Plants with Horticultural and Ecological Attributes for Green Roofs in a Cool, Dry Climate

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Abstract. Green roofs are building surface treatments where plants are grown in medium on a rooftop to cool or insulate buildings and/or to ameliorate negative environmental impacts of buildings. We initiated a 2-year study to characterize medium and weather conditions on a rooftop in a cool-dry climate and to identify plant species with horticultural and ecological attributes that survive and thrive on an unirrigated semi-intensive green roof in a cool-dry climate. Eighty-eight cold-hardy, drought-tolerant species with horticultural or ecological attributes were identified and planted into 12.7-cm-deep medium in trays that were placed on a rooftop. Medium temperatures and moistures were recorded, and plant survival and vigor were quantified. Hourly medium temperature varied from –73.3 to 21.7 °C, 44% to 80%, and from 206 to 1222 μmol·m−2·s−1. Mean survival scores decreased (4 = 100% survival) from 2.6 with grasses, to 2.3 with succulents, to 1.8 with temperate perennials, to 0 for geophytes (all died). Among grasses, temperate perennials, to 0 for geophytes (all died). Among grasses, temperate perennials, to 0 for geophytes (all died).

An unirrigated extensive green roof can be a challenging environment for plants to grow in as temperature, light, wind, and/or drought stresses are more severe and/or frequent on a rooftop than in-ground plantings (Brown and Lundholm, 2015; Dunnett and Kingsbury, 2004; Shafique et al., 2018). Because weather can differ with region, which species perform well on a rooftop in different regions can vary (Dvorak and Volder, 2010; Getter and Rowe, 2008; Shafique et al., 2018). Many green roof studies have been conducted in temperate regions of North America and Europe often moderated by water bodies (Getter and Rowe, 2006; Köhler, 2006). Recommended species varied tremendously among sites and included species as diverse as succulents, grasses, and mosses. However, many species recommended for extensive green roof systems from these studies die on rooftops in the north-central region of the United States (Minneapolis-St. Paul, MN; personal observation). Little information is available on which species survive and thrive on an extensive green roof system in a dry, northern climate such as Minneapolis, MN.

Aside from identifying which species survive and thrive on a rooftop in a cool, dry climate, there is increasing interest in identifying plant species that provide aesthetic and/or ecological benefits to a rooftop (Nagase and Dunnett, 2012; Speak et al., 2012). Different plant species can provide color and/or texture to a roof, can capture air particulates, can be edible, and/or can support pollinators or other native insects such as butterflies (Baraldi et al., 2018). A mix of species on a roof can deliver multiple aesthetic and ecological outcomes (Lundholm, 2015; Lundholm et al., 2010). We initiated a multiyear study to 1) characterize medium and weather conditions on a rooftop in a cool-dry climate and to 2) identify plant species with horticultural and/or ecological attributes that survive and thrive on an unirrigated extensive green roof in a cool-dry climate.

