Effect of Fertilizer Rate on Plant Growth and Leachate Nutrient Content during Production of Sedum-vegetated Green Roof Modules

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Abstract. With the increasing popularity of green roofs, efficient green roof plant production is required to adequately supply the industry. Applying fertilizer at an appropriate rate can provide sufficient plant nutrition for efficient plant growth without excess nutrient leaching into the environment. This study compared rates of controlled-release fertilizer (CRF) applied to green roof modules at the plant production stage to determine an optimum CRF rate for encouraging plant growth and vegetative coverage while minimizing the amount and concentration of leached nutrients. After sedum cuttings were rooted in green roof modules on 29 Aug. 2011, CRF was applied at 5, 10, 15, 20, 25, 30, and 35 g·m⁻² nitrogen (N) and modules were compared with an unfertilized control. Plant growth, vegetative coverage, and overall appearance requirements were met after fertilization at 20 g·m⁻² N. Modules fertilized at less than 20 g·m⁻² N did not reach the target proportion coverage during the study. When fertilized at 20 g·m⁻² N, green roof modules reached the target proportion coverage after 240 days of growth. Differences in leachate volumes were observed among treatments 35 days after fertilization and fertilization at 20 g·m⁻² N minimized leaching of most nutrients. Therefore, with the green roof module system used in this study, an application of 20 g·m⁻² N for green roof module or sedum cutting production is an optimum CRF rate for plant growth and vegetative coverage while minimizing negative environmental impacts.

The expansion of the green roof industry in North America has increased annually and grew by 115% in 2011 alone [Green Roofs for Healthy Cities (GRHC), 2012]. With the increasing area covered by installed green roofs, production demand has also increased for green roof plants. Given the environmental, economic, and aesthetic benefits provided by green roofs (Barker and Lubell, 2012; Berndtsson, 2010; Getter and Rowe, 2006; Oberndorfer et al., 2007) as well as the billions of square feet for potential green roof installations in North America (GRHC, 2012), there is great potential for future growth of plant production for the North American green roof industry. In 2011, the majority of

green roof installations were extensive green roofs (GRHC, 2012), which typically consist solely or mainly of *Sedum* spp. planted in a growing substrate depth of 15 cm or less (FLL, 2008). Sedum are ideal plants for extensive green roof systems as a result of their ability to grow in shallow substrates (Emilsson, 2008; Rowe et al., 2012) and endure environmental stresses (Durham et al., 2006; Getter and Rowe, 2006; Wolf and Lundholm, 2008). Thus, efficient production of sedum as plants, cuttings, and pre-vegetated extensive green roof systems (e.g., modules) is required to meet the needs of the green roof industry.

Similar to ornamental crop production (i.e., Salifu and Jacobs, 2006; Zhang et al., 2012), adequate fertility is essential for green roof plant production to encourage plant growth, ensure desired aesthetics, and achieve full vegetative coverage (Clark and Zheng, 2012, 2013; Emilsson et al., 2007; FLL, 2008; Retzlaff et al., 2009). Green roof growing substrates used during production are markedly different (i.e., lightweight, well-drained and 40 g·L⁻¹ or less organic matter; FLL, 2008) than those used in other horticultural sectors and may require unique fertilizer types and rates. Commercially, sedum-vegetated modules propagated in May with 976 g of cuttings per m² are produced in roughly 10 to

12 weeks based on 95% vegetative coverage at production completion (Barker and Lubell, 2012). It is desirable for growers to minimize module production times, as evaluated primarily by overall vegetative coverage, to increase the quantity of modules produced and, consequently, farm-gate income. In addition, sedum can be grown to produce cuttings for module propagation or direct-to-roof plantings. We have not found literature studying sedum cutting production or the combination of sedum cutting harvest with finished green roof module production, although pruning, clipping, or pinching increases the density and vigor of groundcover plants (Klingeman et al., 2008).

