Recent development of disease and cold resistant cultivars, such as the cultivar, Snow White, which has excellent resistance to entomosporium leaf spot (12), has led to a renewed interest in raphiolepis (7).

Even though 'Snow White' raphiolepis is a popular cultivar due to its dwarf, spreading form, with pure white flowers from early spring through summer, and purplish black fruit from fall into winter, no research has been reported on mineral nutrient nutrition during containerized production of this plant. Determining a fertilization regime to maximize plant growth with minimum mineral nutrient inputs is essential to increase nursery profits while reducing nutrient leaching and, thus potential environmental pollution.

Nitrogen (N) is the mineral nutrient that has the greatest influence on growth and productivity of plants, making N the most frequently applied fertilizer element (1, 24, 25). Most fertilizer programs are based on N concentration, and the levels of other nutrients are typically established relative to N (23). However, while N deficiency limits plant growth, excessive N can be detrimental, causing excess mineral nutrient accumulation or a decrease/halt in growth which can lead to N losses (1, 25).

Nitrogen applied at 20 to 120 mg·L^{-1} (ppm) with every or every other irrigation often maximizes growth of woody perennial species (5, 11, 15, 18, 19, 20, 27, 32), although the nutritional needs of many genera have not been studied (30). Nitrogen application rates (NARs) to maximize growth are a function of N rate and the rate of supply (frequency of application) in relation to the current rate of uptake (18). NARs in the suboptimal range are not only a consequence of the

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concentration of the nutrient(s) in the solution but the rate of supply in relation to the current rate of uptake. Thus, lower NARs will often produce maximum growth with increasing frequency of application.

Excess N is not only potentially detrimental to the crop, but it is wasteful in terms of cost both to the grower and to the environment. NARs > 60 mg·L^{-1} applied to American holly (*Ilex opaca* L.) and 'Tonto' crape myrtle (*Lagerstromeia indica* × *fauriei* 'Tonto') decreased growth of both species (1, 2). Thus, the objective of this study was to determine the optimal NAR for growth and mineral nutrient status of containerized 'Snow White' raphiolepis.

Materials and Methods

On December. 3, 2002, 90 uniform rooted stem cuttings of 'Snow White' raphiolepis were potted into 3.8-liter (#1) black plastic containers with a pine bark:sand (8:1, by vol) substrate amended with 1.8 kg·m^{-3} (4 lb·yd^{-3}) dolomitic limestone. Containers were placed in a glass greenhouse with days/nights of 24 ± 3C (75 ± 5F)/18 ± 3C (65 ± 5F). Plants were grown under natural photoperiod and irradiance from 0800 to 1700 HR daily and received a night interruption from 2300 to 0200 HR from incandescent bulbs. The bulbs provided a photosynthetic photon flux of 3.6 μmol·m^{-2}·s^{-1} plus photomorphogenic radiation of 0.7 W·m^{-2} as measured at the tops of the containers with a cosine corrected LI-COR model LI-185A Quantum/Radiometer/Photometer (LI-COR, Lincoln, NE). Tap water containing NO_3-N, NH_4-N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and alkalinity at 0.10, 0.96, 0.5, 7.0, 10.0, 4.0, and 20.0 mg·L^{-1} (ppm) respectively, with a pH of 7.4 was applied until seven NARs [20, 60, 100, 140, 180, 220, or 260 mg·L^{-1} (ppm)] were initiated on January 16, 2003.

To simplify discussion of the effects of the rate of fertilization, only the N rate will be listed but the reader should be cognizant that as the NARs increased in the nutrient solution from 20 to 260 mg·L^{-1}, N, P, and K rates were also increased to maintain a N:P:K ratio of 4:1:2. Reagent grade ammonium nitrate, potassium phosphate, and potassium sulfate supplied the N, P, and K. A modified Hoagland's solution supplied the micronutrients in the nutrient solutions (17). To deliver the seven N:P:K solutions and micronutrients, two proportional injectors (Dosatron 16I, Dosatron, Inc., Clearwater, FL) were connected in series with one injector used for the N:P:K solutions and the other for micronutrients. All fertilizer solutions were premixed in containers, the injectors adjusted for a 100:1 dilution ratio, and the solutions applied every other day to maintain a ≥ 0.25 leaching fraction (volume leached ÷ volume applied) using pressure compensated spray stakes (Acu-Stick, Wade Mfg. Co., Fresno CA) at a rate of 200 mL·min^{-1} (0.3 in·min^{-1}). No other irrigation was required. Substrate solution was collected from all treatments and replications on February 7, March 5, March 20, May 1, and May 22 using the pour through technique (36) to monitor electrical conductivity (EC) and pH (Accumet 50, Fisher Scientific Co., Pittsburgh, PA). The experiment was a randomized complete block design with nine single plant replications per treatment.

