Research Reports

Green Roof Plant Suitability Analysis for Northern Climates

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SUMMARY. To select plant species and species combinations for northern climates, mats with different plant species and species combinations were constructed on a green roof plant production farm and later transported and installed on an urban rooftop. There were three treatments: two different planting combinations, which together consisted of 10 diverse plant species [both stonecrop (*Sedum*) species and nonstonecrop species], and a control, which consisted of 26 stonecrop species used for standard mat production. Growth measurements and observations were made at both sites and special attention was paid to the performance of species during the harvest, transportation, and installation stages, as well as during recovery post-installation. All species but false rock cress (*Aubrieta cultorum*) were found to be suitable for extensive green roof applications in northern climates, although there were variations of suitability among the species. Good, mediocre, and poor interactions formed between numerous species, displaying different levels of compatibility. Finally, all species were considered appropriate for a mat production system; species that failed to germinate, species planted postinstallation, the frequently displaced rolling hens and chicks (*Jovibarba sobolifera*), and false rock cress were exceptions. Overall, many species in this study displayed successful, well-rounded growth. Based on results, species and species combinations were recommended for extensive green roofs in northern climates.

Green roofs are being incorporated on buildings worldwide but there is a lack of information about plant species in terms of which are suitable for green roofs

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level in countries such as Germany (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, 2008). Germany and much of Europe are advanced in green roof knowledge and implementation (Dvorak and Volder, 2010). However, in North America, much more needs to be learned about creating successful green roofs that are specifically designed for its unique northern climate.

Green roofs are currently in high demand in North America (Carter and Fowler, 2008; Green Roofs for Healthy Cities, 2013). To both meet these demands and maintain the attention and satisfaction of the green roof market, various green roof research has been, and is still being, performed to improve the green roof industry. Such research includes studying the overwintering survival of stonecrop species treated with various rates of fertilizer (Clark and Zheng, 2012); determining the optimum growing substrate pH for commonly used stonecrop species (Zheng and Clark, 2013); testing the performance of native plants to meet legislative regulations for natural landmarks (Hollanda and Wrixon, 2012); surveying green roofs in Ontario, Canada, to identify successful plant species for northern climates (Vinson and Zheng, 2013a); and comparing different life-form groups of plant species native to eastern Canada (MacIvor and Lundholm, 2011). However, more research is needed, especially for different green roof production systems, in creating a reliable and accessible list of plant species and species combinations that green roof companies can incorporate into their product lines.

Currently, more information is required to provide growers, green roof companies, and green roof customers with a wider range of options for nonsucculent (e.g., nonstonecrop) plant species, especially perennials, that can be used on green roofs, specifically for extensive green roofs in northern climates. Determining which species do not, or may not, grow successfully

within a particular climate, how to use certain species in combination with other species, and which species are appropriate for specific production systems. Green roof regulations have reached the municipal level in cities such as Toronto, ON, Canada (City of Toronto, 2009) and the federal

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
2.54	inch(es)	cm	0.3937
6.4516	inch ²	cm ²	0.1550
305.1517	oz/ft ²	g·m ⁻²	0.0033

on green roofs will help eliminate the weaker species and form a robust list of useful species. MacIvor and Lundholm (2011) studied the percent vegetative roof coverage of plant species for green roofs in the Canadian Maritimes. The data from that study may be combined with data from this study to build toward a comprehensive guideline for green roof plant species usage in northern climates. With the use of plants comes maintenance, and therefore, costs; however, if species are chosen correctly so that they are not only suitable for the environmental and growing conditions of a green roof, but also well-suited for the surrounding plant species, then maintenance and costs can be reduced. Therefore, plant interactions must be studied to ensure a healthy and stable coexistence among species. Also, if nonsucculent, perennial species can be used successfully from the beginning of the green roof production stages, specifically for mat production, as opposed to being planted postinstallation of the green roof, then green roof installations can continue to provide instant greening. Providing instant greening without being restricted to the use of stonecrop species would be advantageous for a mat production system because it would mean that green roof companies could offer a wider selection of products to their customers (e.g., a variety of planting designs could be offered to address different visual and or ecological interests). This common green roof system uses prevegetated mats that typically consist (from bottom up) of a root barrier membrane, filter fabric, a layer of interconnected stands, growing substrate, and vegetation, and which measure only a couple of inches or less in thickness. Therefore, there is a need to test a variety of species in a mat production system to determine which species can grow on such shallow formats and endure the production practices leading up to and including installation; with this information the true convenience of the mats can be revealed.