Materials and Methods

On 11 Apr., 88 reportedly cold-hardy and drought-tolerant species with horticultural (ornamental or edible) or ecological (support wildlife) attributes were identified (Table 1). Plants or seed of each were received from different sources and were divided and planted or sown in 38-cell plug sheets (individual cell volume = 15 cm³; Landmark Plastics, Akron, OH) filled with a soilless medium (Sunshine SB 500 High-Porosity Growing Medium, SunGro Horticulture, Bellevue, WA). Planted/sown trays were placed in a greenhouse with a 27 °C air temperature to achieve a 24 to 26 °C medium temperature. Unrooted cuttings and sown seed were misted 6 sec every 8 min; divisions were watered as needed. Once germinated or rooted, plants were fertilized weekly with 14.3 mm N from Peter’s Excel 15–5–15 Cal-Mag through the irrigation water (The Scotts Company, Marysville,
| Species Received | Desirable trait | Vigor | Yr | Source |
|------------------|----------------|-------|----|--------|
| Achillea millefolium 'Paprika' | Vegetative | O,H,E | G | 1 | Linder's |
| Agastache foeniculum | Seed | O,H | G | 2 | Linder's |
| Ajuga reptans 'Bronze Beauty' | Vegetative | O | G | 1 | Bailey's |
| Allium cernuum | Vegetative | O,H,E | G | 2 | Bluebird |
| Allium senescens 'Glaucum' | Vegetative | O,H | G | 1 | Bailey's |
| Antennaria dioica 'Rubra' | Vegetative | O,H,F | G | 2 | Bluebird |
| Aquilegia vulgaris | Vegetative | O,F | G | 1 | Bailey's |
| Artemisia ludoviciana 'Valerie Finnis' | Vegetative | O,F | G | 1 | Bailey's |
| Aster alpinus 'Dunkle Schone' | Vegetative | O,H | G | 2 | Bluebird |
| Bergenia cordifolia | Vegetative | O,F | G | 2 | Bluebird |
| Briza media | Vegetative | O,F | G | 2 | Bluebird |
| Calamagrostis ×acutiflora 'Karl Foerster' | Vegetative | O,F | G | 2 | Bluebird |
| Campanula portenschlagiana | Vegetative | O | G | 2 | Bluebird |
| Chasmanthium latifolium | Vegetative | O,F | G | 2 | Bluebird |
| Coixus 'Siculus' | Bulb | O | C | 1 | Linder's |
| Coixus tommasinianus 'Ruby Giant' | Bulb | O | C | 1 | Linder's |
| Dalea purpurea | Seed | O,H | G | 2 | Linder's |
| Festuca arundinacea 'Raptor' | Vegetative | O,F | G | 1 | UMN Turf |
| Festuca ovina var. commutata 'Jamestown II' | Vegetative | O,F | G | 1 | UMN Turf |
| Festuca rubra var. commutata 'Jamestown II' | Vegetative | O,F | G | 1 | UMN Turf |
| Gresn triforum | Vegetative | O,H | G | 2 | Bluebird |
| Hemerocallis 'Stella d'Oro' | Bulb | O | C | 1 | Linder's |
| Ipheion uniflorum | Bulb | O | C | 1 | Linder's |
| Iris reticulata 'Joyce' | Bulb | O | C | 1 | Linder's |
| Koeleria macrantha 07-901 ND | Vegetative | O,F | G | 1 | UMN Turf |
| Leptinella squilida 'Platt's Black' | Vegetative | O | G | 1 | Bailey's |
| Linum perenne | Seed | O,H | G | 2 | Linder's |
| Lychnis chalcedonica | Seed | O,H | G | 2 | Linder's |
| Mentha piperita | Vegetative | O,H,E | G | 2 | Bailey's |
| Mentha spicata | Vegetative | O,H,E | G | 2 | Bailey's |
| Narcissus bulbocodium var. conspicuus 'Golden Bells' | Bulb | O | C | 1 | Linder's |
| Narcissus cyclamineus 'Jetfire' | Bulb | O | C | 1 | Linder's |
| Narcissus 'Tete e Tete' | Bulb | O | C | 1 | Linder's |
| Nectaroscordum siculum | Vegetative | O,H | G | 1 | Bailey's |
| Papaver alpinum | Seed | O,F | G | 2 | Linder's |
| Papaver alpinum | Vegetative | O,G,C | G | 2 | Bluebird |
| Pulsatilla vulgaris | Vegetative | O | G | 2 | Bluebird |
| Ratibida columnifera | Seed | O,H | G | 2 | Linder's |
| Rudbeckia fulgida 'Goldsturm' | Vegetative | O,H | G | 1 | Bailey's |
| Salvia verticillata 'Purple Rain' | Vegetative | O,H | G | 1 | Bailey's |
| Saxifraga xarensidis 'Highlander Rose Shades' | Vegetative | O | G | 2 | Bailey's |
| Scilla siberica | Bulb | O | C | 1 | Linder's |
| Sedum acre | Vegetative | O,F | G | 1 | Altman |
| Sedum album 'Coral Carpet' | Vegetative | O,F | G | 1 | Altman |
| Sedum album 'Murale' | Vegetative | O,F | G | 1 | Altman |
| Sedum 'Blue Lagoon' | Vegetative | O,F | G | 1 | Altman |
| Sedum 'Blue Spruce' | Vegetative | O,F | G | 1 | Altman |
| Sedum caucicum 'Sunset Cloud' | Vegetative | O,H,F | G | 1 | Altman |
| Sedum 'Czar's Gold' | Vegetative | O,F | G | 1 | Altman |
| Sedum dasyphyllum 'Major' | Vegetative | O,F | G | 1 | Altman |
| Sedum elscobianum | Vegetative | O,H,F | G | 1 | Altman |
| Sedum forsterianum 'Elegans Silverstone' | Vegetative | O,F | G | 1 | Altman |
| Sedum glaucophyllum | Vegetative | O,F | G | 1 | Altman |
| Sedum hispanicum | Vegetative | O,F | G | 1 | Altman |
| Sedum hispanicum 'Minor Aureum' | Vegetative | O,F | G | 1 | Altman |
| Sedum hybridum 'Immergrehlen' | Vegetative | O,F | G | 1 | Altman |
| Sedum kamschaticum 'Takahira Dake' | Vegetative | O,F | G | 1 | Altman |
| Sedum lineare | Vegetative | O,F | G | 1 | Altman |
| Sedum mexicanum | Vegetative | O,F | G | 1 | Altman |
| Sedum oreganum | Vegetative | O,F | G | 1 | Altman |
| Sedum reflexum 'Green Spruce' | Vegetative | O,F | G | 1 | Altman |
| Sedum requieni | Vegetative | O,F | G | 1 | Altman |
| Sedum rupestre 'Angelina' | Vegetative | O,F | G | 1 | Altman |
| Sedum sexangulare | Vegetative | O,F | G | 1 | Altman |
| Sedum spectabile 'Brilliant' | Vegetative | O,H,F | G | 1 | Altman |
| Sedum spurium 'Dragon's Blood' | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium 'Fuldaglut' | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium 'John Creech' | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium 'Pearly Pink' | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium 'Purple Carpet' | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium 'Ruby Mantle' | Vegetative | O,F | G | 1 | Altman |

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Table 1. (Continued) Species and cultivars used in this study including method of plant receipt and propagation, desirable trait or attribute, method of vigor assessment, year of study, and source.

