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# Controlled-release Fertilizer Application Rates for Container Nursery Crop Production in Southwestern Ontario, Canada

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***Abstract*. Region-specific trials examining optimum controlled-release fertilizer (CRF) rates for the Canadian climate are limited. This study was conducted to determine an optimum range of CRF application rates and the effect of the application rate on growth, nitrogen (N), and phosphorus (P) losses of six economically important container-grown woody ornamental shrubs using typical production practices at a southwestern Ontario nursery. *Salix purpurea* 'Nana', *Weigela florida* 'Alexandra', *Cornus sericea* 'Cardinal', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' were potted in 1-gal pots and fertilized with Polyon® 16N-2.6P-10K (5–6 month longevity) incorporated at rates of 0.8, 1.2, 1.7, 2.1, and 2.5 kg·m$^{-3}$ N in 2012. The experiment was repeated for the 2013 growing season with rates of CRF incorporated at 0.05, 0.35, 0.65, 0.95, and 1.25 kg·m$^{-3}$ N. Plant performance (i.e., growth index) and leachate electrical conductivity (EC) and pH were evaluated once every 3 to 4 weeks during the respective growing seasons. The amount of N and P lost to the environment was determined for the 2012 growing season. The interaction between nutrient supply rate and target species affected most response variables. Although higher levels of fertilization produced larger plants and had the potential to decrease production time, increased losses of N and P and higher EC leachate values occurred. Results of this study indicate that an acceptable range of CRF application rates can be used for each species depending on the production goals, i.e., decreased production time, maximum growth, or decreased nutrient leachate. Overall, the highest acceptable CRF rates within the optimal range were: 1.25 kg·m$^{-3}$ N for *Spiraea*; 1.7 kg·m$^{-3}$ N for *Hydrangea*; 2.1 kg·m$^{-3}$ N for *Cornus;* and 2.5 kg·m$^{-3}$ N for *Weigela*, *Salix*, and *Hibiscus*. The lowest acceptable rates within the optimal range were: 0.35 kg·m$^{-3}$ N for *Hibiscus*; 0.65 kg·m$^{-3}$ N for *Cornus*, *Weigela*, *Salix*, and *Spiraea;* and 0.80 kg·m$^{-3}$ N for *Hydrangea*.**

Over the last 30 years, there has been a growing trend of intensified nursery production within Canada (Deliotte and Touche LLP, 2009). Containerized plant production is a major contributor to this intensification, because it allows for greater production per hectare, higher quality, and faster growth (Davidson et al., 1988). However, this form of intensified ornamental horticulture is recognized to have a significant impact on the environment. In particular, the large amount of irrigation water and fertilizer required for containerized plant production can result in an increased amount of nutrient runoff (Majsztrik et al, 2011; Yeager et al., 1993).

To minimize nutrient runoff while ensuring optimum plant growth, it is essential to understand the responses of plants to fertilizer applications and the fate of the applied nutrients [e.g., N, P, potassium (K), etc.]. Insufficient fertilizer can cause plant nutrient deficiencies and reduced crop productivity. On the other hand, overapplication of fertilizer is not only costly, but also can cause injury to plants and damage to the environment. If nutrients are applied in excess of plant demands, these excess nutrients have the potential to pollute both ground and surface water through nursery leachate and runoff. Consequently, when optimal fertilizer application rates are used, crops will perform at their best and environmental impacts will be minimized (Cabrera, 2003).

Controlled-release fertilizers have become the principal method to fertilize container nursery stock in Canada and many other parts of the world (Alam et al., 2009; Chen et al., 2011; Yeager and Cashion, 1993). Application rates and longevity ratings for CRFs are listed on the fertilizer packaging; however, these rates are established during strict laboratory dissolution tests at constant temperatures or in field trials that occur in temperate to warm regions of the United States: i.e., California, Florida, South Carolina (Birrenkott et al., 2005; Chen et al., 2011; Griffin et al., 1999; Ruter, 1992a; Yeager and Cashion, 1993). Therefore, the use of these recommended application rates in the Canadian climate, where temperatures tend to be cooler and fluctuate greatly, are not likely to provide accurate fertilization recommendations (Birrenkott et al., 2005). Consequently, it is essential to conduct region-specific trials to generate fertilizer application rates for the nursery practices and climate conditions common to that region. Furthermore, nutritional needs of ornamental plants vary greatly between species/cultivars and given that there are over 500 different species/cultivars currently grown in container production, the optimal nutritional rate has not been defined for most containerized plants (Chen et al., 2001).

Accordingly, this study was undertaken to address the lack of knowledge regarding CRF application rates for container-produced ornamental plants in Ontario nurseries. As reported by growers during our field visits, most nurseries in Ontario use the same application rates for all of their plants regardless of genius, species, or cultivar. However, research has indicated that fertilizer rates should take into consideration a number of factors including: plant species and cultivar, growing substrate, and the type of fertilizer to achieve the highest nutrient use efficiency (Alam et al., 2009; Chen et al., 2011; Narváez et al., 2012). Therefore, the objective of this study was to determine an optimal CRF range for six species of woody ornamental plants grown in 1-gal (2.29 L) pots using nursery production practices common to southwestern Ontario, Canada.

## Materials and Methods

### 2012

*Plant material and treatments.* Six species of plug-rooted liners (*Salix purpurea* 'Nana', *Weigela florida* 'Alexandra', *Cornus sericea* 'Cardinal', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet') were potted on 3 July 2012 at a southwestern Ontario, wholesale nursery (lat. 42°99′07″ N, long. 81°04′03″ W). The plants were potted in black, 1-gallon, blow-molded (2.29 L with a 16.5 cm diameter × 17.78 cm height) nursery pots filled with a growing substrate consisting of 60% composted pine bark (15/16 inches), 10% yard and leaf feedstock compost (½ inch), and 30% sphagnum peatmoss [Grow-Bark (Ontario) Ltd., Milton, Ontario, Canada]. At the time of planting, the substrate had an EC of 0.76 mS·cm$^{-1}$, pH

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of 5.50, and a plant-available nutrient content of 3.30 mg·kg$^{-1}$ nitrate nitrogen ($NO_3^-$-N), less than 0.50 mg·kg$^{-1}$ ammonia nitrogen ($NH_3$-N), 7.77 mg·kg$^{-1}$ P, and 168.68 mg·kg$^{-1}$ K (analyzed using a saturated paste extraction method by SGS Agri-Food Laboratories, Guelph, Ontario, Canada). Polyon® 16N–2.6P–10K + Minors 5145101, 5–6 month duration CRF consisting of 7.6% $NH_3$-N and 8.4% $NO_3^-$-N (Agrium Advanced Technologies Inc., Brampton, Ontario, Canada) was incorporated into the growing substrate before potting at the following rates: 0.8, 1.2, 1.7, 2.1, and 2.5 kg·m$^{-3}$ N. Fertilizer rates were selected based on recommendations made by Agrium Advanced Technologies Inc. and previous studies (Alam et al., 2009). Irrigation water from an on-site catchment pond was applied to the plants as needed (at the discretion of the grower), and pots were weeded monthly following standard production practices for the nursery. Daily average air temperatures ranged between 20 and 27.3 °C for the first 35 d of the study with daily maximum temperatures reaching as high as 36.1 °C (Fig. 1). Temperatures gradually began to decline for the remaining 59 d of the 2012 growing season with the daily average temperature reaching a low of 8 °C before study completion. Daily maximum air temperatures remained above 20 °C until the 75th day of the study.

*Experimental design.* The experiment was a six (species) × five (CRF rate) factorial in a completely randomized design with 20 replications per treatment. Pots were re-randomized monthly to reduce location error. All pots were placed outside on a black weed barrier fabric surface. The production area was bordered with at least one row of unmeasured pots to reduce perimeter effects.

*Sampling and analysis.* Throughout the 2012–13 growing season, measurements were made every ≈4 weeks between July and Nov. 2012 and Apr. and May 2013 on four replicate plants per treatment for each of the six species. Plant growth was evaluated by measuring plant height, canopy length, and width. Plant height was measured from 2.5 cm below the pot rim to the top of the highest shoot to maintain consistency throughout the growing season. Canopy length and width were determined by measuring the longest span of the plant (the length) and then measuring the growth perpendicular to the longest span (the width). The growth index for each plant was then calculated as per Ruter (1992a) [height (cm) × length (cm) × width (cm)/300]. Substrate pH and EC were determined by the pour-through method as described by Wright and Lundholm (1986). Leachate collected from the pour-through was then analyzed for pH and EC using a portable pH and EC meter (Oakton PC 300; Oakton Instruments, Vernon Hills, IL).

On 28 Aug. 2012, *Salix*, *Weigela*, *Cornus*, and *Hydrangea* were pruned in accordance with standard nursery practices. *Hibiscus and Spiraea* did not require pruning. Pruned samples were dried at 75 °C until a constant weight was achieved and weighed. An average weight of the amount of material pruned for each species was then determined. Total N in the shoot (leaves and stem) was determined using the Association of Analytical Chemists (AOAC) method 990.03 and total P and K were determined using AOAC method 985.01 by SGS Agri-Food Laboratories, Guelph, Ontario, Canada.