At treatment initiation, 10 plants were harvested, roots washed free of substrate, and separated into leaves, stems, and roots. Initial leaf area was measured with a LI-COR 3100 Area Meter (LI-COR, Inc., Lincoln, NE) prior to plant tissue being dried at 70C (158F) until plant weight remained unchanged (96 hr) and weighed. Initial leaf area was 32.8 cm^2. Initial dry weights of leaves, stems, and roots were 0.59 g, 0.08 g, and 0.54 g, respectively, with a root:top ratio (root dry weight ÷ top dry weight) of 0.81.

After 17 weeks, roots were washed free of substrate and each plant separated into leaves, stems, and roots. Dry weights were obtained following drying at 70C (158F) until plant weight remained unchanged (96 hr). Prior to drying, leaf area was measured (LI-COR 3100). The above measurements were used to calculate top dry weight (leaf dry weight + stem dry weight), total plant dry weight (leaf + stem + root), root:top ratio (RTR, root dry weight ÷ top dry weight), specific leaf area (SLA, leaf area ÷ leaf dry weight), leaf weight ratio (LWR, leaf dry weight ÷ total plant dry weight), stem weight ratio (SWR, stem dry weight ÷ total plant dry weight), root weight ratio (RWR, root dry weight ÷ total plant dry weight), plant leaf area ratio (LAR_{plant}, leaf area ÷ total plant dry weight), and top leaf area ratio (LAR_{top}, leaf area ÷ top dry weight). Leaves of plants were ground separately via a Foss Tecator Cyclotec™ 1093 sample mill (Analytical Instruments, LLC, Golden Valley, MN) to pass a ≤ 0.5 mm (0.02 in) sieve. Mineral nutrient [N, P, K, Ca, Mg, sulfur (S), boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn)] analysis of leaves from replicates one to five was conducted by the North Carolina Department of Agriculture and Consumer Services, Raleigh. Nitrogen concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500, CE Elantech Instruments, Milan, Italy). All other mineral nutrient concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corp., Wellesley, MA), following open-vessel nitric acid (HNO_3) digestion in a microwave digestion system (CEM Corp., Matthews, NC). Foliar mineral nutrient content was based on the percentage concentration of a nutrient divided by 100 and multiplied by the leaf dry weight.

Data were subjected to regression and segmented linear regression (quadratic plateau) in SAS version 8.01 (SAS Inst., Inc., Cary, NC). All variables were tested with and without the low N rate (N at 20 mg·L^{-1}, referred to as the control). Analyses showed statistical significance for RTR, LWR, SWR, and RWR only when the control was included. Therefore, for these variables, the control was excluded from the regression analysis and a linear contrast was used to test the differences between a pooled N treatment (N at 60 to 280 mg·L^{-1}) effect and the control (N at 20 mg·L^{-1}). For the remaining variables, simple linear or polynomial curves were fitted to the data when significant trends were identified in regression analyses. The maximum of the polynomial curve was calculated as a first order derivative of the independent variable where the dependent variable equaled zero. Pearson's correlation coefficients were used to examine relationships between the variables.

Results and Discussion

Leaf dry weight, stem dry weight, and top dry weight were highly correlated ($P < 0.001$, $r = 0.94$) and thus only top dry weight is presented. The quadratic plateau model predicted maximum top dry weight (8.7 g) with N at 145 mg·L^{-1} (ppm), whereas the quadratic equation predicted maximum top dry weight (8.9 g) at 188 mg·L^{-1} (Fig. 1). Even though only 0.2 g (2%) separated the predicted top dry weights of the two models, the quadratic plateau indicated maximum top dry

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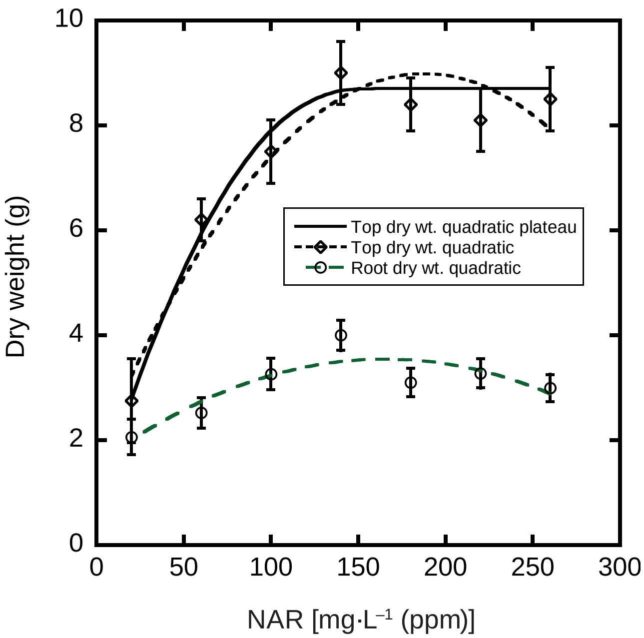