| Species | Received | Desirable trait | Vigor | Yr | Source |
|---------|----------|----------------|-------|----|--------|
| Sedum spurium ‘Summer Glory’ | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium ‘Tricolor’ | Vegetative | O,F | G | 1 | Altman |
| Sedum spurium ‘Voodoo’ | Vegetative | O,F | G | 1 | Altman |
| Semprevivum arachnoideum ‘Cebeneese’ | Vegetative | O | G | 1 | Altman |
| Semprevivum arachnoideum ‘Stansfieldii’ | Vegetative | O | G | 1 | Altman |
| Semprevivum calceolus ‘Sir William Lawrence’ | Vegetative | O | G | 1 | Altman |
| Sempervivum sp. ‘Maryvantic’ | Vegetative | O | G | 1 | Altman |
| Sporobolus heterolepis | Vegetative | O,H,F | G | 2 | Bluebird |
| Talinum calycinum | Vegetative | O,H | G,C | 2 | Bluebird |
| Thalictrum kiusianum | Vegetative | O | G | 1 | Bailey’s |
| Thysanotus praecox ‘Red Creeping’ | Vegetative | O,E | G | 1 | Bailey’s |
| Trifolium repens ‘Atropurpureum’ | Vegetative | O | G | 1 | Bailey’s |
| Tulipa humilis | Bulb | O,C | G | 1 | Linder’s |
| Verbena stricta | Seed | O,H | G | 2 | Linder’s |

C = count measurement; E = edible; F = ecological function; G = grid measurement; H = habitat; O = ornamental.

*Plant sources: Altman = Altman Plants, Vista, CA; Bailey’s = Bailey’s Nursery, Newport, MN; Bluebird = Bluebird Nursery, Clarkson, NE; Linder’s = Linder’s Garden Center, St. Paul, MN; UMN Turf (University of Minnesota Turf Breeding Laboratory, St. Paul, MN).

OH; 15N–2.2P–12.5K). Plants were irrigated with clear water on an as-needed basis otherwise. Plants were grown in the greenhouse until 21 June (Year 1) or 29 June (Year 2).

Four rooted plants of each species in cells were then transplanted (15–20 cm apart) into a soilless medium in extensive green roof tray [36 cm (length) × 36 cm (width) × 12.7 cm (depth); American Horticultural Supply, Oxnard, CA] with a perforated bottom. The soilless medium was composed of Hortifiber rockwool (J.R. Johnson Supply, Roseville, MN), expanded shale aggregate (Rehbein Environmental Solutions, Inc., Minneapolis, MN), and SunGro Horticulture’s Sunshine SB 500 high-porosity growing medium (SunGro Horticulture, Bellevue, WA) in a mixed ratio of 1:1:2 by volume, respectively. This medium provided high water-holding capacity (rockwool) and weight (shale aggregate) while maintaining good porosity and cation exchange capacity (peat) to promote root growth (Kazemi and Mohorko, 2017). Plants were grown in these trays for 2 weeks to allow plants to root into the medium (roots hit the edge of the tray) before being placed onto an experimental rooftop (Williamson Hall, University of Minnesota, Minneapolis, MN) on 5 and 13 July (Years 1 and 2, respectively). Trays were randomly spaced (108 cm apart in staggered rows) on the rooftop in a grid fashion within four blocks arranged 36 cm × 36 cm × 12.7 cm. Blocks were aligned along the longer length of the roof to control for a perceived potential gradient in irradiance, wind and/or precipitation.

Tray medium temperature and moisture levels were recorded on two trays in each block using Spectrum Technologies WatchDog 200 Series dataloggers with an attached soil temperature and Watermark soil moisture sensor (Gypsum block; Spectrum Technologies, Inc., Plainfield, IL) starting when trays were placed on the roof. Soil moisture data ranged from 0 to 200 cbar with 0 to 10 cbar representing saturated soil and 100 to 200 cbar representing dangerously dry –1 kPa = 1 cbar; therefore, data here are referred to in kPa. Data were collected every 30 min, and hourly averages were recorded. Media samples were collected initially and on 5 Aug. and 5 Sept. in Year 1, and on 13 Aug. and 13 Sept. in Year 2 to determine media pH and EC. A Spectrum Technologies WatchDog 2000 Series Weather Station was mounted 2 m above plants on the roof to collect and record air temperature, relative humidity, solar radiation, and precipitation (liquid only) every thirty min.

Starting 20 May (Year 1) and 18 June (Year 2) (≈1 month after initiation of above-ground growth) the year after plants were placed on the rooftop, plants were evaluated for survival and vigor. Individual plant survival data were collected using a four-point rating system where 1 = no survival, 2 = some survival, 3 = moderate survival, and 4 = complete survival. A qualitative point-based measure was used to quantify plant vigor because traditional height/width measurements among species with different growth habits made species vigor comparisons difficult (Monterusso et al., 2005). Specifically, vigor was evaluated on each tray (not plant) with a point frame transect as described by Durham et al. (2007) and Dewey et al. (2004) with a point frame (36.5 cm × 36.5 cm) separated into 81 points.

The experiment was statistically organized and analyzed as a completely randomized block design (four blocks) when evaluating individual plant survival; individual plants were considered replicates within a tray. There were a total of 352 trays in the experiment divided among 4 blocks with 1 tray per block; 88 species × 4 trays each (1 tray per block) × 4 plants per tray = 1408 plants total. When evaluating species vigor, whole tray data were collected, in which case a tray was considered a replicate and the experiment was analyzed as a completely randomized statistical design. We note that different plants were grown in Years 1 and 2, that is, there was no replication across years. Analysis of variance and mean separation (Tukey’s honestly significant difference; P ≤ 0.05) were conducted using SPSS 24 (SPSS Inc., Chicago, IL).