Vegetative coverage and shoot growth for sedum in green roof systems have demonstrated positive responses to CRF rate both during production of commonly installed modules and post-installation module maintenance (Barker and Lubell, 2012; Clark and Zheng, 2013; Emilsson et al., 2007). Building on previous green roof module production results (Barker and Lubell, 2012), research is needed to determine CRF rate recommendations for sedum-vegetated module production, considering additional growing substrates, fertilizer types and rates, and Sedum species combinations. In addition, nutrient runoff (i.e., leaching) to the environment needs to be evaluated and compared with regional water discharge recommendations (e.g., Canadian Council of Ministers of the Environment, 2012; Ministry of the Environment and Energy, 1994) before conscientious CRF rate recommendations can be made. Fertility of the growing substrate influences nutrient leaching (Alsup et al., 2011; Gregoire and Clausen, 2011; Vijayaraghavan et al., 2012) and new green roof plantings leach more nutrients than established plantings (Emilsson et al., 2007). Therefore, CRF rate in combination with the growing substrate fertility should be considered when determining optimum CRF rates for newly propagated green roof systems. Although past fertilization studies have evaluated nutrient runoff during vegetation establishment in a greenhouse (Emilsson et al., 2007) and plant growth and coverage during outdoor production (Barker and Lubell, 2012), to our knowledge, no research has considered both the optimum CRF rate for green roof module production in combination with nutrient loss through leaching in an outdoor trial. Determining an optimum CRF rate for sedum growth in green roof modules while minimizing nutrient leaching will help growers develop environmentally conscious and efficient production systems to meet industry demand.

The current study aims to evaluate the effect of CRF applied during outdoor production of green roof modules. Specifically, the objective of this study was to identify an optimum CRF rate to minimize both green roof module production time and nutrient leaching to the environment.

Materials and Methods

Plant material and treatments. Black plastic LiveRoof® modules (LiveRoof Ontario,

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Inc., Mount Brydges, Ontario, Canada) measuring 30.5 cm × 61.0 cm were filled to a depth of 10.0 cm with a lightweight growing substrate developed at the University of Guelph, having a dry bulk density of 0.59 g·cm⁻³, 6.59% organic matter, 11.3% air-filled porosity, 37% volumetric water content, and 0.037 cm·s⁻¹ permeability factor (Yuristy, 2013). The substrate contained 501 mg·kg⁻¹ total N (total Kjeldahl N determined using a classical Kjeldahl digestion and a Skalar segmented flow auto-analyzer, and NO₂⁻ and NO₃⁻ determined using ion chromatography by SGS Agri-Food Laboratories, Guelph, Ontario, Canada), 490 mg·kg⁻¹ total phosphorus (P), and 1200 mg·kg⁻¹ total potassium (K), both analyzed using a borate fusion-internal standard and X-ray fluorescence spectrometry method (SGS Laboratories, Lakefield, Ontario, Canada). The plant-available nutrient composition of the substrate was 4.00 mg·kg⁻¹ NO₃⁻, less than 1 ppm P, and 49.0 mg·kg⁻¹ K (analyzed using a saturated paste extraction method by SGS Agri-Food Laboratories, Guelph, Ontario, Canada). On 11 July 2011, a mixture of sedum cuttings, consisting of approximately even proportions of *Sedum album* L., *S. hybridum* L. 'Immergrunchen', *S. reflexum* L. 'Blue Spruce', *S. sexangulare* L., and *S. spurium* Bieb. 'Dragon's Blood', was spread evenly on substrate-filled modules at a rate of 915 g·m⁻². To encourage cutting establishment, treatment modules were placed on misting benches outdoors by the Bovey building at the University of Guelph (lat. 43°31'38" N, long. 80°13'45" W) under an elevated 60% knitted black polyethylene shade cloth (Gintec Shade Technologies Inc., Waterford, Ontario, Canada) canopy, and misted with deionized water during the day for 10 s three to four times per hour based on environmental conditions. Once cuttings were rooted on 25 July 2011, modules were placed at ground level to follow typical green roof module production practices. Modules were watered evenly by hand using deionized water as needed (i.e., to supplement rain events) for the duration of the study. On 29 Aug. 2011, treatments were started by applying the following fertilizer rates evenly by hand to experimental modules: Nutricote® Total 18-6-8 with minors 100-d CRF (i.e., 18N-2.6P-6.6K; Plant Products Co. Ltd., Brampton, Ontario, Canada) applied at 0 (control), 5, 10, 15, 20, 25, 30, and 35 g·m⁻² N. Fertilizer type and rate selections were based on suggestions by industry professionals and our previous research (Clark and Zheng, 2013). Each of the eight fertilizer treatments was replicated three times (n = 3) and modules were arranged in a completely randomized design. Two rows of 12 treatment modules per row were surrounded on all sides with a border of non-treatment modules to reduce edge effects. Each module was positioned on top of a leachate collection tray. A 10-cm-wide, clear plastic strip was taped around the perimeter of each module to overlap the rim of the leachate collection tray to eliminate ambient rain or irrigation water from entering the tray. Between 10 Nov. 2011 and 7 Mar. 2012, leachate collection trays were

removed for the winter, leachate was not collected, and the modules were placed directly on ground level to more closely follow standard production practices. Modules were grown until the majority of treatments reached a proportion vegetative coverage of 0.8 or greater. Mean monthly air temperatures ranged from 19.3 °C in Aug. 2011 to -3.7 °C in Jan. 2012.