Fig. 1. Effect of nitrogen application rate (NAR) on top and root dry weight of 'Snow White' raphiolepis. Data points are means of nine observations. Vertical bars = ± 1 SE. Top dry weight: quadratic plateau, if $x \leq 145$, then top dry weight = $0.73 + 0.11x - 0.00038x^2$, $R^2 = 0.90$. If $x \geq 145$, then top dry weight = 8.7; quadratic, top dry weight = $1.77 + 0.077x - 0.0002x^2$, $R^2 = 0.97$. Root dry weight: quadratic, root dry weight = $1.55 + 0.024x - 0.00007x^2$, $R^2 = 0.88$.

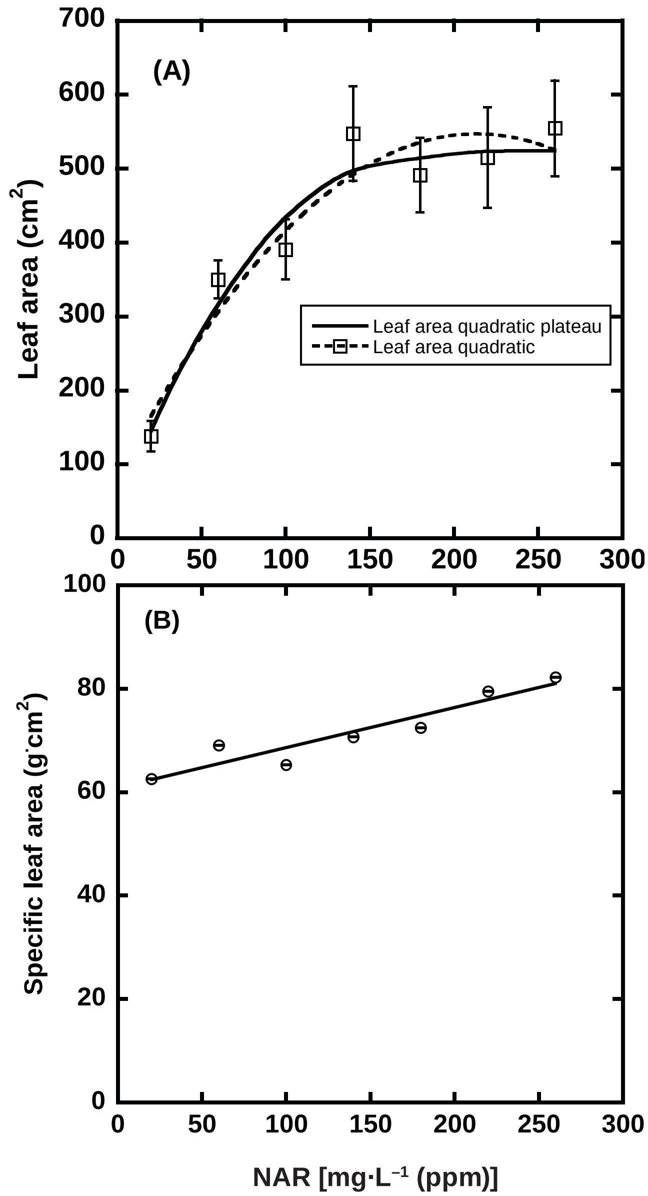

Fig. 2. Effect of nitrogen application rate (NAR) on (A) leaf area and (B) specific leaf area of 'Snow White' raphiolepis. In (A), data points are means of nine observations. Vertical bars = ± 1 SE. Quadratic plateau: If $x \leq 214$, then leaf area = $38.7 + 5.67x - 0.017x^2$, $R^2 = 0.95$; If $x \geq 214$, then leaf area = 524; quadratic: leaf area = $82.1 + 4.36x - 0.010x^2$, $R^2 = 0.98$. In (B), data points are means of nine observations. Standard error bars are hidden by symbols. Specific leaf area = $60.9 + 0.08x$, $R^2 = 0.94$.

weight was reached at NARs 30% less than predicted by the quadratic model. A nutrient regime that produces maximum growth with a minimum amount of fertilizer is desirable. This reduction in applied N would reduce fertilizer costs while minimizing potential environmental pollution of excessive N. While N at 145 mg·L^{-1} is high compared to other woody species, however, it is within the range of N recommendations (100 to 150 mg·L^{-1}) for conifers (23). Increasing the N rate beyond 145 mg·L^{-1} had minimal effect on top dry weight.

