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 temperatures varied from -22.3 to 43 °C. Monthly medium water moistures varied from -2.5 to -73.3 kPa from May to September, and from -7.6 to -195 kPa from October to April. Monthly air temperature, relative humidity and irradiance varied from -9.4 to 21.7 °C, 44% to 80%, and from 206 to 1222 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. 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, *Festuca ovina* VNS, *Koeleria macrantha* 07-901 ND, *Panicum virgatum*, and *Sporobolus heterolepis* performed well. Among succulents, *Sedum acre*, *S. album* ‘Coral Carpet’, *S. cauticola* ‘Sunset Cloud’, *S. ‘Czar’s Gold’*, *S. ellecombianum*, *S. hybridum* ‘Immergruchen’, *S. requienii*, *S. sexangulare*, *S. spurium* ‘Dragon’s Blood’, ‘John Creech’, ‘Pearly Pink’, ‘Ruby Mantle’, and ‘Tricolor’ performed well. Among temperate nonsucculent perennials, *Allium ceranum* and *senescens* ‘Glaucum’, *Geum triflorum*, *Talinum calycinum*, and *Thymus praecox* ‘Red Creeping’ performed well. Data on *Sedum* suggested that medium-low temperature was more limiting to survival than moisture level. The differences in species that performed well here, compared with other studies, underscores the importance of regionally specific green roof plant species studies.

Green roofs are building surface treatments where plants are grown in medium on a rooftop (DeNardo et al., 2005). Green rooftops can cool dwellings in warm climates and insulate buildings in cold climates (Shafique et al., 2018). The earliest examples of green roofs, between the seventh and eighth century BCE in present-day Syria, were installed to cool dwellings (Oberndorfer et al., 2007).

The Greeks, Romans, and Persians also installed green roofs to cool buildings (Dunnett and Kingsbury, 2004). In contrast, Scandinavian “turf-roofs” were installed until the last half of the 19th century to insulate homes during the winter from the cold (Jenkins 1977; Snodgrass and Snodgrass, 2006). Modern green roofs gained popularity in the 1960s in Germany in response to the energy crisis as a tool to reduce building energy consumption (Shafique et al., 2018).

Modern green roofs were described as “extensive” (<20 cm medium depth) or “intensive” (>20 cm medium depth; Oberndorfer et al., 2007). Since then (2017), green roof systems were further divided and described as extensive (4–12 cm), semi-intensive (12–30 cm), and intensive (>30 cm; Lata et al., 2017). Adding a green roof to an existing building often involves installing an extensive green roof system that usually does not require building structural modification for additional weight (Oberndorfer et al., 2007). In contrast, adding an intensive or semi-intensive green roof to an existing building can require additional building structural modification for the additional weight of the medium, plants, and retained water (Oberndorfer et al., 2007).

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 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,