On 5 Oct. 2012, overall appearance was determined by rating four replicate plants from each treatment and each species on a scale from 1 (non-commercial and lowest quality) to 5 (excellent quality and most visually appealing) (Parsons et al., 2009). If the plant was

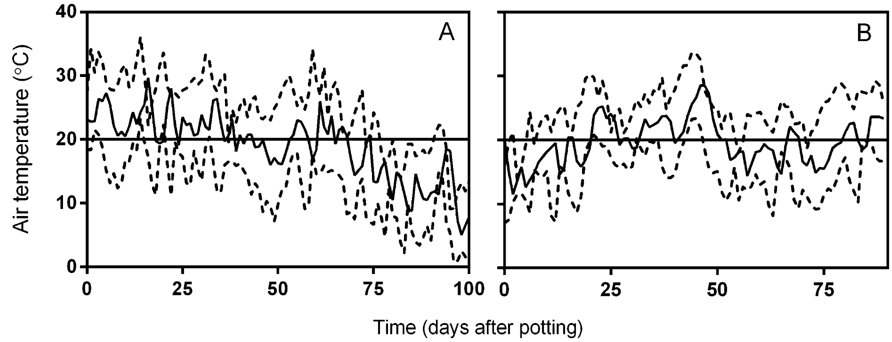


Fig. 1. Daily average (solid line), minimum (lower dotted line), and maximum (upper dotted line) outdoor air temperatures from 3 July 2012 to 5 Oct. 2012 (**A**) and 3 Jun. 2013, to 28 Aug. 2013 (**B**) at the London Central Weather Station (lat. 43°02′00″ N, long. 81°09′00″ W) (adapted from Environment Canada, 2013). Black horizontal line indicates temperature at which the product longevity of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer was determined by Agrium Advanced Technologies Inc.

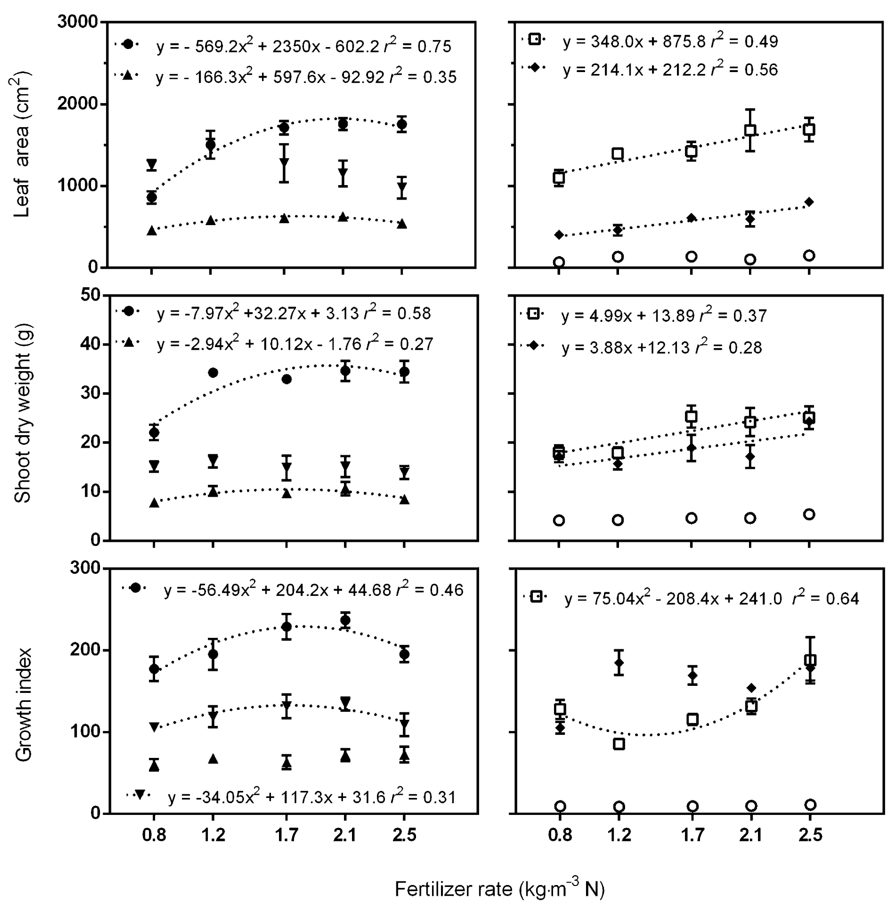


Fig. 2. Leaf area, shoot dry weight, and growth index as measured in Oct. 2012 of *Cornus sericea* 'Cardinal' (●), *Spiraea japonica* 'Magic Carpet' (▼), *Hydrangea paniculata* 'Bombshell' (▲), *Hibiscus syriacus* 'Ardens' (○), *Salix purpurea* 'Nana' (♦), and *Weigela florida* 'Alexandra' (□) after growth with five rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer (CRF). Data are the means of four replicates ± SE. If line is not shown, the relationship is not significant ($P > 0.05$).

dead, it was given a rating of 0. Ratings were based on attributes as identified by Boumaza et al. (2010) to play a role in consumer preference of ornamental plants and included: foliage thickness, plant symmetry, leaf size, leaf color (discoloration of leaf), number of stems, and branching level. The individual ratings for these criteria were then averaged to give an overall appearance rating. Plants were then evaluated by the grower to determine the lowest acceptable CRF rate that produced marketable plants.

After the appearance rating, four replicate plants from each treatment and species were harvested. Total leaf area was determined using a leaf area meter (LI-3100; LI-COR Inc., Lincoln, NE). Shoot dry weight was determined by cutting plants at the substrate surface and drying all above-ground tissues at 75 °C until a constant weight was achieved. The dried shoots were then ground in a laboratory mill to pass through a 2-mm screen (Model 4; Thomas Wiley Laboratory Mill, Swedesboro, NJ). Total N, P, and K were analyzed as per the method described for the pruned samples. The rootball (growing substrate, roots, and unreleased CRF) of each of the four replicate plants was saved to be used for the analysis of N and P losses.

The remaining 16 plants from each treatment and species were overwintered in a hoophouse covered with 0.07-mm (3-mil) white polyethylene plastic sheeting, which is typically used in nurseries across Ontario.

*Winter injury assessment.* The white polyethylene plastic sheeting was removed from the hoophouse on 23 Apr. 2013 and the plants were rated for winter injury and quality 6 weeks after the plastic was removed (29 May 2013) as per Perry (1990). Winter survival and regrowth were evaluated for the remaining 16 plants in each treatment. Each plant was rated on a scale from 0 to 5 adapted from Chong et al. (1979) with 0 being complete death of tops and roots; 1 having severe top kill and root damage at the base and vertical edge of the container; 2 having moderate to severe top kill, little or no growth of uninjured foliage, and damage of all roots facing the outer vertical edge of the container; 3 having moderate top kill, good growth of uninjured foliage, damage of some roots facing the outer vertical edge of the container; 4 having little top kill, healthy new growth, no root damage; and 5 having an excellent appearance, healthy tops and roots, and a large crown diameter.

*Nutrient loss calculations.* Before planting, triplicate samples of plug-rooted liners for each species were analyzed for total N using AOAC method 990.03 and total P and K using AOAC method 985.01 by SGS Agri-Food Laboratories. The rootballs of the harvested replicates (described previously) were oven-dried at 75 °C until a constant weight was achieved. Rootballs were then ground in a laboratory mill to pass through a 2-mm screen (Thomas Wiley Laboratory Mill), subsampled (370 $cm^3$), and analyzed for total N, P, and K as described for the plug-rooted liners. Results collected from the various dried samples were then used to calculate the amount of N and P lost to the environment using an equation based on Stewart et al. (1981):

$$X_F - \Delta X_M - \Delta X_P = X_L$$

where $X_F$ = N or P applied as fertilizer; $\Delta X_M$ = change in growing substrate N or P; $\Delta X_P$ = change in plant N or P; and $X_L$ = loss of N or P. Percent loss of the amount of N and P applied was determined across all species.

### 2013

*Plant material and treatments.* The same six species were used in 2013 as 2012. Plug-rooted liners were potted on 3 June 2013 at the same nursery using the same pots and growing substrate as described in the 2012 methods. At the time of planting, the substrate EC was 0.60 $mS \cdot cm^{-1}$, had a pH of 5.50, and a plant-available nutrient composition of 2.00 $mg \cdot kg^{-1}$ $NO_3^-$-N, less than 0.50 $mg \cdot kg^{-1}$ $NH_3$-N, 9.02 $mg \cdot kg^{-1}$ P, and 122.28 $mg \cdot kg^{-1}$ K (analyzed by SGS Agri-Food Laboratories, Guelph, Ontario, Canada). The same CRF formulation as 2012 was incorporated into the growing substrate at the time of potting at the following rates: 0.05, 0.35, 0.65, 0.95, and 1.25 $kg \cdot m^{-3}$ N. Fertilizer rates were selected based on the results of the 2012 study and recommendations made by Agrium Advanced Technologies Inc. Irrigation and weeding practices were as described for 2012. Daily mean air temperatures were below 20 °C for the first 15 d of the study (Fig. 1). Mean daily temperatures remained over 20 °C for the next 35 d and on the 50th day of the study began to sharply decline until the last 10 d of the study, when the daily mean temperatures were again over 20 °C.