If the mats can sustain various growth forms of different species, the application of mats for green roofs will be increased. This will help encourage more green roof installations, especially for roofs that are limited by load-bearing restrictions (i.e., applies to existing roofs being retrofitted and new roof projects that have insufficient

funds for building the stronger support structures necessary for heavier green roofs), and will create more sale opportunities for green roof production companies because the potential arises for green roofs to appeal to a larger audience. Therefore, there is an opportunity to use new plants on mats that, together, will satisfy the green roof market.

In this study, a variety of plant species and species combinations were grown in a green roof mat production system and installed on a rooftop for further evaluation. The objectives were to 1) determine the suitability of a diverse selection of plant species for use in extensive green roof projects located in northern climates, 2) determine compatibilities between species, and 3) determine the appropriateness of the species chosen for a mat production system.

Materials and methods

EXPERIMENT SETUP. This study had two stages: a mat production stage on a farm and a postinstallation stage on an urban rooftop. Mat production began in July 2010 on Sedum Master's farm (Princeton, ON, Canada) and concluded in the middle of June 2011. The mats were then immediately harvested, transported, and installed using conventional practices on

the rooftop of the Carrot Common building (348 Danforth Avenue, Toronto, ON, Canada), where the study continued until Apr. 2012.

At the production site, the mats (measuring 1 × 2 m) were laid in the field and filled with standard growing substrate [a mixture of brick, compost, sand, and coir (Sedum Master), so that the final thickness measured slightly less than 2 inches. There were three treatments (Table 1): species combination one, species combination two, and the Sedum Master mix [that contained gold moss stonecrop (*Sedum acre* 'Golden Carpet'), mossy stonecrop (*S. acre* 'Oktoberfest'), white stonecrop (*Sedum album*), orange stonecrop (*Sedum ellacombianum*), stonecrop (*Sedum floriferum*), forster's stonecrop (*Sedum forsterianum* ssp. *elegans* 'Silver Stone'), appalachian stonecrop (*Sedum glaucophyllum*), spanish stonecrop (*Sedum hispanicum*), mongolian stonecrop (*Sedum hybridum* 'Czar's Gold'), russian stonecrop (*Sedum kamtschaticum*), mountain stonecrop (*Sedum montanum*), stonecrop (*S. montanum* ssp. *orientale*), stonecrop (*Sedum obtusifolium* var. *listoniae*), european stonecrop (*Sedum ochroleucum*), oregon stonecrop (*Sedum oreganum*), sea star stonecrop (*Sedum pulchellum*), blue spruce stonecrop (*Sedum reflexum*), amur stonecrop (*Sedum selskianum*

Table 1. Plant species analyzed in the study, organized by treatment, and the application rates used for each species.

Treatments and associated species	Application methods	Application rates (g·m ⁻²) ^z
Combination one		
Rosy rock cress	seed	0.7
(Mountain sandwort) ^y , creeping chamomile	(seed), planted	(0.03)
Rolling hens and chicks	clusters	1221
Tricolor stonecrop	cuttings	1221
Creeping thyme	seed	0.2
(Thrift 'maritima splendens'), whitley's speedwell	(seed), planted	(0.03)
Combination two		
False rock cress	seed	0.7
Snow-in-summer	seed	0.5
(Mountain sandwort), creeping chamomile	(seed), planted	(0.03)
Soapwort	seed	2.5
Voodoo stonecrop	cuttings	1221
Sedum Master mix		
(Sedum Master, Princeton, ON, Canada)		
Various stonecrop species ^x	seed	0.7

^z1 g·m⁻² = 0.0033 oz./ft².

^yIn parentheses are species, and associated application rates, which did not germinate successfully at the production site and required replacement (postinstallation of the green roof mats at the new rooftop site). Replacement species, planted at the new site, follow the parentheses.

^xThe 26 different stonecrop species included in this mix are standard, commonly used species in green roof production.

‘Goldilocks’), tasteless stonecrop (*Sedum sexangulare*), spoon-leaved stonecrop (*Sedum spathulifolium*), purple carpet stonecrop (*Sedum spurium* ‘Coccineum’), two-row stonecrop (*S. spurium* ‘Summer Glory’), voodoo stonecrop (*S. spurium* ‘Voodoo’), yellow stonecrop (*Sedum stenopetalum*), stolon stonecrop (*Sedum stoloniferum*), and woodland stonecrop (*Sedum ternatum*)).

Each treatment had three replicates (with each replicate composed of three 1 × 2-m mats). The treatment replicates were arranged to form a completely randomized design.