**Results**

**Rooftop medium and environment.** Hourly media temperatures varied from –22.3 to 43 °C (not reported here) and monthly media temperatures varied from –9.4 to 22.8 °C over both years (Table 2). Hourly media moisture levels varied from 0 (saturated) to –200 kPa (completely frozen; not reported here) and monthly media moisture levels varied from –2.5 to –73.3 kPa from May to September and from –7.6 to –195 kPa from October to April over both years (Table 2). Monthly air temperature, relative humidity and solar radiation (0900–1600 HR) varied from –9.4 to 21.7 °C, 44% to 80%, and from 45 to 267 W·m⁻² (206 to 1222 µmol·m⁻²·s⁻¹; converted based on Thi-mijan and Heins, 1983). Monthly precipitation (liquid only) varied from 0 to 14.7 cm over both years; snow/sleet (frozen) was not recorded. Initial medium EC (soluble salts) was 227 and 189 mhos·cm⁻¹ × 10⁻⁰ in Years 1 and 2, respectively. Follow-up media conductivity measurements varied from 10 to 16 mhos·cm⁻¹ × 10⁻⁵ and from 9 to 13 mhos·cm⁻¹ × 10⁻⁵ in Years 1 and 2, respectively. Media pH values varied from 7.1 to 7.2 and from 7.0 to 7.1 during Years 1 and 2, respectively, during the experiment. Plants showed no evidence of pH, fertility, or high salinity stress.

**Plant survival.** Plant survival differed between years. In Year 1, 28 of 63 species died (44%; Table 3). Among species that survived in Year 1, nine (14%) had a low survival score (>1 to <2), 10 (16%) had a medium score (>2 to <3), and 16 (25%) had a high survival score (>3). In Year 2, 4 of 25 species died (16%; Table 3). Among species that survived in Year 2, seven (23%) had low survival score (>1 to <2), seven (23%) had a medium score (>2 to <3), and seven (23%) had high score (>3).

Tray location (block) interacted with year to affect plant survival across species (Table 4). Block 3 had a lower survival score

**Table 2. Media moisture and environment data for the rooftop experiment.**

| Year | Media moisture | Temperature | Relative humidity | Solar radiation |
|------|----------------|-------------|------------------|----------------|
| 1    | –22.3 to 43 °C | 80% to 267 W·m⁻² | 44% to 80% | –9.4 to 21.7 °C |
| 2    | –7.6 to –195 kPa | 206 to 1222 µmol·m⁻²·s⁻¹ | 45 to 267 W·m⁻² | –9.4 to 22.8 °C |
Table 2. Monthly mean air temperature [mean (among days) ± se], mean daily solar radiation [mean (among days) ± se], and monthly cumulative precipitation on the experimental rooftop (7.7 m from the rooftop study and 2 m above) for Years 1 and 2. Monthly mean medium levels (exclusive of snow and sleet) and temperatures (medium temp) are also shown (sensors placed in media) calculated from daily means.

| Month       | Daily air temperature (°C) | Daily solar radiation (W·m⁻²) | Cumulative precipitation (mm) | Medium moisture (kPa) | Medium temp (°C) |
|-------------|----------------------------|-------------------------------|-------------------------------|----------------------|-----------------|
| **Yr 1**    |                            |                               |                               |                      |                 |
| July        | 21.7 ± 0.2                 | 253 ± 5                       | 31                            | −4 a                  | 23.3 f          |
| August      | 21.7 ± 0.2                 | 224 ± 5                       | 81                            | −6 a                  | 21.8 ef         |
| September   | 20.6 ± 0.5                 | 153 ± 6                       | 20                            | −44 a                 | 19.4 ef         |
| October     | 5.6 ± 0.3                  | 78 ± 4                        | 46                            | −23 a                 | 10.8 d          |
| November    | 2.3 ± 0.1                  | 52 ± 3                        | 0                             | −1.1 c                | −1.3 a          |
| December    | 2.2 ± 0.3                  | 45 ± 2                        | 3                             | −195 d                | −7.2 ab         |
| January     | −3.3 ± 0.7                 | 52 ± 8                        | 13                            | −183 cd               | −9.3 a          |
| February    | −5.0 ± 0.5                 | 107 ± 4                       | 18                            | −165 cd               | −4.4 bc         |
| March       | 1.1 ± 0.1                  | 149 ± 5                       | 48                            | −93 b                 | 2.7 c           |
| April       | 9.4 ± 0.3                  | 220 ± 8                       | 41                            | −15 a                 | 11.1 d          |
| May         | 16.7 ± 0.4                 | 270 ± 7                       | 30                            | −27 a                 | 17.9 e          |
| June        | 20.6 ± 0.5                 | 244 ± 6                       | 79                            | −37 a                 | 20.7 e          |
| Mean        | 9.5 ± 0.5                  | 154 ± 5                       | 390                           | −73b                  | 9.4b            |