*Experimental design.* As described for the 2012 trial, however, the 2013 experiment used eight replications per treatment.

*Sampling and analysis.* Throughout the 2013 growing season, measurements were made every ≈4 weeks between June and Aug. 2013 on four replicate plants per treatment for each of the six species. Plant height, canopy length and width as well as substrate pH and EC were determined using the same methodology as described for the 2012 growing season.

On 28 Aug. 2013 overall appearance was determined for each species by rating four

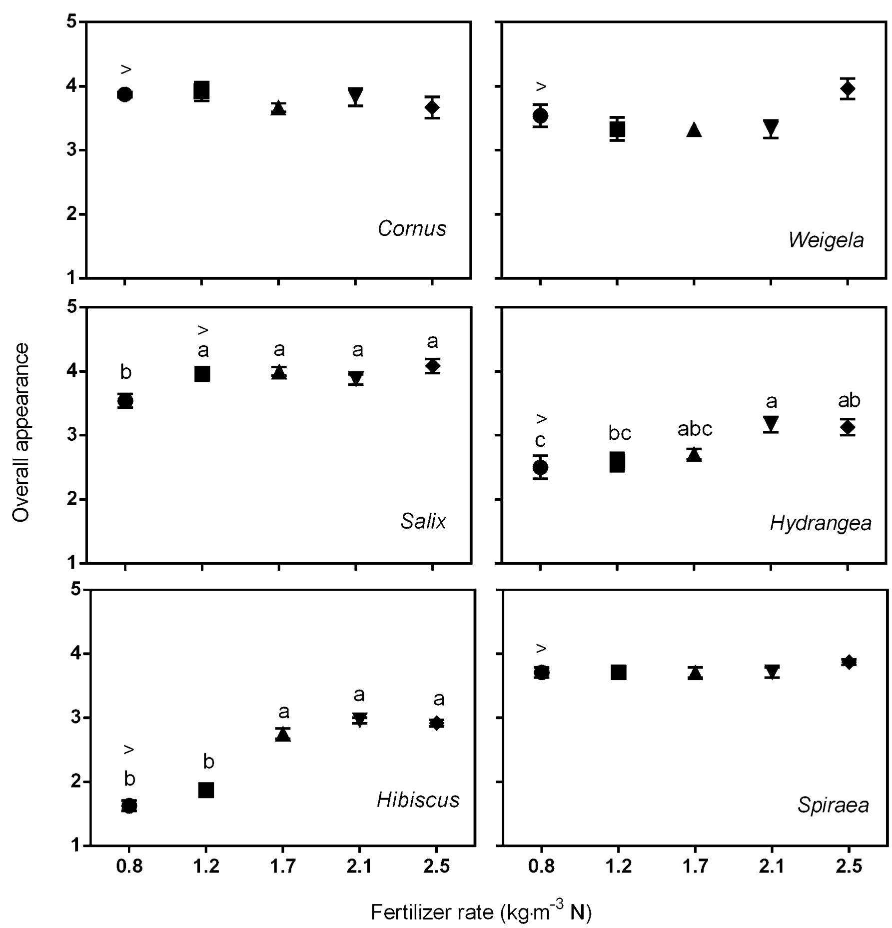


Fig. 3. Overall appearance as measured on 5 Oct. 2012 for *Cornus sericea* 'Cardinal', *Weigela florida* 'Alexandra', *Salix purpurea* 'Nana', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' grown with five rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer. Data are means ± SE (n = 4). Symbols baring the same letter are not significantly different for each species at $P < 0.05$ according to Tukey's multiple comparison test. According to the grower's opinion, the ">" indicates the lowest acceptable fertilizer rate for that species.

replicate plants from each treatment and species as described for the 2012 trial. The grower once again evaluated all plants to determine the lowest acceptable CRF rate that produced marketable plants for each species. The plants were then harvested and roots, stems, and leaves were separated. Total leaf area and leaf N, P, and K were determined as described previously; however, only samples from the 0.35, 0.65, 0.95, and 1.25-kg·m$^{-3}$ N treatments were analyzed, because visual manifestations of nutrient deficiencies were present on all plants grown in 0.05 kg·m$^{-3}$ N. Stem dry weight was determined by cutting plants at the substrate surface and drying the stems at 75 °C until a constant weight was achieved. The dry weight of the leaves and the stems was then added together to determine the shoot dry weight. Roots were removed from growing substrate, washed, and dried at 75 °C until a constant weight was achieved. Root-to-shoot ratio was determined.

*Statistical analysis.* Data for leaf nutrient content, winter injury assessment, and overall appearance were subjected to a one-way analysis of variance (ANOVA). The Tukey-Kramer adjustment was applied to perform a multiple means comparison of all pairwise combinations of the means. Regression analysis was used to relate CRF application rate to leaf area, shoot dry weight, root-to-shoot ratio, growth index, and nutrients lost to estimate regression parameters for the best-fit regression model (linear or quadratic). Analysis of the residuals suggested that assumptions of the regression analysis and ANOVA were met with no need for transformation.

As a result of the high number of related response variables, the likelihood of detecting a false treatment effect (committing a Type 1 error) was inflated. Therefore, the multivariate approach of a principal component analysis (PCA) was used to examine plant growth response (i.e., leaf area, shoot dry weight, growth index, root-to-shoot ratio, and overall appearance) to CRF rate. A PCA is used to reduce the number of non-independent variables into smaller sets of unrelated components, where each component is uncorrelated with any other (Iezzoni and Pritts, 1991). Variables that load heavily onto a component, either positively (loading +0.5 or greater) or negatively (loading –0.5 or less), can be interpreted as increasing or decreasing, respectively, as the component increases. A resulting new ‘‘component’’ value is produced that can replace several original correlated variables in univariate statistical procedures (Iezzoni and Pritts, 1991). Consequently, a new ‘‘plant growth’’ variable was produced from the outcome of the PCA and was subjected to multiple regression analysis to determine the relationship between ‘‘plant growth’’ and CRF rate.

All data sets were analyzed using GraphPad Prism Version 6.0 software (GraphPad Software Inc., La Jolla, CA) except the PCA, which was conducted using JMP, Version 11.1.1 (SAS, Cary, NC). All data were evaluated using a significance level of $\alpha = 0.05$.

## Results

### 2012

*Growth response.* Each species in the study exhibited unique growth responses to increasing CRF rates, as illustrated by the regression analysis of leaf area, shoot dry weight, and growth index (Fig. 2). *Cornus* leaf area and shoot dry weight demonstrated quadratic saturation responses (i.e., asymptotic) to increasing CRF additions, reaching maximum mean values of 1759 cm$^2$ and 35 g, respectively, at a fertilizer rate of 2.1 kg·m$^{-3}$. *Hydrangea* exhibited a quadratic saturation response for leaf area and shoot dry weight, reaching maximum mean values of 627 cm$^2$ and 11 g, respectively, at 2.1 kg·m$^3$ N. The regression analysis of leaf area and shoot dry weight for *Weigela* and *Salix* was best defined by linear relationships between the growth parameters (y) and the CRF treatments (x). No fertilizer treatment effect was detected for the leaf area and shoot dry weight of *Hibiscus* and *Spiraea*. Conversely, final growth index, as measured on 5 Oct. 2012, did not exhibit a significant linear or quadratic relationship for *Salix*, *Hibiscus*, and *Hydrangea*, indicating no differences in growth index with increasing fertilizer rate (Fig. 2). *Cornus*, *Spiraea*, and *Weigela*, however, demonstrated significant quadratic responses in growth index to increasing fertilizer rate. Growth index for *Weigela* continued to increase with increasing CRF application rate, whereas *Cornus* and *Spiraea* demonstrated saturation responses to increasing CRF additions, exhibiting an increase in growth index when the fertilization rate was raised from 0.80 to 2.1 kg·m$^{-3}$ N but decreasing in growth thereafter (Fig. 2).

Overall appearance, as evaluated on 5 Oct. 2012, was different among treatments and species (Fig. 3). Increases in CRF application rates did not result in an increase in appearance (as quantified by attribute ratings) for *Cornus*, *Weigela*, and *Spiraea*. *Salix* exhibited a significant increase in appearance when the CRF rate was increased from 0.8 to 1.2 kg·m$^{-3}$ N but beyond this, no further increases in appearance were observed (Fig. 3). *Hydrangea* and *Hibiscus* both reached a maximum appearance rating when fertilized with 1.7 kg·m$^{-3}$ N.