Measurements. At regular intervals during the 2011 and 2012 growing seasons, four aspects of sedum plant growth response to fertilizer treatments were evaluated: winter injury and overall appearance, vegetative coverage, plant growth (i.e., shoot height), and leaf color. Winter injury can cause plant failure and is indicated by leaf desiccation and shoot dieback (Boivin et al., 2001). Winter injury was ranked per plot in Mar. and Apr. 2012 by visually estimating the percent of shoots per sedum species showing leaf desiccation. Relative to all other modules, winter injury was ranked on a scale of 1 (best appearance resulting from the least injury) to 5 (worst appearance resulting from the most injury). A guideline of green roof plant performance can be obtained by visually evaluating overall appearance (Clark and Zheng, 2012, 2013; Rowe et al., 2006). In 2012, green roof module overall appearance was ranked relative to all other plots on a 1 (least appealing) to 5 (most appealing) scale based on plant growth, leaf color, visual appeal, and perceived plant health. Vegetative coverage per module was visually estimated by comparing vegetation-covered with non-covered areas for the module as a whole. The same observer evaluated overall appearance, winter injury, and vegetative coverage at all time points to ensure consistency in ratings and estimations. Plant growth was evaluated by shoot height measured for three representative shoots per species per module. However, as a result of variability in cutting establishment for *S. album*, shoot height was not measured for this species. For sedum, green leaves are perceived as healthier than red or yellow leaves during the growing season; therefore, green roof visual appeal is influenced by leaf color (Clark and Zheng, 2012). Leaf tissue color was quantitatively evaluated at three locations within each module using a colorimeter (Minolta CR-310; Minolta Camera Co. Ltd., Osaka, Japan). Throughout the 2011 and 2012 growing seasons (i.e., 29 Aug. to 10 Nov. 2011 and 7 Mar. to 22 June 2012), root zone pH and electrical conductivity (EC) of leachate were monitored at regular intervals using pour-through analysis modeled after the method by Wright (1986). Leachate was acquired following substrate saturation and deionized water application and evaluated using a portable pH and EC meter (Oakton PC 300; Oakton Instruments, Vernon Hills, IL).

After pour-through analysis and after rain events, total leachate and rain water volumes were measured, and a subsample was stored at -80 °C. Following study completion, volume-weighted aliquots per subsample per treatment were combined in one container, mixed

by stirring, and subsampled before elemental analysis was conducted using a Varian Vista Pro inductively coupled plasma-optical emission spectroscopy with an axially viewed plasma (Varian Inc., Australia). Nutrient concentrations were diluted as needed to obtain readings within the detection limit of 0.1 µg·L⁻¹. Total nutrient loss (N_{Loss}) was calculated using the total leachate volume captured during the study (V_{tot}) and the volume-weighted nutrient concentration (N_c) by the following equation: N_{Loss} = V_{tot} · N_c.

Statistical analysis. All data sets were analyzed using GraphPad Prism Version 5.03 software (GraphPad Software Inc., La Jolla, CA). A one-way analysis of variance (ANOVA) was used to evaluate differences among treatments over time. Regression analyses were used to relate module overall appearance, leaf color, leachate volume, and nutrient concentration to CRF rate and to estimate regression parameters for the best-fit regression model (linear or quadratic). Pearson correlation calculations were used to determine correlation coefficients between shoot height and fertilizer rate and leachate volume data. All data were evaluated using a significance level of *P* < 0.05.

Results and Discussion

Overall appearance and winter injury. Overall appearance of modules was influenced by both time and fertilizer treatment, but not the interaction of time and treatment (*P* < 0.05). From Oct. to Dec. 2011, and during the 2012 growing season (i.e., May and June 2012), overall appearance of modules linearly increased as fertilizer rate increased (Fig. 1). In Mar. and Apr. 2012, module overall appearance quadratically increased with increasing fertilizer rate with low- and midrate treatments having more distinct visual differences than high-rate modules. Overall appearance was primarily influenced by plant growth, vegetative coverage, and establishment as well as leaf color. In May 2012, some leaves of *S. hybridum* 'Immergrunchen' were brown and desiccated, regardless of treatment. Because *S. hybridum* 'Immergrunchen' had the largest leaves of any species in the study, environmental stresses (i.e., water, wind, etc.) may have caused leaf desiccation (Getter and Rowe, 2006; Teeri et al., 1986). In June 2012, lower leaves within dense canopy growth turned brown only in treatments 15 or greater but did not reduce overall appearance as a result of lush, green top growth in these treatments. Similar lower leaf desiccation in dense sedum growth was observed in previous studies (i.e., Barker and Lubell, 2012; Clark and Zheng 2012, 2013) but rarely reduced overall appearance. For the duration of the study, treatments 20 or greater had a consistently high overall appearance