Plant species for combinations one and two were chosen based on having a minimum U.S. Department of Agriculture hardiness zone 5, having a maximum height of ≈6–8 inches or less (i.e., to provide visual interest without risking too much damage brought on during harvest, transportation, and installation), having a perennial life cycle, being drought tolerant, being suitable for full sun, and having a shallow, nonaggressive root system (e.g., no tap roots). A variety of growth forms were also a factor in the decision process, ensuring that there was a mixture of different groundcovers and accent plants. Stonecrop species were incorporated within combinations one and two as well as exclusively for the Sedum Master mix to compare nonstonecrop species to stonecrop species that are commonly used in green roof production.

The planting designs for combinations one and two were prearranged so that certain species would interact and allow for interspecies compatibility analysis. Neighboring species within a treatment were analyzed as well as species that became neighbors because of displacement of plants and seeds.

On 12 July 2010, seeds were weighed and applied to the designated areas, based on the planting designs, at the appropriate seeding rate (Table 1). Seeds from each species within combinations one and two was separately added to standard, bulk-sized, empty spice containers and mixed with sand (White Lightning no. 2040; Bell & Mackenzie, Hamilton, ON, Canada) to encourage even seed distribution. The seeds for the Sedum Master mix were mixed together and applied evenly by hand over the designated mats. For most species, excluding those that require light for germination, a thin layer of sand was broadcast by hand overtop

to help bury the seeds and provide darkness for germination. Cuttings of stonecrop species and clusters of rolling hens and chicks for combinations one and two (Table 1) were applied on 24 Aug. 2010.

On 13 Apr. 2011, a 16N–2.6P–10.8K controlled-release fertilizer (POLYON® Homogenous NPK plus Minors, 3–4 month; Agrium Advanced Technologies, Brantford, ON, Canada) was applied at a rate of 94 g·m⁻² (i.e., 15 g·m⁻² nitrogen) to advance plant growth toward maturity in preparation for harvest, transportation, and installation.

MAINTENANCE AND IRRIGATION AT THE PRODUCTION SITE. All mats were weeded by hand and irrigated as needed using an overhead sprinkler system with local pond water.

HARVEST, TRANSPORTATION, AND INSTALLATION. All mats were harvested and transported to the Carrot Green Roof, located on the second story of the Carrot Common building, in downtown Toronto. Harvesting involved separating plants that grew onto neighboring mats, lifting the mats from the ground, and cutting through some of the plants when mats were cut into smaller sections. Mats were then stacked flat, or stacked as rolls, on pallets, transported to the site via transport truck, and taken to the roof via a winch lift. The roof’s flooring materials were (from top down) filter cloth, an insulation and drainage layer (3R Foam; Recycled Foam Technologies, Havre de Grace, MD), a water retention and root barrier layer (Platon Foundation Wrap; Armtex Limited Partnership, Guelph, ON, Canada), and the roof surface. The 46-m² plot was sectioned off using 6-inch-high aluminum edging (Nedlaw Living Roofs™; Nedlaw Roofing, Breslau, ON, Canada) and was filled with 4 inches of Gro-Coir Rooftop Mix (Gro-Bark, Waterloo, ON, Canada), selected by Carrot Common associates. The treatment replicates were installed in a completely randomized design on top of the Gro-Coir Rooftop Mix.

Creeping chamomile (*Chamaemelum nobile*) and whitley’s speedwell (*Veronica whitleyi*) plants, grown in 6- and 3-inch pots, respectively, were then added to the plot in the designated areas to replace two species, mountain sandwort (*Arenaria montana*) and thrift ‘maritima splendens’ (*Armeria maritima* ‘Splendens’),

respectively, which failed to germinate at the production site.

MAINTENANCE AND IRRIGATION ON THE ROOFTOP. For the first 6 weeks after installation, the plot was checked daily and irrigated by hand as required. After the sixth week, a 16N–2.6P–10.8K controlled-release fertilizer (POLYON® Homogenous NPK plus Minors, 3–4 month) was applied at a rate of 62.5 g·m⁻² (i.e., 10 g·m⁻² nitrogen) to boost plant establishment and the plot was both weeded and irrigated by hand as needed.