As selected by the grower, the lowest CRF rates that produced marketable size plants on 5 Oct. 2012 were: 0.8 kg·m$^{-3}$ N for *Spiraea*, *Cornus*, *Weigela*, *and Hibiscus* and 1.2 kg·m$^{-3}$ N for *Salix*. Although *Hydrangea* did not

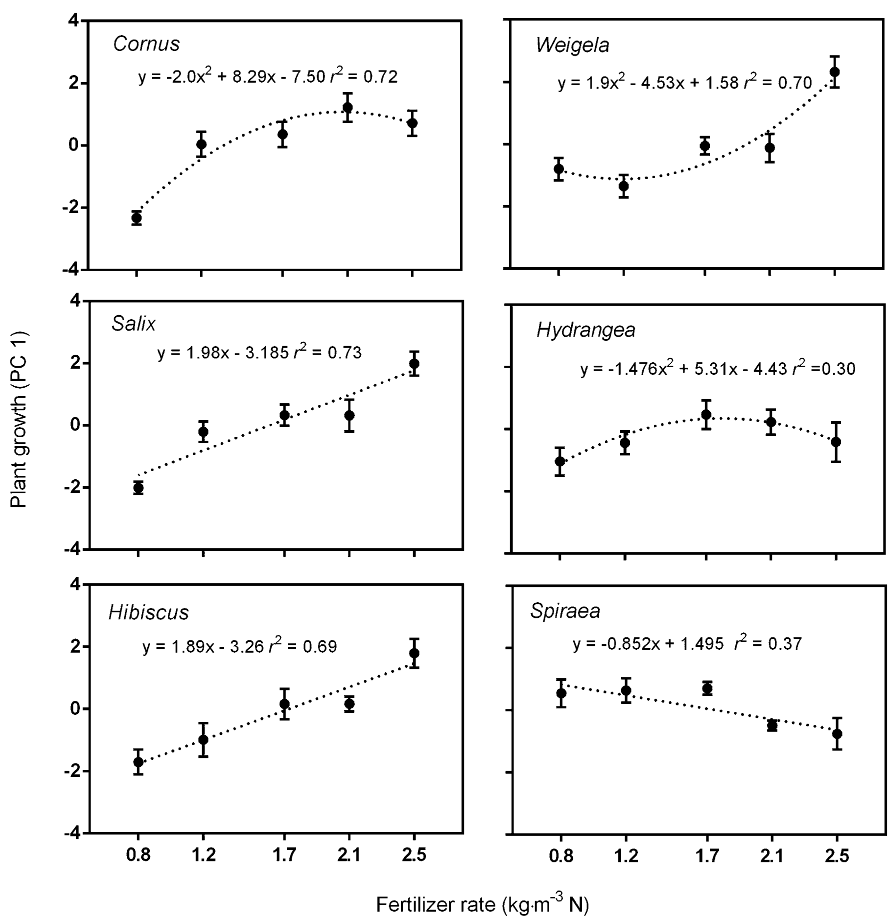


Fig. 4. Response of ‘‘plant growth’’ (PC 1) to application rate of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer for *Cornus sericea* ‘Cardinal’, *Weigela florida* ‘Alexandra’, *Salix purpurea* ‘Nana’, *Hydrangea paniculata* ‘Bombshell’, *Hibiscus syriacus* ‘Ardens’, and *Spiraea japonica* ‘Magic Carpet’ grown in 2012. Data are the means of four replicates ± SE. If a line is not shown, the relationship is not significant ($P > 0.05$).

reach a marketable size when grown in 0.8 kg·m$^{-3}$ N, the grower selected this rate as the lowest acceptable rate because this plant is generally a 2-year crop and can be produced with a lower rate of fertilizer, requiring topdressing the following year.

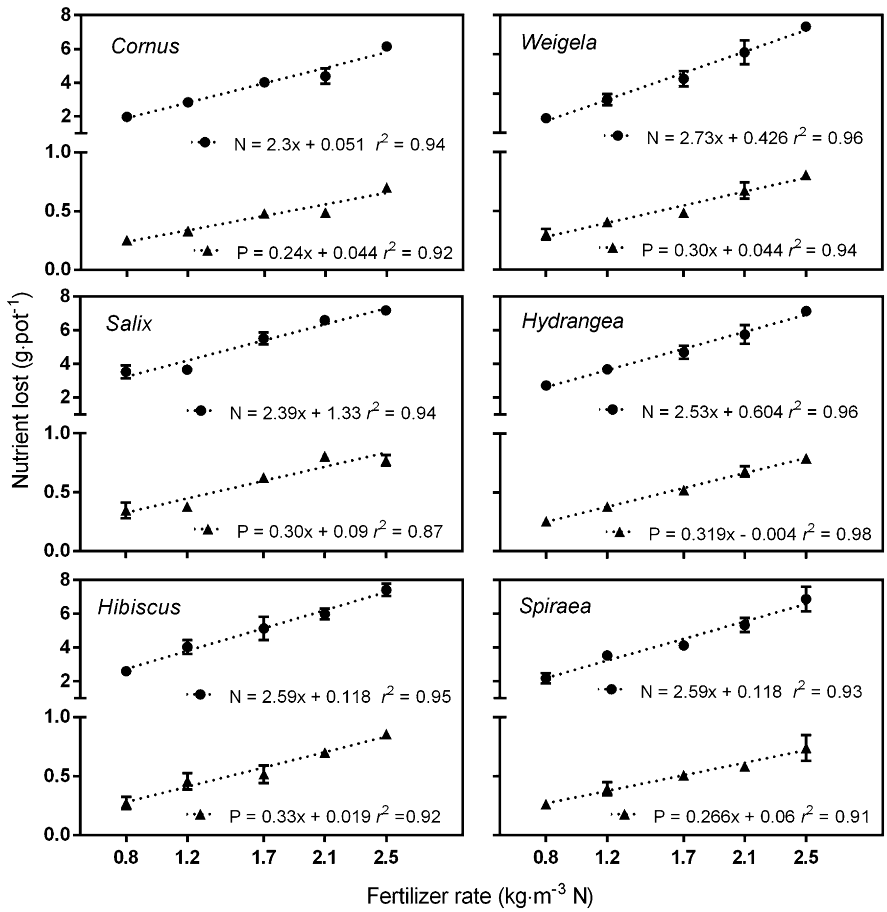


Fig. 5. The calculated amount of nitrogen (N) (●) and phosphorus (P) (▲) lost to the environment (g/pot) from *Cornus sericea* 'Cardinal', *Weigela florida* 'Alexandra', *Salix purpurea* 'Nana', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' grown with five rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer in 2012. Data are means ± SE (n = 3).

Results of the PCA indicate that there is a strong correlation of variables among the univariate analyses. Given that the majority of variables for all species loaded heavily and positively (+0.05 or greater) onto the first principal component (PC1), no further components were retained for analysis. A new "plant growth" variable was subsequently derived from PC1. The regression analysis of "plant growth" demonstrated very similar results to what has been previously illustrated from the univariate analyses (Fig. 4). *Weigela*, *Cornus*, and *Hydrangea* demonstrated a quadratic response in plant growth to CRF rate reaching maximum growth at 2.5, 2.1, and 1.7 kg·m$^{-3}$ N, respectively. Linear regression responses were exhibited for *Salix* and *Hibiscus*, reaching maximum plant growth values at 2.5 kg·m$^{-3}$ N. *Spiraea* plant growth was best defined by a negative linear relationship, where growth decreased with increased CRF rate beyond 0.8 kg·m$^{-3}$ N.

*Winter injury assessment.* As evaluated on 29 May 2013 (37 d after the white polyethylene film was removed from the hoophouse), plants grown in all CRF treatment rates survived equally well for each species and differences among means were not significant at $P < 0.05$ according to Tukey's multiple comparison test. There was 0% mortality in all CRF treatments across all species.

*Environmental nutrient loss.* Calculation of environmental loss of N and P was determined at the completion of the 2012 growing season for each species and fertilizer rate. The pattern of nutrient loss was similar across all species with an increase in the application rate of CRF resulting in an increase in the amount of N and P lost to the environment (Fig. 5). Losses of P were never greater than 1.0 g/pot and were notably less than the losses of N. At the highest CRF treatment rate (2.5 kg·m$^{-3}$ N), *Weigela* lost the greatest amount of N at 7.4 g/pot, whereas *Cornus* lost the least amount at 6.2 g/pot· Similarly, *Hibiscus* lost the greatest amount of P at 0.9 g/pot closely followed by *Weigela*, which lost 0.81 g/pot. *Cornus* lost the least amount of P at 0.3 g/pot.