| **Yr 2**    |                            |                               |                               |                      |                 |
| July        | 21.7 ± 0.2                 | 252 ± 5                       | 48                            | −4 a                  | —               |
| August      | 21.7 ± 0.3                 | 229 ± 5                       | 147                           | −6 a                  | 19.0 ef         |
| September   | 18.9 ± 0.4                 | 167 ± 5                       | 10                            | −60 ab                | 18.3 ef         |
| October     | 6.7 ± 0.2                  | 77 ± 4                        | 58                            | −12 a                 | 6.8 cd          |
| November    | 6.1 ± 0.2                  | 62 ± 3                        | 53                            | −126 bC               | 3.9 bc          |
| December    | −2.7 ± 0.1                 | 48 ± 2                        | 18                            | −188 c                | −3.9 ab         |
| January     | −9.4 ± 1.6                 | 53 ± 9                        | 25                            | −175 e                | −4.4 a          |
| February    | −5.6 ± 0.3                 | 110 ± 3                       | 15                            | −192 c                | −2.6 ab         |
| March       | 5.6 ± 0.2                  | 153 ± 5                       | 23                            | −12 a                 | 5.6 cd          |
| April       | 13.3 ± 0.2                 | 224 ± 7                       | 20                            | −16 a                 | 12.6 de         |
| May         | 16.7 ± 0.6                 | 267 ± 7                       | 10                            | −12 a                 | 15.3 ef         |
| June        | 21.1 ± 0.3                 | 248 ± 6                       | 63                            | −12 a                 | 22.8 f          |
| Mean        | 9.1 ± 0.2                  | 158 ± 5                       | 430                           | −68 a                 | 8.5 a           |

*Lowercase letters indicate mean separations between months using Tukey’s honestly significant difference (P = 0.05) across blocks.

(2.0) than Block 1 (2.3) across species in Year 1 (Table 4). Block 2 had a lower (2.1) survival score than Block 3 (2.7) or 4 (2.5) across species in Year 2 (Table 4).

Plant vigor. Plant vigor scores (among species that survived; whole tray) varied with year. Year 1 vigor was higher (46) than Year 2 (31) across species (Table 5). Within Year 2, 10 of 36 species (28%) had low vigor scores (0–20), 3 (8%) had marginal vigor scores (21–40), 7 (19%) had medium vigor scores (41–60), and 16 (44%) had high vigor scores (61–81; Table 5). In Year 2, 11 of 21 species (52%) had low vigor scores, 2 (10%) had marginal vigor scores, 4 (19%) had medium vigor scores, and 4 (19%) had high vigor scores (Table 5). No species had vigor scores that exceeded 81 (Table 5).

Discussion

Substrate depth can limit plant survival in extensive green roof systems. Dunnett and Nolan (2004) noted shallow medium profiles, typical of extensive green roofs, dry faster than deeper intensive green roof profiles. We note that our medium depth (12.7 cm) would categorize our system as a “semi-intensive” system (12–30 cm) based on new standards (Lata et al., 2017). Therefore, our system may have experienced less medium moisture and/or temperature swings than a more typical extensive (4–12 cm) system depending on medium depth.

Cold and warm air or medium can limit plant survival and vigor on a green roof. Hourly media temperatures fluctuated more here (−22.3 to 43.0 °C) than 65.3 °C change; data not shown) than in other long-term green roof studies in other northern locations such as Halifax, Nova Scotia (−18.2 to 37.6 °C; 55.8 °C change; Brown and Lundholm, 2015). Also, the reported hourly minimum winter media temperatures reported here (−22.3 °C) was lower than reported by others in northern climates as well.

A number of species recommended for extensive green roofs in nearby cities (Chicago; 898 km away) such as Semprevivum arachnoideum, Ratibida columnifera, and Hemerocallis ‘Stella d’Oro’ (City of Chicago, 2010) did not perform (based on survival and vigor scores) well in our study (Tables 3 and 5). In contrast, a number of species such as Ajuga reptans ‘Bronze Beauty’, Rudbeckia fulgida ‘Goldstrum’, Koeleria macrantha 07-901 ND, Sedum caucica ‘Sunset Storm’, Sedum elaeochromanum, Sporobolus heterolepis, and Tilamin calycinum thrived in our study (high survival score and vigor score) performance on a Minneapolis rooftop may differ if bulbs are planted deeper than the 5 cm we planted them; we would recommend 10 cm based on Nagase and Dunnett’s (2013) results.

Among grasses, Festuca ovina VNS, Koeleria macrantha 07-901 ND, Panicum virgatum and Sporobolus heterolepis performed the best (Tables 3, 5, and 6). These grasses were included in this study specifically because of their greater heat and/or drought tolerance while being cold hardy (Watkins, personal communication). Among grasses studied, Festuca ovina VNS appeared to be particularly well suited for the rooftop in our study (Tables 3, 5, and 6). A study in Utah (another northern climate) in an intensive (1 m deep medium) green roof system showed 21 grass/wildflower species performed well (Dewey et al., 2004). We note that their data showed Canadian bluegrass (Poa compressa), wheatgrass (Pseudoroegneria spicata, Elymus trachycaulus ssp. trachycaulus, Elymus lanceolatus ssp. lanceolatus, and Pascoyanum smithii), tufted hairgrasses (Deschampis cespitosa), wild rye (Elymus spp.), and Mountain broom (Bromus carinatus); we note that they did not include statistics in their study. However, we note that temperature perennials in this study were also challenged on a green roof system and had substantially lower survival estimates than Tulipa, Narcissus, Scilla, and Tulipa performance on an extensive green roof in the United Kingdom. However, they noted geophyte performance increased when bulbs were planted deeper (10 cm) in a tray vs. ≤5 cm, where they initially planted them; our bulbs were planted 5 cm below the surface. Therefore, geophyte performance on a Minneapolis rooftop may increase if bulbs are planted deeper than the 5 cm we planted them; we would recommend 10 cm based on Nagase and Dunnett’s (2013) results.
Table 3. Mean survival scores of species evaluated after Years 1 and Year 2. Abbreviations for plant category are also shown used to distinguish differences between plant type/habit and survival.