ranking, suggesting a fertilizer rate at or above $20 \text{ g}\cdot\text{m}^{-2} \text{ N}$ can be considered optimum for overall appearance. These results address the suggestion by Emilsson et al. (2007) that the impact of nutrient requirements on visual characteristics of green roof vegetation should be considered when determining optimal green roof fertilizers.

Winter injury (i.e., leaf desiccation) ranking was influenced by time of year. In Mar. 2012, no leaf desiccation was observed for any treatment, likely as a result of cold protection by snow coverage or plant dormancy. However, winter injury was evident in Apr. 2012 and the mean overall winter injury ranking was lower for the 5 treatment than all other treatments (i.e., 2.0 ± 0.6 vs. 3.1 ± 0.1 , respectively). Winter injury was greatest on new growth and was primarily observed as white leaf tips for *S. album* and *S. sexangulare* species, and brown leaf margins for *S. hybridum* 'Immergrunchen'. These species may have been the most susceptible to springtime air temperature fluctuations. Boivin et al. (2001) also noted brown leaves resulting from winter injury for sedum. Similar to Monterusso et al. (2005), we did not observe any overwintering losses for sedum. In the current study, for plots with winter injury, overall appearance was restored during the 2012 growing season. Using a low fertilizer rate (i.e., $5 \text{ g}\cdot\text{m}^{-2} \text{ N}$) or choosing more cold-tolerant

Sedum spp., such as *S. reflexum* 'Blue Spruce' or *S. spurium* 'Dragon's Blood', may ensure survival and minimize winter injury during module production. However, fertilizer-influenced winter injury does not need to be taken into consideration for the green roof system used in this study if production timing is long enough to facilitate plant recovery. Future research is needed to evaluate the use of physical barriers (i.e., a geotextile cover; Boivin et al., 2001) to prevent early-season cold injury during module production.

Vegetative coverage. Fertilizer treatment, time, and the interaction of treatment and time influenced vegetative coverage of modules during production ($P < 0.05$). Initial vegetative coverage at the time of fertilizer application (i.e., on 29 Aug. 2011) did not differ among treatments. Between Aug. and Nov. 2011, a decrease in coverage occurred over time for the 5, 10, and control treatments, whereas coverage was maintained or increased for treatments 15 or greater (Fig. 2). Although Emilsson et al. (2007) suggest fertilization has no positive effect on sedum establishment, our results demonstrate a positive effect of fertilizer during sedum establishment when applied above a threshold rate (i.e., $15 \text{ g}\cdot\text{m}^{-2} \text{ N}$). When we observed decreased coverage, the cause was leaf senescence and plant mortality for primarily large-leaved species (e.g., *S. hybridum*

'Immergrunchen'), likely resulting from low substrate fertility or environmental stress (Teeri et al., 1986). Thus, for sedum-vegetated modules propagated in August, a fertilizer rate $15 \text{ g}\cdot\text{m}^{-2} \text{ N}$ or greater is needed to maintain or increase initial vegetative coverage levels in the studied green roof system.

The shortest time until the target proportion coverage (i.e., 0.8) was observed occurred for the 25, 30, and 35 treatments (212 d after fertilization) followed by the 20 treatment (240 d). Treatments 15 or less did not reach the target coverage during the study. These results indicate that fertilizer can be used to accelerate or slow green roof module production. Barker and Lubell (2012) evaluated vegetative coverage for May-propagated green roof modules fertilized with 50, 78, or 108 g of $15\text{N}-3.9\text{P}-10\text{K}$, 8-9 month Osmocote® Plus CRF (i.e., 40.4, 63.0, and $87.2 \text{ g}\cdot\text{m}^{-2} \text{ N}$). They observed greater than 60% of modules had vegetative coverage greater than 95% after 56 d of growth (i.e., finished 15 July). Appropriate fertilizer use can help growers increase annual production capacity and farm gate income while meeting the increasing industry need for green roof plants. Further research should project production completion timelines, after spring and late summer propagation, relative to growing degree-days and growth rate of *Sedum* spp. To build on the current study and recent research (Barker and Lubell, 2012; Rowe et al., 2006), further research is needed to determine the post-installation acclimation success for green roof modules produced at a range of fertilizer rates.