MEASUREMENTS AND OBSERVATIONS. Measurements and observations were performed about once per month both at the production site and on the rooftop throughout the growing seasons of 2010 (i.e., July–November) and 2011 (i.e., April–November), with final measurements and observations taken on 24 Apr. 2012. Three representative plants per species per replicate were chosen for height and canopy diameter measurements except rolling hens and chicks, which were too frequently displaced, and all stonecrop species, including the Sedum Master mix, which were excluded because the study was primarily focused on nonstonecrop species. Measurements began once the majority of plants had a minimum of four to six true leaves. Height was measured from the top of the growing substrate to the top of the plant, which included flower stalks when present, and canopy diameters were measured using the longest tips of the plant on opposite sides. Canopy diameters were measured twice, perpendicularly, per plant and used to determine each plant’s canopy with the equation for calculating the area of an ellipse [i.e., $A = (\pi \times d_1 \times d_2)/4$; where A represents the elliptical area, d_1 represents the first diameter, and d_2 represents the second diameter (perpendicular to d_1)], as this best represented the approximate canopy shape of the plants within each species studied. As plant sizes increased and individual plants merged together, it became difficult to distinguish between individual plants within a species, for most species. Therefore, eventually, small clumps of plants (i.e., tightly-spaced and or entangled individuals) were measured instead of individual plants for the necessary species.

Observations were made for both general performance ratings and percent vegetative mat coverage for each

species in each replicate, except for the Sedum Master mix that had an overall performance rating and percent vegetative mat coverage for each replicate. Performance ratings were based on visual appearance and ranged from 1 to 10, with one representing a species with both poor health and appearance, and 10 representing a species with both good health and appearance. Percent vegetative mat coverage was assessed visually for the designated areas of each species (i.e., based on the planting designs) and ranged from 0% to 100%. General visual observations were also recorded as necessary and often documented plant stress (e.g., physical flattening, wilting), damage, displacement (i.e., poor attachment to mats), postinstallation recovery and establishment, and emergence in spring; robustness of species; interspecies interactions; and the germination, rooting, or establishment of species from seeds, cuttings, or clusters, respectively. Photographs were taken to support observations.

Results and discussion

SPECIES SUITABILITY. For this study, plant species that were considered suitable to be used in green roofs in northern climates had the ability to recover from common stresses, such as drought-like conditions and standard green roof production practices, to establish quickly, and to not only withstand, but also to thrive under the intensified environmental conditions presented on rooftops, including the extreme temperatures of both winter and summer. Meeting such criteria confirmed that the species were suitable and therefore robust; however, there was variation in robustness between species.

All but one species (false rock cress) thrived postinstallation on the roof, with 100% winter survival (including false rock cress) and an absence of plant emergence difficulty in the spring. Figures 1A and B and 2A and B depict the vegetative growth of the species measured overtime. Variation of height and canopy within a species, other than immediately postinstallation, was mostly due to plant growth fluctuations throughout the growing season, for example, the presence or absence of flower stalks and plant dieback at the end of the season. Any remaining variation was minor and was attributed to the use of

Fig. 1. Height of plant species in treatment combination one (A) and treatment combination two (B). Each data point represents the mean of nine representative plant heights (i.e., three plant heights collected from each replicate within a treatment) $\pm$ SE. "Post-install" represents a species planted postinstallation of the green roof mats at the new rooftop site to replace another species that failed to germinate at the production site; 1 cm = 0.3937 inch.

different individuals for vegetative growth measurements. The ability of each species to recover, establish, and continue to thrive can be seen in these figures.

Rosy rock cress (*Arabis alpina* ssp. *caucasica*) was more robust than false rock cress, a comparable species; however, it had finished flowering before harvest, unlike false rock cress that was in bloom during harvest. Based on these results, only rosy rock cress was considered suitable for green roofs. False rock cress performed well

at the production site but displayed poor vigor during harvest, transportation, or both, possibly because it was flowering during these stress-inducing stages (Hura et al., 2007). False rock cress was also poor at recovering after installation and still lacked vigor months later with slow establishment. Therefore, false rock cress was considered unsuitable for green roofs.

Snow-in-summer (*Cerastium tomentosum*), soapwort (*Saponaria ocymoides*), and creeping thyme (*Thymus serpyllum*) recovered fairly

Fig. 2. Canopy of plant species in treatment combination one (A) and treatment combination two (B). Each data point represents the mean of nine representative plant canopies (i.e., three plant canopies collected from each replicate within a treatment) $\pm$ SE. "Post-install" represents a species planted postinstallation of the green roof mats at the new rooftop site to replace another species that failed to germinate at the production site; 1 cm² = 0.1550 inch².

quickly and established well on the rooftop. All three species were suitable.

Both creeping chamomile and whitley's speedwell established well once planted on the rooftop and proved to be suitable for green roofs. Although these species did not have to recover from green roof production practices like the rest of the species, they still performed well during extremely hot and dry periods of the 2011 growing season.

Tricolor stonecrop (*S. spurium* 'Tricolor') and voodoo stonecrop were both suitable. Both species performed well overall during harvest, transportation, and installation and recovered

quickly from harvest and transportation stress, as did many other stonecrop species (e.g., species in the Sedum Master mix). Based on observations, these species remained well established on the mats and did not have to become reestablished like some of the other nonstonecrop species. In addition, immediately after installation, both species appeared less stressed than most other nonstonecrop species, with the exception of the planted creeping chamomile and whitley's speedwell.