The quadratic plateau model predicted maximum root dry weight (3.9 g) with N at 146 mg·L^{-1} (data not presented), whereas the quadratic equation predicted the same maximum root dry weight (3.9 g) with N at 166 mg·L^{-1} (Fig. 1). The R^2, however, was low (0.53) for the quadratic plateau compared to the quadratic model ($R^2 = 0.88$) indicating it was a better descriptor. Similarly, Dubois et al. (8) working with 'Margarete' fall flowering anemone (*Anemone* × *hybrida* Paxton 'Margarete') and Conden et al. (5) working with Japanese (*Ternstroemia gymnanthera* Thunb.) reported root dry weight increased quadratically with increasing NAR with calculated maximum root dry weight occurring with N at 119 and 86 mg·L^{-1}, respectively. However, this is in direct contrast to results of Griffin et al. (11) and Cabrera and Devereaux (2) who reported root dry weight decreased quadratically or linearly, respectively, with increasing NARs. It is unusual to see maximum root and top dry weight peaking at similar NARs. Root growth is often maximized at lower NARs (5, 11, 27). Response of root growth to NAR appears to be very species specific. 'Snow White' raphliolepsis appears to require a high NAR to maximize growth.

Based on the quadratic plateau model, leaf area peaked at a NAR of 171 mg·L^{-1} with a plateau at 524 cm^2, whereas the quadratic model predicted a peak (541 cm^2) at 214 mg·L^{-1} (Fig. 2A). Leaf area increased 275% as N increased from 20 to 171 mg·L^{-1}. Data herein agree with results of Ingestad (18) who reported within the suboptimum range of N, there is a direct control of growth by N which is related to a strong effect of N on leaf development. Maximum top dry weight with N at 145 mg·L^{-1} is similar to peak leaf area at 171 mg·L^{-1}. Leaf area was highly correlated to top dry weight ($P < 0.0001$, $r = 0.78$). However, leaf area was not correlated to root dry weight (data not presented).

SLA is a morphological index of leaf expansion with a high ratio corresponding to a thinner leaf (9). SLA increased

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Table 1. **Effect of nitrogen application rate (NAR) on root:top ratio (RTR), leaf weight ratio (LWR), stem weight ratio (SWR), and root weight ratio (RWR) of 'Snow White' raphiolepis.[z]**

NAR (mg·L^{-1})	RTR	LWR	SWR	RWR
20	0.94	0.40	0.13	0.47
60	0.41	0.58	0.13	0.29
100	0.44	0.55	0.15	0.30
140	0.43	0.56	0.14	0.29
180	0.38	0.59	0.14	0.27
220	0.42	0.57	0.15	0.28
260	0.36	0.58	0.16	0.26
Linear[y]	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS
N rate vs. control	**	**	NS	**

[z]RTR = root dry weight ÷ top dry weight, LWR = leaf dry weight ÷ total plant dry weight, SWR = stem dry weight ÷ total plant dry weight, and RWR = root dry weight ÷ total plant dry weight.

[y]NS, ** Nonsignificant or significant at $P \le 0.01$, respectively. Nitrogen at 20 mg·L^{-1} was not included in regression analysis.

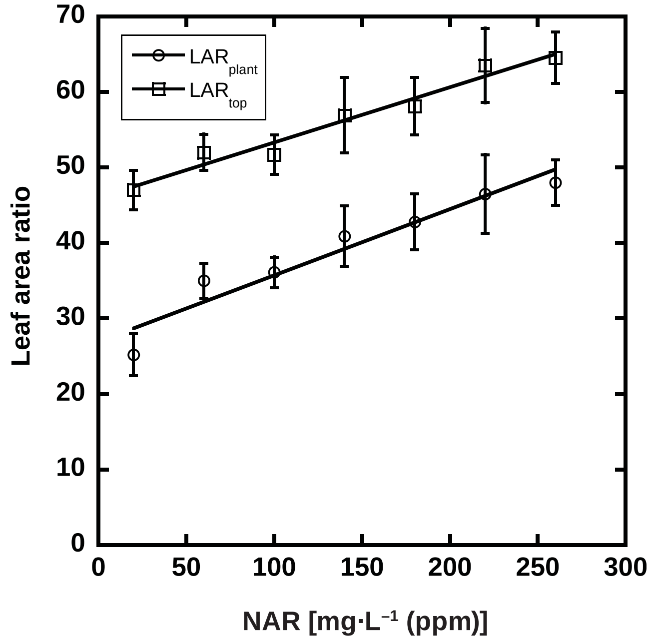

Fig. 3. **Effect of nitrogen application rate (NAR) on plant leaf area ratio (LAR_{plant}) and top leaf area ratio (LAR_{top}) of 'Snow White' raphiolepis. Data points are means of nine observations. Vertical bars = ± 1 SE. LAR_{plant} = 27.0 + 0.088x, R^2 = 0.96; LAR_{top} = 46.0 + 0.073x, R^2 = 0.98.**