Plant growth. Shoot height of *S. reflexum* 'Blue Spruce', *S. spurium* 'Dragon's Blood', *S. hybridum* 'Immergrunchen', and *S. sexangulare* was influenced by fertilizer rate, time, and the interaction between fertilizer rate and time ($P < 0.05$). For all four species, an increase in shoot height was observed over time for treatments 10 or greater, whereas shoot height in the 5 and control treatments decreased or was similar to the initial height (Fig. 3).

In addition to finished modules, growers may produce sedum cuttings to sell or use on-farm for propagation; however, we have not found literature providing propagation recommendations for sedum cutting production. Shoot height determines suitability of sedum plants for cutting harvest and an increased rate of shoot growth will permit an earlier harvest date. Cutting lengths from 2.5 to 5 cm are often used for propagation (David Gilmore, personal communication); therefore, an estimated minimum shoot height of 5.5 to 8 cm at harvest is appropriate to ensure a height of 3 cm or greater remains after cutting removal. Fertilization of *S. reflexum* 'Blue Spruce' with $15 \text{ g}\cdot\text{m}^{-2} \text{ N}$ or greater as well as *S. hybridum* 'Immergrunchen' and *S. spurium* 'Dragon's Blood' with 30 and $35 \text{ g}\cdot\text{m}^{-2} \text{ N}$, respectively, produced shoots tall enough for cutting harvest during the study (Fig. 3). Because shoot growth response to fertilizer rate is species-specific, fertilizer rate application can be customized to produce cuttings as required

Fig. 1. Overall appearance of green roof modules grown under eight controlled-released fertilizer rates. The overall appearance was ranked using a scale ranging from 1 (least appealing) to 5 (most appealing), visually determined by plant growth, leaf color, and perceived health. Data are means $\pm$ SE ($n = 3$). Where fertilizer rate effect was significant ($P < 0.05$), a solid line indicates the calculated regression.

Fig. 2. Proportion vegetative coverage of green roof modules after fertilization on 29 Aug. 2011 with 5, 10, 15, 20, 25, 30, or 35 g-m⁻² nitrogen (N) or unfertilized (Control). Data are means $\pm$ SE (n = 3). Module production was considered complete on the date indicated in parentheses when proportion coverage 0.8 or greater (dashed line) was observed.

for individual *Sedum* spp. Further research is needed to determine cutting production timelines for established, formerly cut *Sedum* spp. stands after application of a range of fertilizer rates and types.

Leaf color. Between Mar. and May 2012, leaf color was significantly influenced by time, treatment, and the interaction of time and treatment ($P < 0.05$). In Mar. 2012, leaves in all treatments were greener than the control. In May 2012, leaves in the 35, 30, 20, 15, and 10 treatments were greener than the 5 and control treatments and leaves in the 25 treatment were greener than the 10, 5, and control treatments. Fertilizer rate required to achieve maximum sedum leaf greenness, calculated based on monthly color evaluations, ranged from 21.5 g-m⁻² N in March to 32.0 g-m⁻² N in July 2012 with an overall average of 25.2 g-m⁻² N (Fig. 4). In addition, the average upper 5% of leaf greenness ranged from 16.6 to 33.7 g-m⁻² N. Leaf color

in the yellow and red spectrum for the 5 and control treatments in the cooler months (i.e., Mar. and May 2012) may have resulted from low N levels (Lee et al., 2003) or low nutrient content in leaves as a result of air temperature-influenced nutrient remobilization (Field et al., 2001; Matile, 2000; Vollenweider and Gunthardt-Goerg, 2005). Sparse leaf density for the control in June and July 2012, and for the 5 treatment in July 2012, did not permit leaf color measurements. By fertilizing modules at an appropriate rate (i.e., within the 16.6 to 33.7 g-m⁻² N range for the studied green roof system), a grower can ensure a visually appealing green leaf color before sale.

Leachate pH and EC. Time influenced leachate pH and EC collected from green roof modules, whereas the interaction of time and treatment was significant for leachate pH but not EC ($P < 0.05$). Leachate pH differed among treatments at all time points except

Fig. 3. Shoot height of four *Sedum* spp. planted in green roof modules after fertilization on 29 Aug. 2011 with 5, 10, 15, 20, 25, 30, or 35 g-m⁻² nitrogen (N) or unfertilized (Control). Data are means $\pm$ SE (n = 9). Cutting harvest can occur at shoot heights between 5.5 and 8 cm, indicated by the dashed lines and shaded region.