Finally, rolling hens and chicks was also considered suitable. Because of its tough, succulent structure, its

performance resembled that of tricolor stonecrop and voodoo stonecrop in that the plants had undergone a quick recovery and showed minimal stress postinstallation.

More research needs to be completed to study the survival and overall success of a variety of perennial plant species undergoing the major stresses of common green roof plant production practices (e.g., harvest, transportation, and installation) to uncover additional suitable species.

COMPATIBILITIES BETWEEN SPECIES.

The term "compatible," when used to describe the relationship between two species in this study, means that neither species was harmed, nor appeared to be at risk of being harmed by the other species. Compatible species often have growth forms and aggression levels or growth rates that complement each other. For example, a tall species with a medium growth rate may be compatible with a short species with a fast growth rate. To contrast, a short or medium-height species with a medium or slow growth rate may be incompatible with a medium-height or tall species with a fast growth rate. These examples, however, are not always the case; a study analyzing the interactions between stonecrop and nonstonecrop species found that the shorter stonecrop species were detrimental to some of the taller nonstonecrop species because of the fast and opportunistic growth of the stonecrop species (Vinson and Zheng, 2013b). Therefore, caution should be taken when planning the planting combinations.

Table 2 outlines all of the species interactions that were observed based on the following criteria. Good interactions involved two species that were compatible, as described earlier; mediocre interactions involved two species that were neither completely compatible nor completely incompatible, but there was potential for the interaction to become detrimental to at least one of the species; and poor interactions involved two species that were incompatible.

GOOD SPECIES INTERACTIONS.

Rosy rock cress and creeping thyme complemented each other well because they became equally well established and the individual plants of creeping thyme were dense enough to avoid competition from the individuals of rosy rock cress.

Table 2. Quality ratings of the interspecies interactions observed during the study.

	Rosy rock cress	False rock cress	Snow-in-summer	Creeping chamomile	Rolling hens and chicks	Soapwort	Tricolor stonecrop	Voodoo stonecrop	Creeping thyme	Whitley's speedwell
Rosy rock cress	—	— ²	—	—	—	—	—	—	G	G
False rock cress	—	—	P	—	—	P	—	—	—	—
Snow-in-summer	—	P	—	M	—	M	—	—	—	—
Creeping chamomile	—	—	M	—	M	P	P	—	M	—
Rolling hens and chicks	—	—	—	M	—	—	—	—	—	M
Soapwort	—	P	M	P	—	—	—	M	—	—
Tricolor stonecrop	—	—	—	P	—	—	—	—	—	—
Voodoo stonecrop	—	—	—	—	—	M	—	—	—	—
Creeping thyme	G	—	—	M	—	—	—	—	—	—
Whitley's speedwell	G	—	—	—	M	—	—	—	—	—
Stonecrop species (similar height to neighboring species)	M	—	—	—	—	—	—	G	—	—
Stonecrop species (similar/larger height than neighboring species)	—	—	—	—	—	—	—	—	M	—
Stonecrop species (various species with different heights/growth rates)	—	P	M	P	P	—	—	—	—	P
White stonecrop	P	—	M	P	P	—	—	—	—	—

G = Good interactions, involved two species that were compatible; M = mediocre interactions, involved two species that were neither completely compatible nor completely incompatible but there was potential for the interaction to become detrimental to at least one of the species; and P = poor interactions, involved two species that were incompatible.

²No interaction occurred between the two intersecting species in the table.

Rosy rock cress and whitley's speedwell were also compatible (Fig. 3). Whitley's speedwell was a shorter species with a fast growth rate, and rosy rock cress was a taller species with a medium growth rate. Neither of the species outcompeted the other and this species interaction was possibly the most compatible of all species interactions in this study.

Voodoo stonecrop and other groundcover stonecrop species of similar height came in contact with one another in some cases likely due to seed dispersal of preexisting stonecrop species, displaced stonecrop cuttings, or both. The random, non-designated stonecrop species were tall enough to survive within the areas dominated by voodoo stonecrop but were not overly competitive (Fig. 4).

MEDIOCRE SPECIES INTERACTIONS.

Rosy rock cress was slightly compatible with groundcover stonecrop species of similar height, such as two-row stonecrop cultivars, but as all plants became larger and denser, it was speculated that at least some of the stonecrop species may restrict the growth of rosy rock cress during growing seasons in the near future.