| Species                                 | Type | Yr 1 | Yr 2 |
|------------------------------------------|------|------|------|
| Achillea millefolium ‘Paprika’           | T    | 2.3  | cd   |
| Agastache foeniculum                     | T    | —    | 1.0  |
| Ajuga reptans ‘Bronze Beauty’             | T    | 1.0  | a    |
| Allium cernuum                           | T    | —    | 4.0  |
| Allium senescens ‘Glaucum’               | T    | 3.7  | hijk |
| Antennaria dioica                        | T    | —    | 2.7  |
| Aquilegia vulgaris                       | T    | —    | 1.2  |
| Artemisia ludoviciana ‘Valerie Finnis’   | T    | 1.0  | a    |
| Aster alpinus ‘Dunkle Schone’            | T    | —    | 3.1  |
| Bergenia cordifolia                      | T    | —    | 2.0  |
| Briza media                              | G    | —    | 1.3  |
| Calamagrostis xacutiflora ‘Karl Foerster’| G    | 3.8  | abc  |
| Campanula cochlearifolia                | T    | —    | 2.2  |
| Chasmanthium latifolium                 | G    | —    | 1.0  |
| Crocus ‘Minimus’                         | B    | 1.0  | a    |
| Crocus tommasinianus ‘Ruby Giant’       | B    | 1.0  | a    |
| Dalea purpurea                           | T    | —    | 1.0  |
| Festuca arundinacea ‘Raptor’             | G    | 1.3  | a    |
| Festuca longifolia ‘Osprey’              | G    | 2.5  | cde  |
| Festuca ovina VNS                        | G    | 4.0  | k    |
| Festuca rubra var. commutata ‘Jamestown II’ | G  | 2.9  | defgh|
| Geum triflorum                           | T    | —    | 4.0  |
| Hemerocallis ‘Stella d’Oro’              | T    | 1.0  | a    |
| Ipheion uniflorum                        | B    | 1.0  | a    |
| Iris reticulata ‘Joyce’                  | B    | 1.0  | a    |
| Koeleria macrantha 07-901 ND             | G    | 3.3  | efghk|
| Leptinella squalida ‘Platt’s Black’      | T    | 1.0  | a    |
| Linum perenne                            | T    | —    | 1.8  |
| Lychnis chalcedonica                     | T    | —    | 1.8  |
| Mentha piperita                          | T    | —    | 1.9  |
| Mentha spicata                           | T    | —    | 1.0  |
| Narcissus bulbocodium var. conspicuous ‘Golden Bells’ | B  | 1.0  | a    |
| Narcissus cyclamineus ‘Jetfire’          | B    | 1.0  | a    |
| Narcissus ‘Tete e Tete’                  | B    | 1.0  | a    |
| Nectaroscordum siculum                   | B    | 1.0  | a    |
| Nepeta xfaasseni ‘Kit Cat’               | T    | 1.0  | a    |
| Panicum virgatum                        | G    | —    | 3.4  |
| Papaver alpinum                          | T    | —    | 2.9  |
| Pulsatilla vulgaris                      | T    | —    | 2.8  |
| Ratibida columnifera                     | T    | —    | 2.1  |
| Rudbeckia fulgida ‘Goldsturm’            | T    | 1.0  | a    |
| Salvia verticillata ‘Purple Rain’        | T    | 1.3  | a    |
| Saxifraga xarendii ‘Highlander Rose Shades’ | T  | —    | 1.8  |
| Scillaiberica                            | B    | 1.0  | a    |
| Sedum acre                               | S    | 3.6  | ghijk|
| Sedum album ‘Coral Carpet’               | S    | 3.1  | efghk|
| Sedum album ‘Murale’                     | S    | 2.1  | bcd  |
| Sedum ‘Blue Lagoon’                      | S    | 1.4  | ab   |
| Sedum ‘Blue Spruce’                      | S    | 2.8  | defg  |
| Sedum cauticola ‘Sunset Cloud’            | S    | 3.8  | ijk  |
| Sedum ‘Czar’s Gold’                      | S    | 4.0  | k    |
| Sedum dasyphyllum ‘Major’                | S    | 1.0  | a    |
| Sedum elatumandonum                      | S    | 4.0  | k    |
| Sedum forsterianum ‘Elegans Silverstone’ | S  | 1.2  | a    |
| Sedum glaucophyllum                      | S    | 1.2  | a    |
| Sedum hispanicum                         | S    | 1.0  | a    |
| Sedum hispanicum ‘Minor Aureum’          | S    | 1.0  | a    |
| Sedum hybridum ‘immergruenen’             | S    | 3.8  | jk   |
| Sedum kamschaticum ‘Takahira Dake’       | S    | 1.1  | a    |
| Sedum lineare                            | S    | 1.0  | a    |
| Sedum mexicanum                          | S    | 1.0  | a    |
| Sedum oreganum                           | S    | 1.0  | a    |
| Sedum pulchellum                         | S    | 1.0  | a    |
| Sedum reflexum ‘Green Spruce’             | S    | 2.7  | def  |
| Sedum requieni                           | S    | —    | 3.4  |
| Sedum rupestre ‘Angelina’                | S    | 2.9  | defgh|
| Sedum sexangulare                        | S    | 3.6  | ghijk|
| Sedum spectabilis ‘Brilliant’            | S    | 2.6  | de   |
| Sedum spurium ‘Dragon’s Blood’           | S    | 3.5  | fghjk|
| Sedum spurium ‘Fuldaglut’                | S    | 1.7  | abc  |
| Sedum spurium ‘John Creech’              | S    | 3.8  | abc  |
| Sedum spurium ‘Pearly Pink’              | S    | 3.4  | fghjk|
| Sedum spurium ‘Purple Carpet’            | S    | 2.8  | defg  |
the before mentioned grasses (Dewey et al., 2004).