35 d after fertilization (i.e., 3 Oct. 2011; Fig. 5). Throughout the study, the substrate pH was greater than the pH range generally recommended for plant growth (i.e., 5.6 to 6.2; Reed, 1996) or specifically for sedum growth (i.e., 6.43 or less; Zheng and Clark, 2013) in a soilless media. For example, in Oct. 2011, the mean pH was 7.87 ± 0.02 for all treatments. Root-zone pH levels likely restricted plant growth for some species as a result of species-specific pH preferences (Zheng and

Fig. 4. Sedum leaf color in green roof modules grown at eight fertilizer rates. Leaf color is presented as hue angle. Data are means $\pm$ SE ($n = 9$). Where fertilizer rate effect was significant ($P < 0.05$), a solid line indicates the calculated regression. For each date, the regression equation and R^2 value are presented and the fertilizer rate ($\text{g}\cdot\text{m}^{-2}$ N) calculated to produce maximum leaf greenness is given in parentheses.

Fig. 5. Leachate pH (A) and electrical conductivity (EC) (B) of green roof modules fertilized with 0, 5, 10, 15, 20, 25, 30, or 35 $\text{g}\cdot\text{m}^{-2}$ nitrogen (N) of Nutricote® Total 18N–2.6P–6.6K 100 d controlled-release fertilizer. Data are means $\pm$ SE ($n = 3$).

Clark, 2013). In the current study, the pH for all treatments was above the preferred range for *S. hybridum* 'Immergrunchen' (Zheng and Clark, 2013). Although shoot height increased over the course of the study for *S. hybridum* 'Immergrunchen' in 20 and 30 treatments, a greater increase may have been possible if grown at a lower pH level. Because sedum growth can decrease as pH levels

increase (Zheng and Clark, 2013), maintaining the growing substrate pH within a preferred range may have increased sedum growth in the studied green roof system.

Leachate EC only differed significantly among treatments 35 d after fertilization (i.e., 3 Oct. 2011; Fig. 5) and was also the greatest on Day 35 compared with all other time points. This result is consistent with observations by

Emilsson et al. (2007), which showed a high level of nutrient leaching from a newly planted green roof. However, leachate EC at Day 35 was within the 0.6- to 2.0- $\text{mS}\cdot\text{cm}^{-1}$ range recommended by Wright (1986) for healthy plant growth but was below the recommended range at all other time points. In the current study, the high EC value 35 d after fertilization was likely caused by slow plant growth resulting from cool air temperatures, nutrient loss from growing substrate components, and excess CRF nutrient release for high fertilizer treatments (Clark and Zheng, 2013). After Day 35, a balance in nutrient release and nutrient uptake during plant growth may have produced adequate fertility levels (Chen et al., 2001) and prevented leachate EC differences among treatments. Further research is needed to determine the optimum root-zone EC range for sedum growth in commonly planted green roof systems.

Fertilizer rate for optimum plant performance. To produce modules in the green roof system used in this study, fertilizing August-propagated cuttings with 25 $\text{g}\cdot\text{m}^{-2}$ N or greater would result in the shortest production time (212 d) required to achieve a proportion vegetative coverage of 0.8. By considering the market demand, fertilizer rate can be appropriately adjusted to accelerate or slow sedum growth to meet production timelines. In addition, fertilizing *S. reflexum* 'Blue Spruce' with 15 $\text{g}\cdot\text{m}^{-2}$ N or greater as well as *S. hybridum* 'Immergrunchen' and *S. spurium* 'Dragon's Blood' with 30 and 35 $\text{g}\cdot\text{m}^{-2}$ N, respectively, would most efficiently produce sedum cuttings. However, to achieve optimum leaf color before production completion, a fertilizer application rate ranging from 16.6 to 33.7 $\text{g}\cdot\text{m}^{-2}$ N is sufficient for the studied green roof system.

Environmental Impact

Leachate quantity. Volume of collected leachate was influenced by the effects of fertilizer treatment, time, and the interaction of treatment and time on green roof modules ($P < 0.05$). Total leachate quantity collected over the duration of the study was quadratically related to the effects of fertilizer rate on green roof modules (Fig. 6). Leachate volumes collected after individual rain events differed among treatments from Day 35 (3 Oct. 2011) until the study completion (22 June 2012), except after a large rainstorm on day 53 (21 Oct. 2011) and during the freeze and thaw period between day 73 and 197 (i.e., 10 Nov. 2011 and 13 Mar. 2012, respectively; Fig. 7). The differences in leachate volumes among treatments over time may have been affected by fertilizer-influenced differences in plant growth. Specifically, after 35 d, sedum cuttings in high fertilizer treatments may have rooted and established more than those in low fertilizer treatments. Beginning in Oct. 2011, shoot height of *S. spurium* 'Dragon's Blood' was highly correlated with the effects of fertilizer rate ($r = 0.82$) and leachate volume ($r = -0.73$). Above- and below-ground plant

tissues may have held water within the growing system to prevent water from leaching out.