Snow-in-summer and soapwort were compatible to some extent; however, soapwort grew more quickly than snow-in-summer, especially during the spring after the first winter on the rooftop.

Snow-in-summer and various groundcover stonecrop species were compatible only if snow-in-summer was densely massed. Some of the shorter stonecrop species (e.g., white stonecrop) attempted to spread into the masses of snow-in-summer by crowding the spaces at the edges of a mass (Fig. 5). Therefore, snow-in-summer also needed to be well established before interacting with the stonecrop species.

Creeping chamomile and snow-in-summer were initially compatible, but it was speculated that snow-in-summer could soon (i.e., within the 2012 or subsequent growing seasons) flow overtop of creeping chamomile during early or late season when there was an absence of creeping chamomile flower stalks that would help prevent it.

Rolling hens and chicks and creeping chamomile came in contact via seed dispersal by creeping chamomile. The two species displayed compatibility

Fig. 3. An example of the interaction observed between rosy rock cress (1) and whitley's speedwell (2), rated as a good species interaction.

Fig. 4. An example of the interaction observed between voodoo stonecrop (1) and other groundcover stonecrop species of similar height (2), rated as a good species interaction.

during early spring while the creeping chamomile seedlings were short; however, the seedlings quickly gained height later in the season, shading some of the rolling hens and chicks. Because of the ease and high quantity of seed dispersal by creeping chamomile, it was speculated that more

rolling hens and chicks could quickly become surrounded and shaded by creeping chamomile, thus threatening the robust growth of rolling hens and chicks.

Soapwort and voodoo stonecrop combined fairly well; however, soapwort grew more quickly than voodoo

stonecrop and began to gradually spread into the area occupied by voodoo stonecrop. No detrimental effects to voodoo stonecrop by soapwort were observed, but with time, due to the observed fast growth rate of soapwort, voodoo stonecrop growth could be negatively affected.

Creeping thyme and creeping chamomile were almost compatible, but there appeared to be a risk of creeping thyme growing slightly too quickly for creeping chamomile, especially during times when the flower stalks of creeping chamomile were absent, thus making it shorter than creeping thyme and at risk of being covered by its competitor.

Creeping thyme and groundcover stonecrop species of similar or larger heights, such as tricolor stonecrop and voodoo stonecrop, displayed mediocre interactions when both species were about equal in height at the beginning of the growing season. It was speculated that with progression of the growing season, the stonecrop species will grow taller than creeping thyme, especially when creeping thyme is without flower stalks, and therefore place creeping thyme in danger of being restricted by some stonecrop species.

Whitley's speedwell did not damage rolling hens and chicks, but it was highly possible that the spreading stems might cover some of the rolling hens and chicks rosettes as whitley's speedwell kept growing. During the final observations, whitley's speedwell had begun to creep over the edges of some rosettes (Fig. 6). If these species are to be used together, it may be worthwhile to mound the growing substrate where rolling hens and chicks will be planted (i.e., postinstallation) and to plant rolling hens and chicks densely on the mound to help reduce any risk of being covered by whitley's speedwell.

POOR SPECIES INTERACTIONS.

Rosy rock cress and white stonecrop were highly incompatible. White stonecrop crowded the base of rosy rock cress and grew up the stems to avoid being shaded. The fast and opportunistic growth of white stonecrop will eventually lead to weakened growth and possibly the death of rosy rock cress.

Only a few plants of false rock cress interacted with snow-in-summer. Those which did were sparse and

Fig. 5. An example of the interaction observed between snow-in-summer (1) and various groundcover stonecrop species (2), rated as a mediocre species interaction.

Fig. 6. An example of the interaction observed between whitley's speedwell (1) and rolling hens and chicks (2), rated as a mediocre species interaction.

single, as opposed to being in clumps, and therefore were restricted and vulnerable to being completely covered by snow-in-summer.

False rock cress also combined poorly with soapwort because of its lack of vigor, small size, and slower growth rate, compared with soapwort.

Soapwort shoots grew quickly to surround and cover some of the false rock cress plants without any competition, because it had additional advantages of recovering from stress and establishing quickly and having a fast growth rate.

False rock cress was not robust enough to be combined with various

groundcover stonecrop species because it displayed poor vigor and slow recovery. The result of these interactions was growth restrictions for false rock cress.

Creeping chamomile and soapwort interacted poorly due to the long and tall branches of soapwort that easily covered the basal foliage of creeping chamomile. By speculation, creeping chamomile had an increased risk of being covered during early spring and late fall when its flower stalks were either absent or senesced.