According to growers within Ontario, the average number of pots per hectare is ≈30,000 (using an average pot spacing of 60 cm and including space for walkways and roads). Across all species, an average minimum N loss of 2.63 g/pot occurred for plants fertilized with 0.80 kg·m$^{-3}$ N and an average maximum N loss of 7.03 g/pot occurred for plants fertilized with 2.5 kg·m$^{-3}$ N. Therefore, given that there are ≈30,000 pots per hectare, the range of N loss within this study is between 79 and 211 kg·ha$^{-1}$ per year. Similarly, the average minimum P loss for plants fertilized with 0.80 kg·m$^{-3}$ N was 0.24 g/pot and the average maximum P loss for plants fertilized with 2.5 kg·m$^{-3}$ N was 0.78 g/pot; thus, the range of P loss is 7.2 to 23.4 kg·ha$^{-1}$ per year. Overall, the percentage of applied N and P that was lost to the environment increased from an average of 32.3% and 32.8%, respectively, in plants fertilized with 0.8 kg·m$^{-3}$ N to an average of 52.0% and 41.3% for those plants fertilized with 2.5 kg·m$^{-3}$ N.

*Growing substrate EC and pH.* For all species, growing substrate EC of all CRF treatments was greater than 2.0 mS·cm$^{-1}$ 20 d after potting with *Cornus*, *Weigela*, *Salix*, and *Spiraea* grown in 2.1 and 2.5 kg·m$^{-3}$ N demonstrating substrate EC values greater than 3.0 mS·cm$^{-1}$. At 43 d after potting, there was a sharp decline in growing substrate EC for all treatments and species. However, from Day 43 until the end of the study, EC gradually declined to less than 0.5 mS·cm$^{-1}$ for all fertilizer rates and species. Notably, growing substrate EC was significantly reduced during the period between 30 Apr. 2013 (the first measurement after winter) and 29 May 2013 (6 weeks after the polyethylene cover was removed from the hoophouses). The lowest CRF rate of 0.8 kg·m$^{-3}$ N consistently produced the lowest EC values across all species throughout the study.

Despite minor fluctuations, growing substrate pH measurements remained relatively consistent throughout the course of the study and ranged between 6.5 and 7.3 for all species and treatments. Generally, higher pH levels were seen in plants receiving lower CRF application rates. Plants treated with CRF rates at 0.8 kg·m$^{-3}$ N consistently exhibited the highest pH measurements across all species. Plants fertilized with 2.1 and 2.5 kg·m$^{-3}$ N consistently produced more acidic substrate pH values (less than 6.5).

## 2013

*Growth response.* At the end of Aug. 2013, leaf area and shoot dry weight were greater at higher vs. lower CRF treatments for the majority of species (Fig. 6). Linear regression responses were demonstrated between leaf area/shoot dry weight and CRF application rate for the majority of species. However, typical saturation (asymptotic) responses were demonstrated by *Weigela* for leaf area and shoot dry weight with maximums of 2727 cm$^2$ and 31.7 g, respectively, achieved when grown with 0.95 kg·m$^{-3}$ N, by *Spiraea* for shoot dry weight with a maximum of 11.9 g achieved when grown with 0.95 kg·m$^{-3}$ N, and *Salix* reaching a maximum

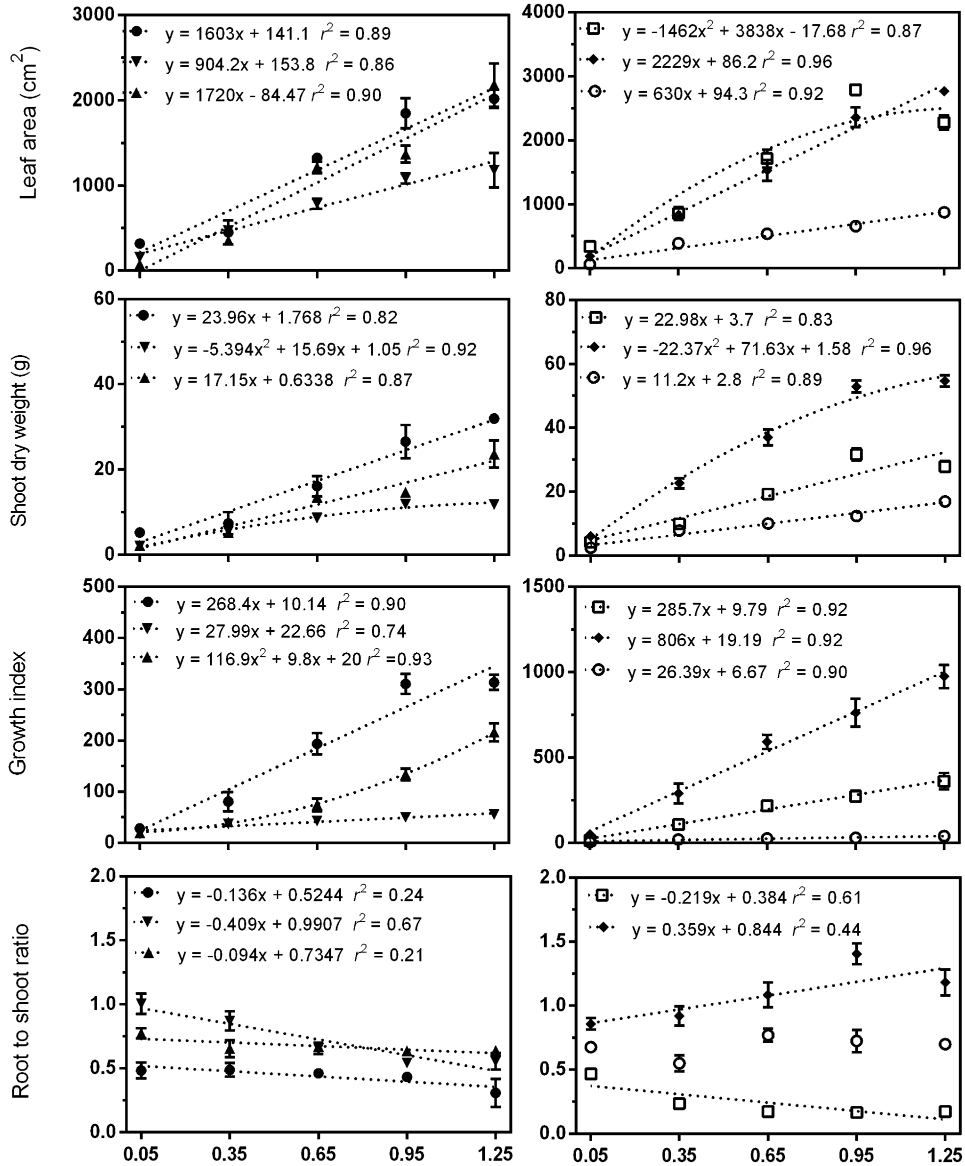


Fig. 6. Leaf area, shoot dry weight, growth index, and root-to-shoot ratio, as measured in Aug. 2013 of *Cornus sericea* 'Cardinal' (●), *Spiraea japonica* 'Magic Carpet' (▼), *Hydrangea paniculata* 'Grandiflora' (▲), *Hibiscus syriacus* 'Ardens' (○), *Salix purpurea* 'Nana' (♦), and *Weigela florida* 'Alexandra' (□) after grown with five rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer. Data are means ± SE (n = 4). If a line is not shown, the relationship is not significant ($P > 0.05$).

shoot dry weight of 54.6 g when grown with 0.95 kg·m$^{-3}$ N (Fig. 6).

Over time, the majority of species exhibited a typical linear increase in growth index, achieving the highest mean growth index value at the final harvest (28 Aug. 2013). Examination of the growth index at this time point revealed significant regression relationships between growth index and CRF rate; the greatest growth index was at the highest CRF application rate for all species (Fig. 6).

Root-to-shoot ratio decreased with increasing CRF rate for the majority of species as illustrated by the significant negative linear regression exhibited by *Cornus*, *Hydrangea*, *Spiraea*, and *Weigela* (Fig. 6). Contrary to the trend, *Salix* root-to-shoot ratio increased with increasing CRF. The relationship of root-to-shoot ratio and CRF rate was not significant for *Hibiscus* (Fig. 6).

Most plants were deemed to be of a marketable size by the grower on 28 Aug. 2013 when grown with 0.65 kg·m$^{-3}$ N and consequently, this was the lowest acceptable rate for *Cornus*, *Weigela*, *Salix*, and *Spiraea* (Fig. 7). The grower indicated that fertilization at 0.35 kg·m$^{-3}$ N was sufficient for *Hibiscus* because this species is always a 2-year crop and can be topdressed the next growing season. Similarly, the lowest acceptable CRF rate for *Hydrangea* that produced a marketable plant was 0.95 kg·m$^{-3}$ N, but this plant would require topdressing the next year.

The PCA indicated that the majority of variables loaded heavily, either positively (+0.05 or greater) or negatively (–0.05 or less), onto PC 1; therefore, no further components were retained for analysis. Interestingly, although most of the variables loaded positively for each species, root-to-shoot ratio loaded negatively for *Weigela*, *Hydrangea*, and *Spiraea*; positively for *Salix;* and was not a significant contributor to PC 1 for *Hibiscus* and *Cornus*.