linearly with increasing NARs (Fig. 2B) indicating leaves were getting thinner with increasing NARs. Variation in SLA, however, may also be due to differences in leaf density (dry mass per unit volume). Leaf density varies due to differences in the amount of cell wall and cell contents and the presence of air spaces in the tissue. Leaves with high SLA are likely to have reduced tolerance to biotic and abiotic stress, and shorter leaf life-span (22). Since 'Snow White' raphliolepsis is an evergreen, higher NARs may compromise leaf quality.

Carbon (C) allocation between roots and top (RTR) was unaffected by NARs from 60 to 280 mg·L^{-1} indicating root and top growth responded similarly to increasing NARs (Table 1). This was unexpected as increasing NARs typically reduce RTR (9). However, RTR decreased 56% between the pooled NARs and N at 20 mg·L^{-1}. Even though both root and top dry weight increased quadratically with increasing NARs (Fig. 1), top dry weight increased 125% from 20 to 60 mg·L^{-1}, whereas root dry weight only increased 22% from 20 to 60 mg·L^{-1} resulting in a dramatic decrease in RTR. Henry et al. (15) reported RTR of eastern red cedar (*Juniperus virginiana* L.) decreased 85% as NARs increased from 5 to 80 mg·L^{-1}, whereas RTR was unchanged from 80 to 640 mg·L^{-1}. As plants move from N deficient to adequate N, most plants typically allocate a larger fraction of carbohydrates to top growth (9). There is some concern with a low RTR as field studies have demonstrated plants with a high RTR at planting had greater growth in the second year (9). However, Cabrera and Devereaux (3) reported RTR did not affect landscape performance of 'Tonto' crape myrtle.

Similar to RTR, LWR and RWR were unaffected by NARs if N at 20 mg·L^{-1} was excluded from the regression (Table 1). However the pooled NARs (60 to 280 mg·L^{-1}) were significantly different from 20 mg·L^{-1} for both LWR and RWR. LWR increased 47% from 0.40 to 0.58 as N increased from 20 to 60 mg·L^{-1}, whereas RWR decreased 38% from 0.47 to 0.29 as N increased from 20 to 60 mg·L^{-1}. SWR was unaffected by NARs (mean = 0.14) indicating it was C allocation between leaves and roots that was responding to NARs. Cromer and Jarvis (6) also reported NARs affected C balance between leaves and roots of rose gum (*Eucalyptus grandis* Hill ex Maiden) while C allocation to the stem was unaffected.

LAR_{plant} increased linearly with increasing NARs (Fig. 3). Because LAR_{plant} is a measure of leaf area produced per gram of dry matter, a high LAR_{plant} indicates the plant is efficient at producing leaf area. Leaf area influences light interception, which in turn affects plant growth. Thus, an increasing LAR_{plant} would be expected to increase rate of growth. Fertilizer effects on growth of pansy (*Viola × wittrockiana* Gams.) and 'Scarlet Sage' salvia (*Salvia splendens* F. Sellow ex Roem. & Schult. 'Scarlet Sage') were closely correlated to effects on LAR_{plant} (21, 34). Veneklaas et al. (35) also reported differences in growth among several woody species were related to LAR of these species. However, for the data herein, LAR_{plant} was weakly correlated to top dry weight ($P < 0.01$, $r = 0.33$), whereas leaf area was highly correlated with top dry weight ($P < 0.0001$, $r = 0.78$). As the RTR was unaffected by NARs ≥ 60 mg·L^{-1} (Table 1), differences in LAR_{plant} were due to differences in SLA. LAR_{plant} was highly correlated to SLA ($P < 0.0001$, $r = 0.93$) and LAR_{top} ($P < 0.0001$, $r = 0.93$) (Fig. 3). LAR_{plant} increased as leaves became thinner with increasing NAR. However, leaf area increased without allocating more dry matter to the leaf fraction (Table 1). Venklaas et al. (35) reported similar results. Thus, even though LAR_{plant} increased linearly with increasing NARs, net photosynthesis may not have increased similarly. However, from our data it is not clear why there was not a higher correlation between LAR_{plant} and growth.