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Table 1. 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 ^z
<i>Achillea millefolium</i> 'Paprika'	Vegetative	O,H,E	G	1	Linder's
<i>Agastache foeniculum</i>	Seed	O,H	G	2	Linder's
<i>Ajuga reptans</i> 'Bronze Beauty'	Vegetative	O	G	1	Bailey's
<i>Allium cernuum</i>	Vegetative	O,H,E	G	2	Bluebird
<i>Allium senescens</i> 'Glaucum'	Vegetative	O,H	G	1	Bailey's
<i>Antennaria dioica</i> 'Rubra'	Vegetative	O,H,F	G	2	Bluebird
<i>Aquilegia vulgaris</i>					
<i>Artemisia ludoviciana</i> 'Valerie Finnis'	Vegetative	O,F	G	1	Bailey's
<i>Aster alpinus</i> 'Dunkle Schone'	Vegetative	O,H	G	2	Bluebird
<i>Bergenia cordifolia</i>	Vegetative	O,F	G	2	Bluebird
<i>Briza media</i>	Vegetative	O,F	G	2	Bluebird
<i>Calamagrostis xacutiflora</i> 'Karl Foerster'	Vegetative	O,F	G	2	Bluebird
<i>Campanula cochleariifolia</i>	Vegetative	O	G	2	Bluebird
<i>Chasmanthium latifolium</i>	Vegetative	O,F	G	2	Bluebird
<i>Crocus</i> 'Minimus'	Bulb	O	C	1	Linder's
<i>Crocus tommasinianus</i> 'Ruby Giant'	Bulb	O	C	1	Linder's
<i>Dalea purpurea</i>	Seed	O,H	G	2	Linder's
<i>Festuca arundinacea</i> 'Raptor'	Vegetative	O,F	G	1	UMN Turf
<i>Festuca longifolia</i> 'Osprey'	Vegetative	O,F	G	1	UMN Turf
<i>Festuca ovina</i> VNS	Vegetative	O,F	G	1	UMN Turf
<i>Festuca rubra</i> var. <i>commutata</i> 'Jamestown II'	Vegetative	O,F	G	1	UMN Turf
<i>Geum triflorum</i>	Vegetative	O,H	G	2	Bluebird
<i>Hemerocallis</i> 'Stella d'Oro'	Vegetative	O	G	1	Bailey's
<i>Ipheion uniflorum</i>	Bulb	O	C	1	Linder's
<i>Iris reticulata</i> 'Joyce'	Bulb	O	C	1	Linder's
<i>Koeleria macrantha</i> 07-901 ND	Vegetative	O,F	G	1	UMN Turf
<i>Leptinella squalida</i> 'Platt's Black'	Vegetative	O	G	1	Bailey's
<i>Linum perenne</i>	Seed	O,H	G	2	Linder's
<i>Lychnis chalcedonica</i>	Seed	O,H	G	2	Linder's
<i>Mentha piperita</i>	Vegetative	O,H,E	G	2	Bailey's
<i>Mentha spicata</i>	Vegetative	O,H,E	G	2	Bailey's
<i>Narcissus bulbocodium</i> var. <i>conspicuous</i> 'Golden Bells'	Bulb	O	C	1	Linder's
<i>Narcissus cyclamineus</i> 'Jetfire'	Bulb	O	C	1	Linder's
<i>Narcissus</i> 'Tete e Tete'	Bulb	O	C	1	Linder's
<i>Nectaroscordum siculum</i>	Bulb	O	C	1	Linder's
<i>Nepeta xfaassenii</i> 'Kit Cat'	Vegetative	O,H	G	1	Bailey's
<i>Panicum virgatum</i>	Seed	O,F	G	2	Linder's
<i>Papaver alpinum</i>	Vegetative	O	G,C	2	Bluebird
<i>Pulsatilla vulgaris</i>	Vegetative	O	G	2	Bluebird
<i>Ratibida columnifera</i>	Seed	O,H	G	2	Linder's
<i>Rudbeckia fulgida</i> 'Goldsturm'	Vegetative	O,H	G	1	Bailey's
<i>Salvia verticillata</i> 'Purple Rain'	Vegetative	O,H	G	1	Bailey's
<i>Saxifraga xarendsii</i> 'Highlander Rose Shades'	Vegetative	O	G	2	Bailey's
<i>Scilla siberica</i>	Bulb	O	C	1	Linder's
<i>Sedum acre</i>	Vegetative	O,F	G	1	Altman
<i>Sedum album</i> 'Coral Carpet'	Vegetative	O,F	G	1	Altman
<i>Sedum album</i> 'Murale'	Vegetative	O,F	G	1	Altman
<i>Sedum</i> 'Blue Lagoon'	Vegetative	O,F	G	1	Altman
<i>Sedum</i> 'Blue Spruce'	Vegetative	O,F	G	1	Altman
<i>Sedum cauticola</i> 'Sunset Cloud'	Vegetative	O,H,F	G	1	Altman
<i>Sedum</i> 'Czar's Gold'	Vegetative	O,F	G	1	Altman
<i>Sedum dasyphyllum</i> 'Major'	Vegetative	O,F	G	1	Altman
<i>Sedum ellecombianum</i>	Vegetative	O,H,F	G	1	Altman
<i>Sedum forsterianum</i> 'Elegans Silverstone'	Vegetative	O,F	G	1	Altman
<i>Sedum glaucophyllum</i>	Vegetative	O,F	G	1	Altman
<i>Sedum hispanicum</i>	Vegetative	O, F	G	1	Altman
<i>Sedum hispanicum</i> 'Minor Aureum'	Vegetative	O,F	G	1	Altman
<i>Sedum hybridum</i> 'Immergruchen'	Vegetative	O,F	G	1	Altman
<i>Sedum kamschaticum</i> 'Takahira Dake'	Vegetative	O,F	G	1	Altman
<i>Sedum lineare</i>	Vegetative	O,F	G	1	Altman
<i>Sedum mexicanum</i>	Vegetative	O,F	G	1	Altman
<i>Sedum oreganum</i>	Vegetative	O,F	G	1	Altman
<i>Sedum reflexum</i> 'Green Spruce'	Vegetative	O,F	G	1	Altman
<i>Sedum requienii</i>	Vegetative	O,F	G	1	Altman
<i>Sedum rupestre</i> 'Angelina'	Vegetative	O,F	G	1	Altman
<i>Sedum sexangulare</i>	Vegetative	O,F	G	1	Altman
<i>Sedum spectabilis</i> 'Brilliant'	Vegetative	O,H,F	G	1	Altman
<i>Sedum spurium</i> 'Dragon's Blood'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Fuldaglut'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'John Creech'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Pearly Pink'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Purple Carpet'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Ruby Mantle'	Vegetative	O,F	G	1	Altman