At all time points except Days 35 and 53, leachate volume of all treatments was less than the mean precipitation volume ($P < 0.05$). Before leachate collection on Day 35, frequent rain events occurred on Days 28, 29, and 32, whereas a heavy rainstorm occurred on Day 53. This suggests high leachate volumes on Days 35 and 53 were likely the

Fig. 6. Leachate volume per green roof module under eight fertilizer rates. Leachate volume refers to total leachate volume collected between 29 Aug. 2011 and 22 June 2012 from green roof modules. Data are means $\pm$ SE ($n = 3$). Where fertilizer rate effect was significant ($P < 0.05$), a solid line indicates the calculated regression.

result of green roof substrate saturation and rainfall intensity, respectively (Berndtsson, 2010; Monterusso et al., 2005; Teemusk and Mander, 2007). Preceding leachate collection, after thaw and rain events on Days 73 and 197, frozen water in the substrate or plant canopy was likely released to influence leachate volumes (Teemusk and Mander, 2007). Therefore, besides the effects of fertilizer rate, the frequency and intensity of rain storms as well as climatic conditions likely influenced green roof leachate quantity in this study. Although substrate thickness and type are known to influence green roof water retention (Berndtsson, 2010), fertilization can now also be considered a vital influence in runoff quantity for established (Clark and Zheng, 2014) and newly propagated green roofs. Therefore, during sedum-vegetated green roof module production, and direct-to-roof applications, calculations of leachate quantity should consider fertilization rate as an influencing factor. Further research is needed to evaluate the relationship among fertilization, plant biomass, and leachate quantity for commonly planted green roof systems.

Nutrient leaching. To prevent nutrient leaching and environmental pollution from green roofs during production, overfertilization must be avoided (Berndtsson, 2010;

Clark and Zheng, 2013, 2014). Although nutrient runoff levels in green roof and nursery crop production are regulated on a case-by-case basis, provincial and federal guidelines (e.g., Canadian Council of Ministers of the Environment, 2012; Ministry of the Environment and Energy, 1994) provide target levels to avoid environmental pollution from runoff water.

The total amount of NH_4^+ , K, calcium (Ca), magnesium (Mg), sulfur (S), sodium (Na), and iron (Fe) leached did not differ among treatments (Fig. 8A). The amount of NO_3^- leached was greater for the 30 and 35 treatments than treatments 20 or less and the control (Fig. 8B). The amount of P leached was greatest for the control and lower for the

Fig. 7. Volume of rain (bars) and leachate (symbols) collected from 0.2-m² green roof modules after fertilization with 0, 5, 10, 15, 20, 25, 30, or 35 g·m⁻² nitrogen (N) of Nutricote® Total 18N-2.6P-6.6K 100 d controlled-release fertilizer on 29 Aug. 2011. Bars and symbols represent the mean of three replications $\pm$ SE, respectively. Dashed lines indicate the start and end of the freeze-thaw period (shaded gray), whereas an asterisk (*) represents significant differences between the 35 and 0 (Control) treatments per time point ($P < 0.05$).

Fig. 8. Amount of each nutrient leached from green roof modules, between Sept. 2011 and June 2012, among all (A; $n = 24$) or individual (B; $n = 3$) treatments fertilized with Nutricote® Total 18N-2.6P-6.6K 100 d controlled-release fertilizer. A grouped mean was presented for nutrients having no difference among treatments (A), whereas differences among treatments were presented for NO_3^- , phosphorus (P), and zinc (Zn) (B). Error bars represent $\pm$ SE. Bars bearing the same letter are not significantly different at $P < 0.05$.

Fig. 9. Regression analyses of the effect of fertilizer (Nutricote® Total 18N-2.6P-6.6K 100 d controlled-release fertilizer) rate on leachate nutrient concentration from volume-weighted samples collected from green roof modules between Sept. 2011 and June 2012. Data are means $\pm$ SE ($n = 3$). Where fertilizer rate effect was significant ($P < 0.05$), a solid line indicates the calculated regression. Dashed lines mark the upper threshold to meet Canadian (i.e., NO₃⁻; Canadian Council of Ministers of the Environment, 2012) and Ontario [i.e., phosphorus (P), iron (Fe), and zinc (Zn); Ministry of the Environment and Energy, 1994] runoff water quality objectives.