Foliar mineral nutrient concentrations of N, P, and S increased linearly with increasing NAR, whereas foliar mineral nutrient concentrations of K, Ca, Mg, and Cu responded quadratically to increasing NARs (Table 2). Nitrogen concentrations in tops of 'Carolina Sapphire' smooth Arizona cypress [*Cupressus arizonica* var. *glabra* (Sudw.)

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Table 2. Effect of nitrogen application rate (NAR) on foliar mineral nutrient concentration of 'Snow White' raphiolepis.[z]

NAR ($mg \cdot L^{-1}$)	N	P	K	Ca	Mg	S	Cu ($\mu g \cdot g^{-1}$)
	$mg \cdot g^{-1}$						
20	18.7 ± 0.3	2.1 ± 0.02	11.2 ± 0.4	12.9 ± 0.7	2.9 ± 0.01	7.8 ± 0.04	4.5 ± 0.4
60	21.7 ± 0.2	2.4 ± 0.03	12.5 ± 0.4	11.3 ± 0.6	3.0 ± 0.01	8.8 ± 0.05	5.7 ± 0.3
100	22.1 ± 0.2	3.4 ± 0.03	12.5 ± 0.4	10.0 ± 0.4	3.1 ± 0.01	10.0 ± 0.06	6.0 ± 0.5
140	23.3 ± 0.3	4.1 ± 0.02	12.8 ± 0.3	9.7 ± 0.5	3.2 ± 0.01	10.1 ± 0.04	6.4 ± 0.2
180	25.8 ± 0.3	5.4 ± 0.03	14.3 ± 0.3	10.4 ± 0.4	3.4 ± 0.01	10.6 ± 0.04	6.4 ± 0.2
220	26.5 ± 0.3	6.6 ± 0.04	13.9 ± 0.3	9.4 ± 0.4	3.2 ± 0.01	11.4 ± 0.04	6.4 ± 0.3
260	27.9 ± 0.2	6.7 ± 0.03	13.9 ± 0.4	9.6 ± 0.5	3.3 ± 0.01	11.4 ± 0.05	6.5 ± 0.2
Significance[y]							
Linear	***	***	**	*	**	***	*
Quadratic	*	*	***	***	***	**	***

[z]Data are means of five observations ± 1 SE.

[y]*, **, *** Significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Control (N at 20 $mg \cdot L^{-1}$) was included in regression analysis. N = 19 + 0.037x, R^2 = 0.97; P = 1.3 + 0.022x, R^2 = 0.97; K = 11 + 0.024x – 0.000045x², R^2 = 0.88; Ca = 13 – 0.038x + 0.000093x², R^2= 0.88; Mg = 2.8 + 0.0044x – 0.000009x², R^2 = 0.84; S = 8 + 0.015x, R^2 = 0.93; Cu = 4.3 + 0.023x – 0.00006x², R^2 = 0.93.

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Little 'Carolina Sapphire'], eastern red cedar, and Japanese ternstroemia responded similarly (5, 15, 32). Nitrate will be absorbed continually by plants as long as it is present in the substrate solution with excess nitrate being stored when supply exceeds demand for growth. Maximum top dry weight occurred at a NAR of 145 $mg \cdot L^{-1}$, with a corresponding foliar N concentration of 24.4 $mg \cdot g^{-1}$ (Table 3). This foliar N concentration is higher than the 11.9 $mg \cdot g^{-1}$ or the 16.1 to 22.2 $mg \cdot g^{-1}$ reported for *R. indica* or *R. umbellata* 'Minor', respectively (26) (Table 3). However, it is not possible to determine if these mineral nutrient concentrations represent values at maximum growth. Similarly, maximum dry weight of *Ilex opaca* 'Hedgeholly' and 'Tonto' crape myrtle were observed at foliar N concentrations of 25.3 and 26.5 $mg \cdot g^{-1}$, respectively (1).

NAR may have affected LAR_{plant} through its affect on foliar N content in the leaves (data not presented). Leaf expansion is strongly affected by internal N concentration (29). Foliar N content was correlated to leaf area ($P < 0.0001$, $r = 0.64$). This could account for the linear increase in both LAR_{plant} and LAR_{top} without the subsequent linear increase in top dry weight.