(Continued on next page)

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 ²
<i>Sedum spurium</i> 'Summer Glory'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Tricolor'	Vegetative	O,F	G	1	Altman
<i>Sedum spurium</i> 'Voodoo'	Vegetative	O,F	G	1	Altman
<i>Sempervivum arachnoideum</i> 'Cebenese'	Vegetative	O	G	1	Altman
<i>Sempervivum arachnoideum</i> 'Stansfieldii'	Vegetative	O	G	1	Altman
<i>Sempervivum calcareum</i> 'Sir William Lawrence'	Vegetative	O	G	1	Altman
<i>Sempervivum</i> sp. 'Maryente'	Vegetative	O	G	1	Altman
<i>Sporobolus heterolepis</i>	Vegetative	O,H,F	G	2	Bluebird
<i>Talinum calycinum</i>	Vegetative	O,H	G,C	2	Bluebird
<i>Thalictrum kiusianum</i>	Vegetative	O	G	1	Bailey's
<i>Thymus praecox</i> 'Red Creeping'	Vegetative	O,E	G	1	Bailey's
<i>Trifolium repens</i> 'Atropurpureum'	Vegetative	O	G	1	Bailey's
<i>Tulipa humilis</i> 'Violacea'	Bulb	O	C	1	Linder's
<i>Verbena stricta</i>	Seed	O,H	G	2	Linder's

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

²Plant 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 lengthwise along the roof (rooftop was ≈8 m wide × 23 m long). 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 cbars with 0 to 10 cbars representing saturated soil and 100 to 200 cbars 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 Durhman 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 not replication across years. Analysis of variance and mean separation (Tukey's honestly significant difference; $P \leq 0.05$)

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 umol·m^{–2}·s^{–1}; converted based on Thimijan 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^{–5} 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. Monthly mean air temperature [mean (among days) $\pm$ SE], mean daily solar radiation [mean (among days) $\pm$ 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 moisture 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)	Monthly cumulative precipitation (mm)	Medium moisture (kPa)	Medium temp (°C)
Yr 1					
July	21.7 $\pm$ 0.2	253 $\pm$ 5	31	-4 a ^z	23.3 f
August	21.7 $\pm$ 0.2	224 $\pm$ 5	81	-6 a	21.8 ef
September	20.6 $\pm$ 0.5	153 $\pm$ 6	20	-44 a	19.4 ef
October	5.6 $\pm$ 0.3	78 $\pm$ 4	46	-23 a	10.8 d
November	2.3 $\pm$ 0.1	52 $\pm$ 3	0	-140 b	-1.1 c
December	2.2 $\pm$ 0.3	45 $\pm$ 2	3	-195 d	-7.2 ab
January	-3.3 $\pm$ 0.7	52 $\pm$ 8	13	-183 cd	-9.3 a
February	-5.0 $\pm$ 0.5	107 $\pm$ 4	18	-165 cd	-4.4 bc
March	1.1 $\pm$ 0.1	149 $\pm$ 5	48	-93 b	-2.7 c
April	9.4 $\pm$ 0.3	220 $\pm$ 8	41	-15 a	11.1 d
May	16.7 $\pm$ 0.4	270 $\pm$ 7	10	-27 a	17.9 e
June	20.6 $\pm$ 0.5	244 $\pm$ 6	79	-37 a	20.7 e
Mean	9.5 $\pm$ 0.5	154 $\pm$ 5	390	-73b	9.4b
Yr 2					
July	21.7 $\pm$ 0.2	252 $\pm$ 5	48	-4 a	—
August	21.7 $\pm$ 0.3	229 $\pm$ 5	147	-6 a	19.0 ef
September	18.9 $\pm$ 0.4	167 $\pm$ 5	10	-60 ab	18.3 ef
October	6.7 $\pm$ 0.2	77 $\pm$ 4	58	-12 a	6.8 cd
November	6.1 $\pm$ 0.2	62 $\pm$ 3	53	-126 bc	3.9 bc
December	-7.2 $\pm$ 0.1	48 $\pm$ 2	18	-188 c	-3.9 ab
January	-9.4 $\pm$ 1.6	53 $\pm$ 9	25	-175 c	-4.4 a
February	-5.6 $\pm$ 0.3	110 $\pm$ 3	15	-192 c	-2.6 ab
March	5.6 $\pm$ 0.2	153 $\pm$ 5	23	-12 a	5.6 cd
April	13.3 $\pm$ 0.2	224 $\pm$ 7	20	-16 a	12.6 de
May	16.7 $\pm$ 0.6	267 $\pm$ 7	10	-12 a	15.3 ef
June	21.1 $\pm$ 0.3	248 $\pm$ 6	03	-12 a	22.8 f
Mean	9.1 $\pm$ 0.2	158 $\pm$ 5	430	-68 a	8.5 a