Hardy succulents are often recommended for extensive green roofs in many locations (Table 2; Lata et al., 2017). Bousselot et al. (2011) showed succulents retained foliage five times longer than herbaceous “nonsucculent” species on a green roof. Among the 88 species we evaluated, 37 were succulents in the genera Sempervivum and Sedum. All Sempervivum died in our study, however, a number of Sedum species/varieties here, S. hispanicum, S. lineare, S. mexicanum, S. oreganum, and S. pulchellum did not survive. In contrast, S. acre, S. album ‘Coral Carpet’, S. cauticola ‘Sunset Cloud’, Sedum ‘Czar’s Gold’, S. ellecombianum, S. hybridum ‘Immergruen’, S. requieni, S. sexangulare, and S. spurium ‘Dragon’s Blood’, ‘John Creech’, ‘Pearly Pink’, ‘Ruby Mantle’, and ‘Tri-color’ had high survival and vigor scores (Tables 3, 5, and 6). Our data agree with previous studies showing S. acre, S. sexangulare, and S. spurium ‘John Creech’ perform well on an extensive green roof, but differed in that S. cauticola, S. reflexum performed well in our study, but performed poorly in other studies (Durhman et al., 2007; Getter and Rowe, 2009); medium in our trays was 12.7 cm deep.

Whether deeper media increases survival because of increased water availability or more moderate media temperature is unclear. Boivin et al. (2001) reported Sedum survival was higher when medium depth was 7–10 cm vs. 2.5–5 cm (Durhman et al., 2007; Getter and Rowe, 2009); medium in our trays was 12.7 cm deep.

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Sedum kamtschaticum switched from C3 to CAM photosynthesis on a green roof in a study by Starry et al. (2014), which increased S. kamtschaticum water use efficiency, however, S. album had higher water use efficiency than S. kamtschaticum throughout their study. Yet survival of both species was similar in our study, as also reported by Durhman et al. (2007), suggesting cold media temperature may limit Sedum survival more than water availability (Table 3). When we specifically examined Sedum survival in Year 1, we found survival was highest in the block with the warmest winter (December–February) media temperatures and lowest media moisture levels (block 1). Therefore, our data support the suggestion that low temperatures may limit Sedum survival, but raises the question as to whether medium moisture interacts with cold temperature to affect survival (Table 4).

Many nonsucculent herbaceous temperate perennials can survive and thrive on an extensive green roof (Dvorak and Volder, 2010). Among perennials evaluated in our study, Allium, Ceranum and senescens ‘Glaucum’, Geum triflorum, Talinum calycinum, and Thymus praecox ‘Red Creeping’ performed well (survival score >3.0; Table 3).

Table 5. Mean vigor scores for species that survived Years 1 and 2. The difference between leaf and air temperature on 12 Sept. (end of experiment) is also shown (ambient conditions: air temperature = 23.9 °C, relative humidity = 45%, wind from SW at 8 mph; full sun (1200–1300 HR).