Increasing NARs have been reported to suppress uptake of P (4, 31) but more recent studies have reported foliar P concentration increased quadratically or linearly with increasing NARs (5, 13). The linear response reported herein probably reflects the 4:1:2 ratio that was maintained at each NAR. Foliar P concentration of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* Karst.) increased linearly with increasing NARs from 20 to 400 $mg \cdot L^{-1}$ with a constant 6:1:3 N:P:K ratio (18). Harvey et al. (13) also reported foliar P concentration of 'Aureola' Hakone grass (*Hakonechloa macra* Makino 'Aureola') increased with increasing NARs from 0 to 450 $mg \cdot L^{-1}$ with N:P ratios ranging from 5:1 to 20:1, whereas top growth was unaffected by N:P ratios. They concluded P supply did not limit growth of 'Aureola' Hakone grass even at a N:P of 20:1. The lowest foliar P concentration reported herein (2.1 $mg \cdot g^{-1}$) was greater than the foliar P concentrations (1.2 to 1.5 $mg \cdot g^{-1}$) reported by Mills and Jones (26) suggesting even the lowest P rate (2.5 $mg \cdot L^{-1}$) was not limiting growth in this study. In addition, P at 2.5 $mg \cdot L^{-1}$ and 5 $mg \cdot L^{-1}$ (lowest rate applied) was adequate for maximum growth of *Rhododendron* 'Victor' and 'Helleri' holly, respectively (14, 37).

Foliar K and Mg concentrations were 14.5 $mg \cdot g^{-1}$ and 3.4 $mg \cdot g^{-1}$, respectively, with N at 145 $mg \cdot L^{-1}$ (Table 3). Harvey et al. (13) reported foliar K concentration increased quadratically with increasing NARs. Conden et al. (5) also reported

Table 3. Leaf mineral nutrient concentration at optimal N rate for top growth of 'Snow White' raphiolepis.

Mineral nutrient	Reported foliar concentration ($mg \cdot g^{-1}$)[z]	Predicted concentration ($mg \cdot g^{-1}$) at maximum top growth (N at 145 $mg \cdot L^{-1}$)	Predicted maximum leaf concentration ($mg \cdot g^{-1}$)
N	11.9[z] 16.1 to 22.2[y]	24.4	28.6
P	1.5 1.1 to 1.3	4.5	7.0
K	9.4 14.4 to 15.3	14.5	14.5
Ca	21.5 22.9 to 24.9	10.0	12.9
Mg	2.1 3.0 to 3.3	3.4	3.9
S	9.0 7.0 to 9.0	10.2	11.9

[z]Means for 'Minor' yeddo raphiolepsis (*Raphiolepis umbellata* 'Minor') (26).
[y]Range for Indian hawthorn (*R. indica*) (26).

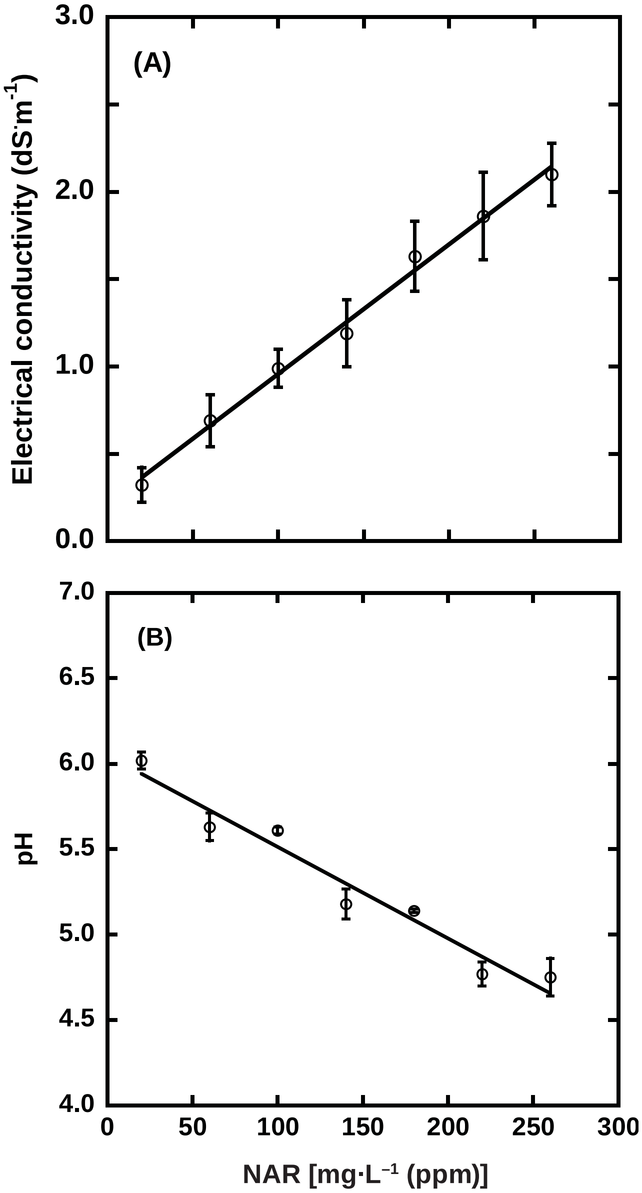

Fig. 4. Effect of nitrogen application rate (NAR) on (A) substrate solution electrical conductivity (EC) and (B) pH. Data points are means of 45 observations. Vertical bars = ± 1 SE. EC = 0.21 + 0.0074x, R^2 = 0.99 and pH = 6.05 – 0.005x, R^2 = 0.98.