Creeping chamomile and various groundcover stonecrop species interacted poorly due to the low basal foliage of creeping chamomile that stonecrop species can either climb, causing shade (e.g., tricolor stonecrop), or can grow in between and crowd (e.g., white stonecrop and tasteless stonecrop) (Fig. 7).

Rolling hens and chicks and various groundcover stonecrop species interacted poorly because rolling hens and chicks was used in small groups as an accent species and lacked both the quantity of growth, especially height, and the speed of growth that was presented by the stonecrop groundcovers. As an example, Fig. 8 shows how rolling hens and chicks was crowded and overgrown by the fast and opportunistic white stonecrop.

Whitley's speedwell is low-growing and was vulnerable to being overtaken when planted near various groundcover stonecrop species. Many stonecrop species can grow too fast and may climb and cover whitley's speedwell causing shade, weakened growth, and possibly death. This type of growth seen in many stonecrop species, and the negative effects caused to other nonstonecrop species, were frequently noted in a similar species interactions study by Vinson and Zheng (2013b). Therefore, planting combinations of whitley's speedwell and stonecrop species, especially taller stonecrop species, is not recommended.

Note that the poor species interactions listed earlier do not necessarily mean that the species cannot be used together. For example, if the slower growing species is well established and matured to a sufficient size, then it may stand a better chance against the faster growing species; this is important for both the production site and postinstallation on the roof, and may create the need to plant the faster growing species at a later time,

Fig. 7. An example of the interaction observed between creeping chamomile (1) and various groundcover stonecrop species (2), rated as a poor species interaction.

Fig. 8. An example of the interaction observed between rolling hens and chicks (1) and various groundcover stonecrop species (2), [e.g., white stonecrop (3)], rated as a poor species interaction.

possibly even postinstallation. Also, if used together, they will most likely require frequent maintenance, such as cutting the fast growing plants back to an appropriate size. Extra caution and frequent monitoring of these species, if used together, is highly recommended.

Finally, note that there is always a chance that some of the species interactions mentioned here will evolve and belong to a different category (e.g., change from compatible to incompatible or vice versa). Therefore, it is important that future green roof experiments

study the long-term species relationships and interactions as green roofs mature. It is also important for green roof maintenance personnel to monitor species for evolutions in their interactions because thinning or cutting back of aggressive species may be required to ensure better plant survival. To be preventative, it may be best to pair aggressive species with other species that are equally aggressive, tall enough, or both to avoid being overtaken by the initial species.

APPROPRIATENESS OF THE SPECIES CHOSEN FOR A MAT PRODUCTION SYSTEM. To be classified as appropriate for a mat production system, a species must grow successfully on the mats from the start of production to post-installation of the green roof. In the beginning of production, the species must be able to germinate, root, or establish successfully from seeds, cuttings, or clusters, respectively; species that accomplish this quickly are most favorable to growers because it reduces the time taken to produce a salable mat. The species must then be able to withstand common production practices, including harvesting, transporting, and installing the mats, during which the plants are often flattened and stressed. Postinstallation, species need to be able to recover from the environmental and physical stresses that they had recently undergone.

Another important quality is that the species must be able to establish and spread fairly quickly so that the mats can attain rapid plant coverage for visual appeal and to reduce weed establishment.

Finally, species must have an appropriate root system. A somewhat sufficient root system is necessary to help keep the plants attached and anchored to the mats during external disturbances.

All seeded species germinated successfully, with the exception of mountain sandwort and thrift ‘maritima splendens’ that were later replaced (postinstallation), and all species applied by cuttings and clusters rooted and established successfully, although the clusters took slightly longer than the cuttings.

As discussed earlier for plant suitability, all species, except false rock cress, were successful at recovering quickly from the harvest, transportation, and installation stresses and were able to establish well at the new site.

Fig. 9. Percent vegetative mat coverage of a species in its designated area, measured for species in treatment combination one (A), treatment combination two (B), and the Sedum Master mix (Sedum Master, Princeton, ON, Canada) treatment (C). Each data point in A and B represents the mean of all three replicates of a species within a treatment $\pm$ SE, and each data point in C represents the mean of all three replicates of the Sedum Master mix treatment $\pm$ SE. "Post-install" represents a species planted postinstallation of the green roof mats at the new rooftop site to replace another species that failed to germinate at the production site.

Creeping chamomile and whitley's speedwell also quickly established on the roof (Fig. 9A and B). Snow-in-summer and soapwort, as well as tricolor stonecrop and voodoo stonecrop, rapidly covered their designated areas during production and after installation (Fig. 9A and B). Rosy rock cress and creeping thyme were able to increase their coverage as well, but at slower rates, especially postinstallation due to the stress that was caused (i.e., from harvest, transportation, and installation); rolling hens and chicks lost and displaced too many individuals (i.e., during harvest, transportation, and installation) to show any increase in coverage; and false rock cress showed a steady increase in coverage, but only preharvest because there was a reduction in vigor and growth postinstallation (Fig. 9A and B).