| Species | Difference (°C) | Yr 1 | Yr 2 |
|---------|----------------|------|------|
| Achillea millefolium ‘Paprika’ | +2.7 | 40 abcdefghi | — |
| Allium cernuum | -4.3 | — | 65 d |
| Allium senescens ‘Glaucum’ | -2.0 | 60 efgi | — |
| Antennaria dioica ‘Rubra’ | 3.4 | — | 39 abcd |
| Aquilegia vulgaris | 5.2 | 5 a | — |
| Aster alpinus ‘Dunkle Schone’ | -2.9 | 28 abcd | — |
| Bergenia cordifolia | 2.0 | — | 20 abc |
| Briza media | -2.9 | — | 6 a |
| Calamagrostis × acutiflora ‘Karl Foerster’ | 1.6 | — | 16 abc |
| Campanula cochlearifolia | 6.3 | — | 25 abc |
| Festuca arundinacea ‘Raptor’ | 9.2 | 4 abc | — |
| Festuca longifolia ‘Osprey’ | 6.3 | 43 edefghi | — |
| Festuca ovina VNS | -1.1 | 77 ghi | — |
| Festuca rubra var. commutate ‘Jamestown II’ | 4.0 | 52 defghi | — |
| Geum triflorum | -1.1 | — | 76 d |
| Koeleria macrantha 07-901 ND | 3.6 | 67 fghi | — |
| Linum perenne | 5.2 | — | 8 ab |
| Lychins chalcedonica | 1.8 | — | 8 ab |
| Mentha piperita | -2.0 | 13 ab | — |
| Panicum virgatum | 10.6 | — | 55 bcd |
| Papaver alpinum | 5.8 | — | 6 a |
| Pulsatilla vulgaris | -0.7 | — | 45 abcd |
| Ratibida columnifera | 3.1 | — | 5 a |
| Salvia verticillata ‘Purple Rain’ | 3.4 | 2.3 a | — |
| Saxifraga xarendtsi ‘Highlander Rose Shades’ | 5.2 | — | 8 ab |
| Sedum acre | 8.8 | 77 ghi | — |
| Sedum album ‘Coral Carpet’ | 7.9 | 75 ghi | — |
| Sedum album ‘Murele’ | 4.5 | 27 abcede | — |
| Sedum ‘Blue Lagoon’ | 9.0 | 3 ab | — |
| Sedum ‘Blue Spruce’ | 5.4 | 53 efgi | — |
| Sedum cauticola ‘Sunset Cloud’ | 6.5 | 77 ghi | — |
| Sedum ‘Czar’s Gold’ | 4.0 | 81 I | — |
| Sedum dasyphyllum ‘Major’ | 4.2 | 2 a | — |
| Sedum ellecombianum | 1.6 | 81 I | — |
| Sedum forsterianum ‘Elegans Silverstone’ | 0.0 | 2 a | — |
| Sedum glaucophyllum | 4.9 | 2 a | — |
| Sedum hybridum ‘Immergruchen’ | 4.5 | 77 ghi | — |
| Sedum kamschaticum ‘Takahira Dake’ | 5.8 | 2 a | — |
| Sedum reflexum ‘Green Spruce’ | 5.8 | 43 edefghi | — |
| Sedum requieni | 7.4 | — | 56 bcd |
| Sedum rupestre ‘Angelina’ | 6.0 | 28 abedefg | — |
| Sedum sexangulare | 4.5 | 70 ghi | — |
| Sedum spectabilis ‘Brilliant’ | -0.5 | 43 bedefghi | — |
| Sedum spurium ‘Dragon’s Blood’ | 4.0 | 78 ghi | — |
| Sedum spurium ‘Fuldaglut’ | 4.0 | 12 abcd | — |
| Sedum spurium ‘John Creech’ | 3.1 | 79 hi | — |
| Sedum spurium ‘Pearly Pink’ | 3.1 | 73 ghi | — |
| Sedum spurium ‘Purple Carpet’ | 4.9 | 38 abedefg | — |
| Sedum spurium ‘Ruby Mantle’ | 5.2 | 70 ghi | — |
| Sedum spurium ‘Summer Glory’ | 2.2 | 57 efgi | — |
| Sedum spurium ‘Tricolor’ | 18.4 | 79 hi | — |
| Sedum spurium ‘Voodoo’ | 16.8 | 6 abc | — |
| Sporobolus heterolepis | 6.3 | — | 76 d |
| Talinum calycinum | 3.8 | — | 62 cd |
| Thalictrum kiusianum | 6.1 | 1 a | — |
| Thymus praecox ‘Red Creeping’ | 10.3 | 69 ghi | — |
| Verbena stricta | 10.3 | — | 19 abc |
| Vigor (across species) within a year | 46 b | — | 31 a |

ANOVA

Source

Species *** ***

*, lowercase letters indicate mean separation between species within a year or between years using Tukey’s honestly significant difference.

*Denotes statistical significance as determined by analysis of variance (ANOVA). ***Significant at P ≤ 0.001.
Interestingly, many of the species that performed well in our study were indigenous to mountainous regions (Bailey and Bailey, 1976). For instance, *Aster alpinus* ‘Dunkle Schöne’ (native to European Alps with subspecies native in Canada and United States) and *Thymus praecox* ‘Red Creeping’ (indigenous to palaearctic zone of Europe and Asia) survived well (Table 3, 5, and 6; Bailey and Bailey, 1976).

When plants are planted on an extensive green roof may impact plant survival. Getter and Rowe (2007) reported *Sedum* plug survival was higher when plants were planted on a rooftop in the spring vs. the fall in Michigan. We observed that late summer/early fall planting increased species survival in a separate study (Hensley and Erwin, personal observation). The basis for this is unclear; however, adequate moisture during the establishment period appears to be critical to long-term survival (Durham et al., 2007). Therefore, either spring planting or fall planting may be preferable if water is limiting; if water is not limiting, plant establishment may likely be similar across spring, summer and fall. Given media moisture may impact initial survival, periodic watering (VanWoert et al., 2005), increasing of media depth (Boussol et al., 2011; Dunnett et al., 2008; Nektarios et al., 2011) and/or increasing media water holding capacity (Lata et al., 2017) all show potential for increasing plant survival on an extensive green roof. Yet our data suggested media moisture content may not be as limiting on a northern green roof as minimum media temperature (Table 4).

The leaf temperature of a single leaf of each species was recorded [1200–1300 HR, 8 Sept. (clear day)]; one replicate, therefore, no statistics. Darker leafed species or varieties had leaf temperatures higher that the air temperatures (Table 5). For instance, *Sedum spurium* ‘Tricolor’ and ‘Voodoo’ (some or all red foliage) had leaf temperatures 18.4 and 16.8 °C warmer than the air temperature, respectively (Table 5). Plants with lighter colored foliage had leaf temperatures similar or less than air temperatures (Table 5). For instance, *Allium cernuum* and *Aster alpinus* ‘Dunkle Schöne’ (lighter green/silver foliage) had leaf temperatures 4.3 and 2.9 °C less than the air temperature (Table 5).

Taken together, we recommend the species and varieties listed in Table 6 for an unirrigated semiextensive green roof system (12.7 cm deep) in a cool, dry environment in the Upper Midwest such as Minneapolis, MN. Further, we suggest the expanded list of species in Table 6 may be recommended if media temperatures are above those observed in our study and, perhaps, if media depth was deeper (Shafique et al., 2018). The differences observed in this list compared with others nearby underscores the importance of regionally specific studies (Getter and Rowe, 2008). Interesting recent work (Fulthorpe et al., 2019) suggests that inoculation of medium with specific microbes may increase plant survival on a green roof.

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