foliar K concentration of Japanese ternstroemia responded similarly to increasing NARs, whereas foliar Mg concentration was unaffected by NARs. However, increased foliar Mg concentrations with increasing NARs might be expected as it is a vital component of chlorophyll and a cofactor for many regulatory enzymes (26) all of which should increase from chlorotic, N stressed to healthy, N sufficient plants due to increasing NARs. Conversely, reductions in major cations (K, Ca, and Mg) in leaf tissue concentration with increasing NARs have been reported in studies in which the NH_4^+ form is a significant fraction of the N supply (2). Likewise, since S is also attributed to many proteins and enzymes associated with growth, foliar S concentration might be expected to increase with increasing NARs (24, 26). However, Cabrera (2) reported foliar S concentrations decreased with increasing NARs which impacted the N:S ratio. He attributed a decrease in growth to the increasing N:S ratio. The N:S ratio was unaffected by NARs in this study (data not presented) possibly due to the increasing S rate (potassium sulfate) with increasing NARs.

Foliar Ca concentration reached a minimum with N at 141 mg·L^{-1}. Reduced levels of Ca can be attributed to antagonistic effects between cations in the substrate solution competing for uptake by the roots or dilution due to increased growth with increasing NARs. Foliar Ca content increased quadratically with increasing NARs with a maximum at a NAR of 141 mg·L^{-1} (data not presented), indicating the decreasing foliar Ca concentration with increasing NARs was due to dilution. Mills and Jones (26) reported very high foliar Ca concentration for *R. indica* and *R. umbellata* ranging from 21.5 to 24.9 mg·g^{-1}. Foliar mineral nutrient concentrations of B (mean = 41 μg·g^{-1} ± 2), Fe (mean = 55 μg·g^{-1} ± 6), Mn (mean = 94 μg·g^{-1} ± 2), and Zn (mean = 63 μg·g^{-1} ± 3) were unaffected by NARs (data not presented).

Since there was a linear relationship between NARs and leaf concentrations of N, P, and S, but a quadratic relationship between NAR and dry weight (Fig. 1), it seems unlikely the effects of NARs on dry weight can be explained by direct effects of leaf nutrient status. In particular, the plateauing in dry weight at higher than optimal NARs does not appear to be related to mineral nutrient concentration in the plants.

Tracking fertility levels of substrates by measuring EC of solution displacement extractions is a recommended practice for nursery production (36). EC increased linearly with increasing NAR with maximum growth occurring at 145 mg·L^{-1} resulting in an EC of 1.28 dS·m^{-1} (Fig. 4A). Similarly, Kang and van Iersel (21) reported growth of 'Scarlet Sage' salvia increased greatly with increasing EC from 0.4 to 2.0 dS·m^{-1} with maximum growth occurring between 2.0 and 3.7 dS·m^{-1}. However, this is high compared to the 0.60 and 0.94 dS·m^{-1} reported to maximize growth of Japanese ternstroemia and 'Green Giant' arborvitae (*Thuja* L. × 'Green Giant'), respectively (5, 11). Substrate solution pH decreased linearly with increasing NAR ranging from 6.02 to 4.75 with a pH of 5.3 at 145 mg·L^{-1} (Fig. 4B). Peterson (28) reported nutrient availability in organic container substrate is optimal at a pH range of 5.0 to 6.0. Nutrient availability did not appear to be affected by pH as most nutrients except for Ca increased with increasing NAR (Table 2) or were unaffected by NAR.

Top growth increased from inadequate at a NAR of 60 mg·L^{-1} to optimum at 145 mg·L^{-1}, whereas root growth was relatively similar over the same range. With N at 145 mg·L^{-1}, nutrient concentrations of the top are well within or exceed the accepted levels reported, and growers can expect rapid growth of rooted cuttings.

Limiting fertilizer inputs to the lowest nutrient concentrations consistent with adequate growth is an important consideration for growers. It should be implemented whenever possible because it is a cost-saving technique that can significantly reduce levels of mineral nutrient runoff from nurseries (33).

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