By comparing the percent vegetative mat coverage of the Sedum Master mix (Fig. 9C) with that of the non-stonecrop species in combinations one and two (Fig. 9A and B), it can be seen that, from seed, stonecrop species were able to reach a high percent vegetative mat coverage (e.g., 100%) faster than the nonstonecrop species. Only snow-in-summer and soapwort closely resembled the strong and constant increase of the Sedum Master mix's percent vegetative mat coverage. Stonecrop species often have the advantage of rapid coverage, but nonstonecrop species can eventually reach full coverage as well.

Shown in Fig. 10A and B, the effects of the harvest, transportation, and installation on the plants are obvious through the performance ratings (i.e., the immediate reduction in performance ratings for many species). Again, comparing the performance ratings of the Sedum Master mix (Fig. 10C) with those of the nonstonecrop species in combinations one and two (Fig. 10A and B), it is clear that the Sedum Master mix was unaffected much or at all by harvest, transportation, and installation, whereas the nonstonecrop species were strongly affected. All species were negatively affected by these stresses, except for most of tricolor stonecrop and voodoo stonecrop, because of their naturally tough and succulent structure, and creeping chamomile and whitley's speedwell because of their post-installation planting. Performance ratings for creeping thyme (Fig. 10A,

Fig. 10. Performance ratings of each species in treatment combination one (A), treatment combination two (B), and the Sedum Master mix (Sedum Master, Princeton, ON, Canada) treatment (C). Performance ratings were based on visual appearance and ranged from 1 to 10, with one representing a species with both poor health and appearance, and 10 representing a species with both good health and appearance. Each data point in A and B represents the mean of all three replicates of a species within a treatment $\pm$ SE, and each data point in C represents the mean of all three replicates of the Sedum Master mix treatment $\pm$ SE. "Post-install" represents a species planted postinstallation of the green roof mats at the new rooftop site to replace another species that failed to germinate at the production site.

postinstallation) did not display any negative effects because the plants were able to recover quickly before the first observation was made postinstallation.

Based on observations, the root systems of all species, except rolling hens and chicks, were well suited for the mats because they proved to do well at anchoring the plants to the mats. Rolling hens and chicks did not perform well because the plants were easily displaced and shifted too much during harvest, transportation, and installation, resulting in the loss of some plant material. Because of this, height and canopy data were not collected for this species. To be more efficient, this species should be planted after the mats are installed.

All species, except false rock cress, rolling hens and chicks, and most certainly, mountain sandwort and thrift 'maritima splendens', were found to be appropriate for use in a mat production system. Because creeping chamomile and whitley's speedwell were planted after the mats were installed, future research is needed to determine their suitability as seed-propagated species in a mat production system.

All species, with the obvious exception of creeping chamomile and whitley's speedwell, were crushed from rolling and stacking of the mats; however, most species returned to their normal state once installation was complete and time was given for recovery. Reducing the time that mats are rolled or stacked, either by reducing transport time and or reducing the time between delivery and installation, may help maximize plant recovery and survival.

Because of the inevitable but temporary crushing of plants, proper species selection is crucial. Species with excessive heights, with rigid stems, and or with delicate foliage would not be appropriate for mat production unless rolling and stacking was avoided and or unless the mats were harvested, transported, and installed before plants emerged in spring. Although this results in a slight reduction in overall species selection for mat production, there is still a vast quantity of species to be explored for this application.

Conclusion

With the exception of false rock cress, all species were found to be suitable for use in extensive green roof

applications in northern climates, specifically in the area of southwestern Ontario. Further research is needed to extend the list of suitable species. Overall, the species that showed one of the greatest compatibilities were rosy rock cress and whitley's speedwell; the growth rates and growth forms of each species were found to complement each other. In comparison, the species that showed one of the greatest incompatibilities were creeping chamomile and various ground-cover stonecrop species; the short basal foliage of creeping chamomile could not compete well enough with the fast growing stonecrop species, which caused shading and crowding at the bases of creeping chamomile. All seeded species, except mountain sandwort and thrift 'maritima splendens', were appropriate for a mat production system, as were cutting-propagated tricolor stonecrop and voodoo stonecrop. Rolling hens and chicks, applied with clusters, was inappropriate due to substantial displacement on the mats, especially throughout the production process. The appropriateness of creeping chamomile and whitley's speedwell for mats was undetermined because of postinstallation planting of both species.

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