Results of the regression analysis of "plant growth" (PC 1) vs. CRF rate (Fig. 8) are similar to what has been demonstrated by the previous univariate analyses. *Hydrangea*, *Hibiscus*, and *Spiraea* exhibited a linear increase in "plant growth" with increasing CRF rate, reaching maximum plant growth values at 1.25 kg·m$^{-3}$ N, whereas *Cornus*, *Salix*, and *Weigela* exhibited a quadratic response to CRF rate, reaching maximum plant growth values at 0.95 kg·m$^{-3}$ N.

*Leaf nutrient content.* Chlorosis was visible on both the upper and lower leaves of *Hibiscus* grown in the CRF rates of 0.05, 0.35, and 0.65 kg·m$^{-3}$ N, but for the remaining species and treatments, no changes in leaf

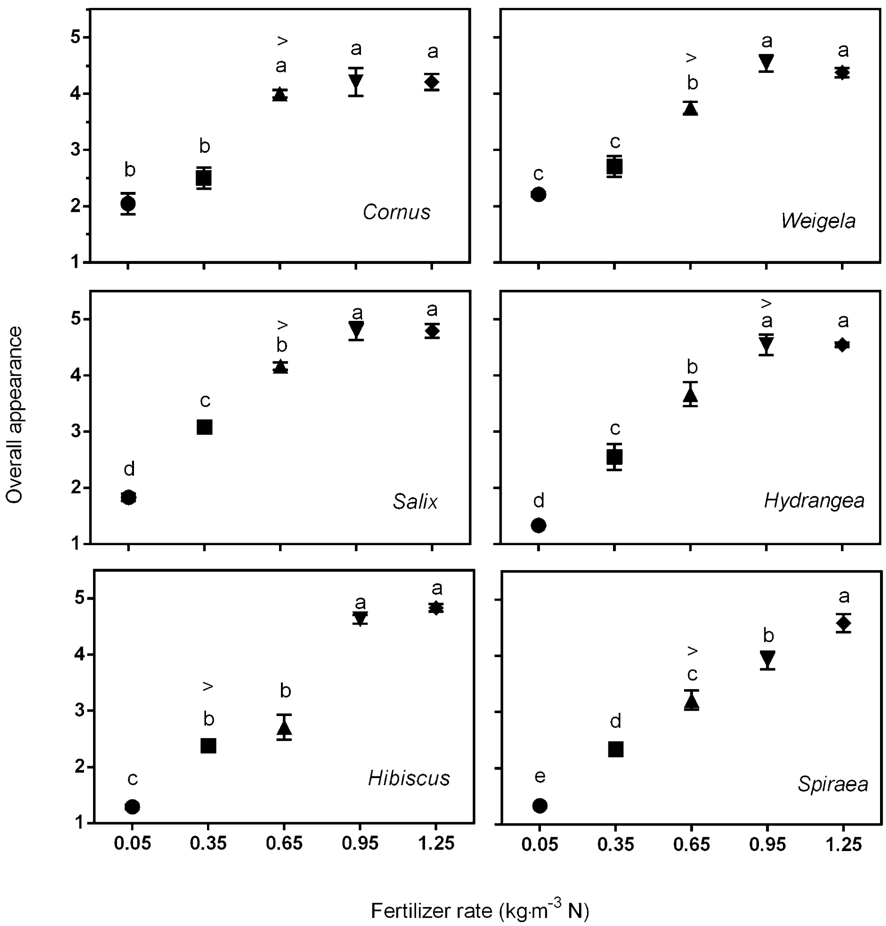


Fig. 7. Overall appearance as measured on 28 Aug. 2013 for *Cornus sericea* 'Cardinal', *Weigela florida* 'Alexandra', *Salix purpurea* 'Nana', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' grown with five rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer. Data are means ± SE (n = 4). Symbols baring the same letter are not significantly different for each species at $P < 0.05$ according to Tukey's multiple comparison test. According to the grower's opinion, the ">" indicates the lowest acceptable fertilizer rate for that species.

color (as an indication of nutrient deficiencies or toxicities) were apparent. All species grown in 0.05 kg·m$^{-3}$ N and *Cornus* grown in 0.35 kg·m$^{-3}$ N were visibly smaller and had severely stunted growth. N content in leaves was only significantly different between CRF rates for *Salix*, *Hibiscus*, and *Spiraea* (Fig. 9). Leaf content of P and K increased at higher CRF rates for some but not all species (Fig. 9).

*Growing substrate EC and pH.* For all species except *Salix*, growing substrate EC was less than 2.0 mS·cm$^{-1}$ 24 d after planting and for the remainder of the study. *Salix* plants fertilized with 0.95 and 1.25 kg·m$^{-3}$ N had a growing substrate EC greater than 2.0 mS·cm$^{-1}$ 24 d after planting and remained 2.0 mS·cm$^{-1}$ or greater for the rest of the study. For all other species and CRF rates, growing substrate EC was significantly reduced over the course of the study (i.e., between 27 June and 28 Aug. 2013) with the lowest EC values for all species observed on the final day of study (28 Aug. 2012; 0.05 mS·cm$^{-1}$ or less).

Growing substrate pH for all species and CRF rates ranged from 6.3 to 7.3. For all rates and species, growing substrate pH increased over time. In general, higher CRF rates produced lower pH values.

## Discussion

A relationship exists between the growth of a plant and its supply of mineral nutrients (i.e., N, P, and K). Because N is required more than any other fertilizer element, it has the greatest impact on plant growth and development (Marschner, 2002). Consequently, increasing the rate of N application will enhance plant biomass production, but only to a point (Cabrera, 2003). Beyond that, plant growth will remain constant and biomass production may even decrease despite continued increases in N application (Marschner, 2002). In this experiment, three typical growth responses were observed among the species in response to the varying CRF application rates: 1) growth increased with increasing fertilizer supply; 2) growth reached a maximum and remained unaffected by further fertilizer additions; and 3) growth decreased with increasing fertilizer supply. Accordingly, the 2012 trial best illustrated these growth responses because the plants became non-responsive to increases in fertilizer application rates, and in some cases, plant biomass decreased with increasing fertilizer rate. Leaf area and shoot dry weight for both *Spiraea* and *Hibiscus* were not significantly correlated to CRF rate, indicating that growth had become non-responsive to additional increases in CRF (Fig. 2). Although leaf area and shoot dry weight of *Weigela* increased linearly with increases in CRF application rates (Fig. 2), overall appearance (Fig. 3) demonstrated that *Weigela* achieved a marketable size when grown in 0.8 kg·m$^{-3}$ N. Conversely, maximum leaf area and shoot dry weight were observed in *Cornus* and *Hydrangea* grown in 2.1 kg·m$^{-3}$ N, after which further increases in CRF application rates resulted in a reduction in shoot biomass and leaf area (Fig. 2). Similar results were noted by Cabrera (2003) and Parks et al. (2007), demonstrating that overapplication of fertilizer does not always translate to an increase in biomass.

In 2013, all species demonstrated positive correlations of leaf area, shoot dry weight, and growth index to an increase in CRF rate (Fig. 6). This is consistent with findings from other reports establishing significant linear relationships between growth parameters in woody ornamentals as N rates are increased from deficient to adequate levels (Hicklenton and Cairns, 1992; Ruter, 1992b; Worall et al., 1987). The reduction in root-to-shoot ratio (Fig. 6) observed in the majority of species with increasing fertilizer supply is also in agreement with previous research examining a variety of plant species and woody ornamentals (Cabrera, 2003; Yeager and Wright, 1981). This allocation of resources to the shoot is consistent with the resources optimization hypothesis as proposed by Ågren and Franklin (2003), which states: when nutrient availability increases, less effort is required to attain nutrient resources and plants will allocate fewer nutrients to their roots, resulting in a decrease in root growth. Unlike the other species, *Salix* root-to-shoot ratio increased with increasing CRF rate. This contradictory increase in root-to-shoot ratio can be attributed to a number of physiological characteristics exhibited by genus. Compared with other woody plants, *Salix* has superior growth and productivity and has the highest capacity to convert solar radiation into chemical energy (Wilkinson, 1999). Furthermore, *Salix* tends to develop an extensive fibrous root system that continually grows from May through to October (Rytter and Hansson, 1996). Accordingly, it can be concluded that the root mass of *Salix* continued to accumulate biomass over the growing season, which resulted in an increase in root-to-shoot ratio with the increasing CRF rate observed in this study (Fig. 6).