30 and 35 than the 5 and 10 treatments, likely as a result of high P in the substrate and greater P uptake by sedum in the 30 and 35 than the lower fertilizer treatments (Fig. 8B). No zinc (Zn) was leached in treatments 25 or less (Fig. 8B) and more Zn was leached from the 35 than 30 treatment, likely as a result of more Zn applied than was required for plant growth (Clark and Zheng, 2013). No detectable amounts of aluminum, copper, cadmium, chromium, mercury, nickel, or lead were contained in leachate from any treatment.

Mean leachate NO₃⁻ and Fe concentrations for all treatments were below threshold limits for runoff water quality (Canadian Council of Ministers of the Environment, 2012; Ministry of the Environment and Energy, 1994; Fig. 9). However, leachate P concentration in all treatments and leachate Zn concentrations in the 30 and 35 treatments were above the provincial limit. Provincial concentration limits for Ca, K, Mg, Na, and S are not specified (Ministry of the Environment and Energy, 1994). We observed increasing leachate NO₃⁻, Fe, and Zn concentrations with increasing fertilizer rate, which was likely the result of overfertilization (Fig. 9; Chen et al., 2001). Leachate P amount and concentration decreased with increasing fertilizer rate relative to plant growth. Similar to the plant growth vs. fertilizer rate relationship outlined by Chen et al. (2001), our results suggest P application rate was adequate relative to plant growth at high fertilization rates, but P was overapplied, relative to plant growth, at low fertilizer rates. This overapplication of P likely resulted in the high levels of leached P at low fertilizer rates. Although adjusting the fertilizer rate alone may not prevent P leaching above threshold concentrations when using this growing substrate, fertilization at 20 g·m⁻² N would prevent the amount of leached NO₃⁻ from exceeding that of the control. Fertilizing at 20 g·m⁻² N would also

prevent NO₃⁻ and Zn from leaching in concentrations greater than threshold limits for runoff water quality (Canadian Council of Ministers of the Environment, 2012; Ministry of the Environment and Energy, 1994). Berndtsson et al. (2009) also found green roof growing substrate contributed to the amount of P leached from an extensive green roof as well as the amount of Zn leached for certain green roofs. Therefore, a substrate with a low P level, in combination with fertilizer that contains low P and Zn rates, should be used in the studied green roof system to minimize negative environmental effects of module production.

Conclusion

An appropriate fertilizer rate for green roof module production must minimize nutrient leaching to remain within legislated water quality guidelines while also providing appropriate nutrition for efficient plant growth to meet production timelines. With increasing fertilizer rate, leachate quantity decreased, compared with the control, for most nutrients. Only at rates of 20 or less and 25 g·m⁻² N or less were NO₃⁻ and Zn, respectively, leached at amounts no different from the control. Although leached P decreased with increasing fertilizer rate, leachate P concentrations, and Zn concentrations when fertilized above 30 g·m⁻² N, it remained above runoff water quality guideline limits (Canadian Council of Ministers of the Environment, 2012; Ministry of the Environment and Energy, 1994). Thus, fertilizing modules with 20 g·m⁻² N meets most nutrient leaching criteria while also reducing growing substrate P concentration. Plant growth, vegetative coverage, and overall appearance requirements can also be met by fertilizing modules with 20 g·m⁻² N and both leachate pH and EC did not differ from the control at the majority of time points after

fertilization with 20 g·m⁻² N. Although module production was faster with 25 g·m⁻² N or greater vs. 20 g·m⁻² N (i.e., 212 vs. 240 d), and cutting production would be delayed for *S. spurium* 'Dragon's Blood' and *S. sexangulare* after fertilization with 20 vs. 30 or 35 g·m⁻² N, 20 g·m⁻² N was the upper limit to ensure below-threshold nutrient runoff levels.

Overall, fertilizing newly propagated green roof modules in August at a rate of 20 g·m⁻² N is recommended to prevent negative environmental impacts from nutrient leaching, reduce leachate quantity compared with lower fertilizer rates, and encourage efficient plant growth for green roof module and sedum cutting production. In addition to environmental benefits, applying the optimum fertilizer rate will also benefit growers by keeping production costs low. Further research is needed to evaluate the effect of additional fertilizer types (i.e., sustainable and organic), fertilizer rates and release durations, green roof module components (i.e., substrate mixes and fertilizer types), and date of propagation on green roof module production timing. As well, further research is needed to identify fertilization schedules and production strategies (i.e., combining greenhouse propagation and outdoor nursery finishing, cutting application rates, etc.) to optimize green roof module and cutting production to help growers meet industry demands.

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