Results of the PCA in both 2012 and 2013 indicate a high degree of redundancy among the individual univariate analyses. Therefore, the "plant growth" variable derived from PC1 is the most accurate representation of overall plant response to CRF rate for both years. Consequently, it was used to determine

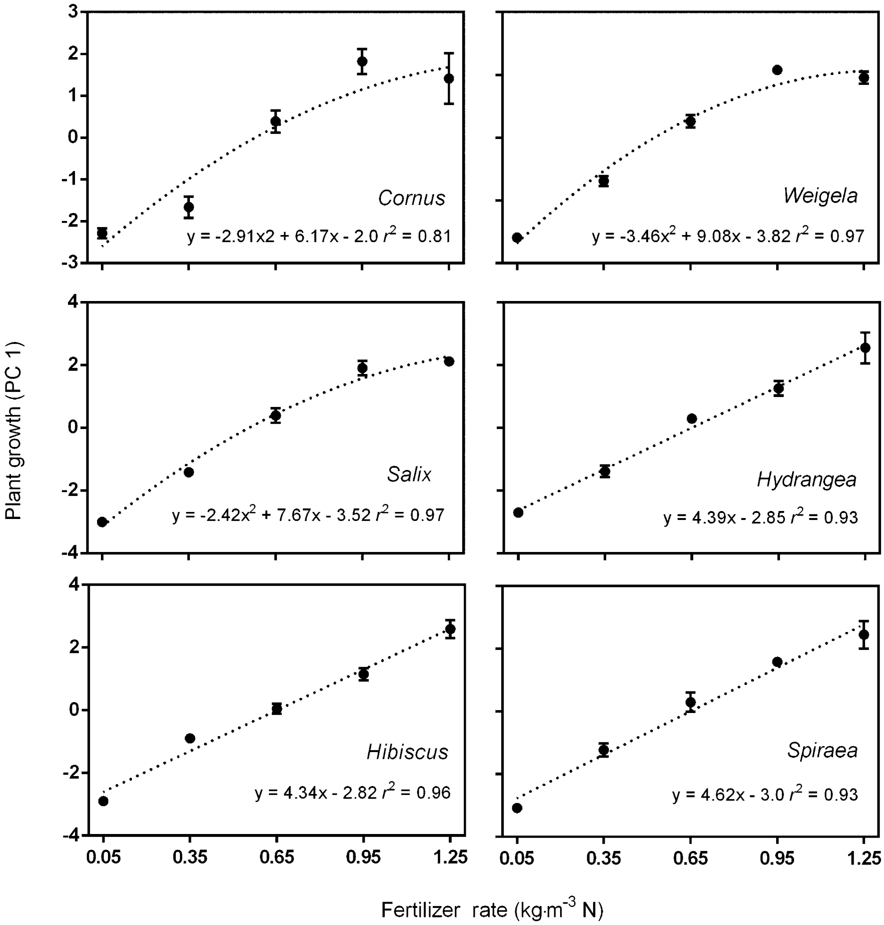


Fig. 8. Response of "plant growth" (PC 1) to application rate of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer for *Cornus sericea* 'Cardinal', *Weigela florida* 'Alexandra', *Salix purpurea* 'Nana', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' grown in 2013. Data are the means of four replicates ± SE. If a line is not shown, the relationship is not significant ($P > 0.05$).

which CRF rates resulted in maximum growth for each of the species examined. The CRF rates that resulted in the maximum "plant growth" for each species were: 1.25 kg·m$^{-3}$ N for *Spiraea*, 1.7 kg·m$^{-3}$ N for *Hydrangea*, 2.1 kg·m$^{-3}$ N *Cornus*, and 2.5 kg·m$^{-3}$ N for *Weigela*, *Salix*, and *Hibiscus* (Fig. 4).

Nevertheless, examination of plant growth under lower CRF rates revealed that the grower was satisfied with the results, signifying that marketable plants could be produced when grown with less fertilizer (Figs. 3 and 7). Although maximum plant growth had not been achieved at these lower CRF rates, the plant was still of marketable quality. As a result, the lowest acceptable rates of CRF were: 0.35 kg·m$^{-3}$ N for *Hibiscus*; 0.65 kg·m$^{-3}$ N for *Cornus*, *Weigela*, *Salix*, and *Spiraea*; and 0.80 kg·m$^{-3}$ N for *Hydrangea*. Consequently, the results of this study validate an optimum range, rather than a specific rate of CRF, where the highest rate in the range achieves maximum plant growth and the lowest rate is the lowest acceptable rate for plant production according to the grower's specifications.

All plants grown within the optimal range of CRF application were of acceptable quality to the grower in this study; therefore, it is up to the discretion of the nursery grower to select a CRF rate within the optimum range appropriate to his or her desired outcome or specific production practice. For example, *Hibiscus* growth was maximized and reached a marketable size in one growing season when grown with 2.5 kg·m$^{-3}$ N in 2012. However, on 28 Aug. 2013, the grower selected the lower rate of 0.35 kg·m$^{-3}$ N as adequate for the production of *Hibiscus.* This is because, according to the grower, *Hibiscus* is generally produced as a 2-year crop, which requires topdressing in the second year; therefore, fertilization with a lower rate in the first year will not impede the quality of the plant in the second. This illustrates the potential for a decrease in production time by using CRF as a tool for growth management, i.e., selecting the higher rate of CRF to reduce production time to 1 year. Similarly, in the 2012 trial, the grower deemed *Hydrangea* grown in 0.80 kg·m$^{-3}$ N to be the lowest acceptable rate of CRF because *Hydrangea* is also produced in two growing seasons, requiring topdressing the next year, yet *Hydrangea* grown in 1.7 kg·m$^{-3}$ N achieved maximum growth and was able to reach a marketable size in one growing season, illustrating that production time for *Hydrangea* could also be decreased to 1 year by increasing the CRF rate.

Although certain benefits can be derived from a higher application of CRF (i.e., increased plant growth, decreased production time), the rate of loss of both N and P increased as the CRF rate was increased (Fig. 5). In terms of N, the range of loss observed in this study is consistent with the N losses reported by Birrenkott et al. (2005) and Narváez et al. (2012), supporting the fact that nursery crops have relatively low nutrient demands and marketable plants can be produced without superfluous fertilization (Hicklenton and Cairns, 1992). Accordingly, when fertilizer is supplied in excess of plant demands, the result is clearly an accumulation of nutrients in the substrate solution, which leads to a higher nutrient content in leachate under normal nursery practices (Cabrera, 2003; Marschner, 2002). In addition to such losses by leaching, denitrification could have influenced the amount of N lost (Majsztrik et al., 2011; Niemiera and Leda, 1993).

In comparison with N, the amount of P lost was lower with losses never reaching over 1.0 g/pot for any of the species (Fig. 5). Losses were undoubtedly lower than N as a result of the relatively lower ratio of P in the fertilizer mix and the possibility of P binding to the composted material in the growing substrate, a phenomenon that has been observed in previous studies (Handrek, 1996; Newman et al., 2006).

As reported in this study, the losses of N and P per pot translate to a cumulative leaching loss of ≈79 to 211 kg·ha$^{-1}$ per year of N and 7.2 to 23.4 kg·ha$^{-1}$per year of P, depending on CRF rate. Although these calculations can only provide an estimate of the nutrient losses per year, the losses calculated are in line with reports from recent publications. Mangiafico et al. (2008) reported median nutrient runoff losses from a survey of 11 production nurseries to be 40.9 and 3.64 kg·ha$^{-1}$ per year for N and P, respectively. Million et al. (2011) reported cumulative leaching losses of applied N and P to be in excess of 250 and 33 kg·ha$^{-1}$ per year, respectively. This study highlights valuable information regarding cumulative nutrient leaching from container nurseries in Ontario and the potential for ground and surface water contamination if the nutrient-rich runoff is allowed to enter nearby water bodies. Consequently, given the stringent regulations on nursery production practices in Ontario (Nutrient Management Act, 2002), levels of N and P in nursery runoff have been under increasing scrutiny (Alam et al., 2009). Accordingly, lower CRF rates that can produce marketable plants should preferably be used to ensure environmental losses of N and P are minimized. Because ornamental plant quality ultimately depends on qualitative measurements of aesthetic and consumer appeal (Brand and Leonard, 2001; Stroup et al., 1998), production goals should be geared toward increasing the overall appearance of the plant and not necessarily achieving maximum growth. As the results of the overall

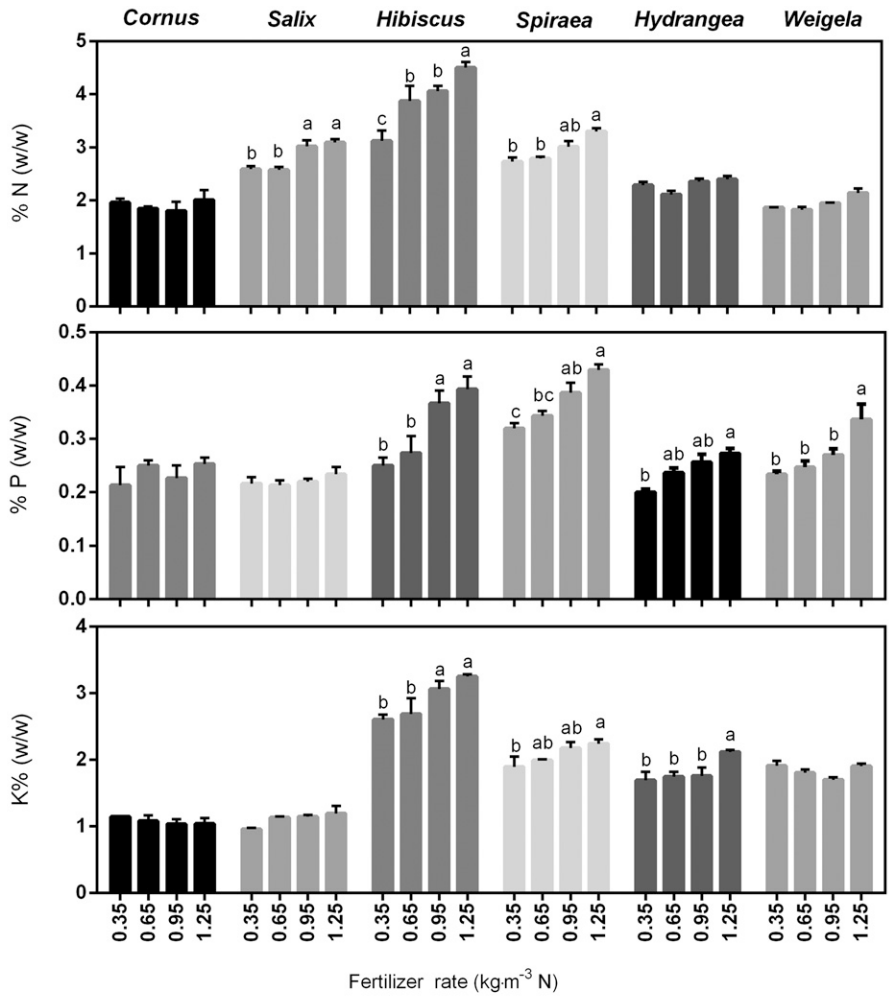


Fig. 9. Percent nutrient content in leaf tissue of *Cornus sericea* 'Cardinal', *Weigela florida* 'Alexandra', *Salix purpurea* 'Nana', *Hydrangea paniculata* 'Bombshell', *Hibiscus syriacus* 'Ardens', and *Spiraea japonica* 'Magic Carpet' grown with four rates of Polyon® 16N–2.6P–10K, 5–6 month controlled-release fertilizer. Data are means ± SE (n = 3). Bars bearing the same letter are not significantly different for each species at $P < 0.05$, according to Tukey's multiple comparison test.

appearance ratings for 2012 and 2013 illustrate (Figs. 3 and 7), all species, except *Hydrangea* and *Spiraea*, can be grown in lower CRF rates and can achieve statistically equivalent appearance ratings as plants grown in the CRF rate, which maximizes growth (i.e., *Cornus*: 0.8 vs. 2.1 kg·m$^{-3}$ N, *Weigela*: 0.8 vs. 2.5 kg·m$^{-3}$ N, *Salix*: 1.2 vs. 2.5 kg·m$^{-3}$ N, and *Hibiscus*: 1.2 vs. 2.5 kg·m$^{-3}$ N). Therefore, by using lower CRF rates to produce ornamentals, growers cannot only decrease the amount of N and P lost to the environment (Fig. 5), but can also achieve a similar appearance to plants that have been grown with the CRF rate that maximizes growth.

Nutritional requirements for container-grown crops are known to vary widely among species and even between cultivars (Chen et al., 2001; Chong et al., 2004). This is consistent with the results of this study, which clearly demonstrate species-specific responses to different rates of CRF for container-grown ornamentals. Manufacturers of CRF list rate recommendations on the fertilizer packaging for heavy, medium, and sensitive feeders; however, because the CRF release times and recommended application rates are largely determined in a controlled laboratory setting, it is difficult to rely on these recommendations when field can conditions vary greatly (Birrenkott et al., 2005). In this study, the lowest CRF rates within the optimum range that were determined were all less than the CRF manufacture-recommended application rates of 1.12 kg·m$^{-3}$ N for high feeders (i.e., *Hydrangea* and *Weigela*) and 0.80 kg·m$^{-3}$ N for medium feeders (i.e., *Hibiscus*, *Cornus*, *Spiraea*, and *Salix*) (Agrium Advanced Technologies Inc., 2013). Consequently, the growing conditions of the 2012 and the 2013 trial may have influenced the release rate and the recommended fertilizer rate for optimum growth. For example, the nutrient release rates of CRFs are temperature-dependent and the release is positively correlated with increasing temperature (Newman et al., 2006). Manufacturers of Polyon® 16N–2.6P–10K have established a release rate of 5 to 6 months based on a temperature of 20 °C (Agrium Advanced Technologies Inc., 2013). However, for the 2012 trial, daily average air temperatures ranged between 20 and 27.3 °C for the first 35 d of the study with daily maximum temperatures reaching as high as 36.1 °C (Fig. 1). These high temperatures likely created an elevated release of nutrients in the root zone, which was responsible for the high EC values recorded during this time. Narváez et al. (2012) also observed high EC in leachates at the beginning of their trial attributed to the release of soluble salts resulting from high temperatures. This increased nutrient release would not only shorten the longevity of the product, but also increase the requirements for CRF. Furthermore, because the root system of a newly planted woody ornamental is essentially still confined to the liner (Newman et al., 2006), this high release of nutrients during the first few days of the study would not be used by the plant and would end up being released to the environment. Conversely, later in the season, the CRF may be depleted and not release enough nutrients for actively growing plants with fully developed root systems (Sandrock et al., 2005). This conundrum illustrates the need for further research on CRF use efficiency because the N release patterns of many CRF do not match the N requirements of the plant and can vary greatly with environmental conditions (Sandrock et al., 2005).

Growing substrate pH of the 2013 trial was higher than that of the 2012 trial. The lower pH of the growing substrate in 2012 can be attributed to the higher rates of CRF applied as a result of the acidifying effect of the fertilizer used. This acidification potential of CRFs has been previously noted by Ivy et al. (2002) and Zheng et al. (2013). Because most irrigation water in southwest Ontario has high alkalinity levels (Zheng et al., 2011), the opportunity exists to counteract the alkalinity of irrigation water with the acidifying potential of a CRF; however, further research is required in this area.

In 2013, leaf tissue N, P, and K concentrations for CRF treatments 0.35, 0.65, 0.95, and 1.25 kg·m$^{-3}$ N were all within the sufficiency ranges typically reported [Bryson et al., 2014; Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), 2006] for deciduous ornamental shrubs (Fig. 9). However, *Hibiscus* had visual symptoms of a N deficiency with leaf yellowing observed in CRF treatments of 0.05 to 0.65 kg·m$^{-3}$ N and *Cornus*' growth was severely stunted at 0.05 and 0.35 kg·m$^{-3}$ N. This suggests that leaf N sufficiency ranges, as suggested by some of the existing publications (Bryson et al., 2014; OMAFRA, 2006), may not be accurate for these species. Previous research has also suggested that leaf tissue analysis alone may not be sufficient in diagnosing nutrient deficiencies as a result of "dilution" or "concentration effects," i.e., a nutrient may be diluted or concentrated relative to the size of the plant (Jarrell and Beverly, 1981). Therefore, alternate methods such as leaf chlorophyll measurements or visual observations should be used in combination with leaf and substrate nutrient analysis to determine nutrient deficiencies.

## Conclusion

Nutritional requirements for container-grown crops are known to vary widely among species and even between cultivars (Chen et al., 2001; Chong et al., 2004). This is consistent with our results, which clearly demonstrate species-specific responses to CRF rates. Accordingly, to produce high-quality plants while limiting overfertilization, growers should apply CRF rates within the optimal range for each species or cultivar. Overall, the highest acceptable CRF rates within the optimal range were 1.25 $kg·m^{-3}$ N for *Spiraea*, 1.7 $kg·m^{-3}$ N for *Hydrangea*, 2.1 $kg·m^{-3}$ N for *Cornus*, and 2.5 $kg·m^{-3}$ N for *Weigela*, *Salix*, and *Hibiscus*. The lowest acceptable rates within the optimal range were: 0.35 $kg·m^{-3}$ N for *Hibiscus;* 0.65 $kg·m^{-3}$ N for *Cornus*, *Weigela*, *Salix*, and *Spiraea;* and 0.80 $kg·m^{-3}$ N for *Hydrangea*. For the first time, this research was able to provide optimal ranges of CRF application rates for container shrub production in southwestern Ontario. Further research is required to identify CRF application rates for additional commonly grown ornamentals in Ontario so that growers may select fertilizer rates based on species and location-specific requirements.

The undesirable and substantial leaching losses associated with overfertilization require further attention in the nursery industry as well as an adjustment to the CRF recommended rates for container-grown crops. The cumulative nutrient leaching losses calculated within this study indicate that significant amounts of N and P can be lost under normal production practices. These substantial losses pose a potential threat to ground and drinking water resources and further research is required to mitigate potential pollution issues regarding nutrient-rich runoff from containerized nurseries in Ontario.

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