^zLowercase 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 = 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 *Sempervivum 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 caudicicola* ‘Sunset Cloud’, *Sedum ellecombianum*, *Sporobolus heterolepis*, and *Talinum calycinum* thrived in our study (high survival score and vigor score) but performed marginally in other studies (Table 5; Monterusso et al., 2005).

Plants evaluated in our experiment could be grouped by growth habit: succulents, geophytes, grasses, and temperate herbaceous perennials (Table 3). When comparing groups, survival scores decreased from 2.6 with grasses, to 2.3 with succulents, to 1.8 with temperate perennials and were least with geophytes (all geophytes died; survival = 1.0; Table 3). It was interesting to note the low survival scores of geophytes (*Tulipa*, *Narcissus*, *Crocus*, and *Scilla*) given they are indigenous to the Mediterranean region with large temperature and precipitation fluctuations (Bailey and Bailey, 1976). Nagase and Dunnett (2013) also reported poor geophyte (*Crocus*, *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.

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 *Pascopyrum smithii*, tufted hairgrasses (*Deschampsia caespitosa*), wild rye (*Elymus* spp.), and Mountain brome (*Bromus carinatus*); we note that they did not include statistics in their study. However, we note that temperate perennials in this study were also challenged on a green roof system and had substantially lower survival estimates than

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 ^z	Yr 1	Yr 2
<i>Achillea millefolium</i> 'Paprika'	T	2.3 cd ^y	—
<i>Agastache foeniculum</i>	T	—	1.0 a
<i>Ajuga reptans</i> 'Bronze Beauty	T	1.0 a	—
<i>Allium cernuum</i>	T	—	4.0 g
<i>Allium senescens</i> 'Glaucum'	T	3.7 hijk	—
<i>Antennaria dioica</i> 'Rubra'	T	—	2.7 cdef
<i>Aquilegia vulgaris</i>	T	—	1.2 ab
<i>Artemesia ludoviciana</i> 'Valerie Finnis'	T	1.0 a	—
<i>Aster alpinus</i> 'Dunkle Schone'	T	—	3.1 efg
<i>Bergenia cordifolia</i>	T	—	2.0 abcde
<i>Briza media</i>	G	—	1.3 ab
<i>Calamagrostis</i> × <i>acutiflora</i> 'Karl Foerster'	G	—	1.8 abc
<i>Campanula cochleariifolia</i>	T	—	2.2 bcde
<i>Chasmanthium latifolium</i>	G	—	1.0 a
<i>Crocus</i> 'Minimus'	B	1.0 a	—
<i>Crocus tommasinianus</i> 'Ruby Giant'	B	1.0 a	—
<i>Dalea purpurea</i>	T	—	1.0 a
<i>Festuca arundinacea</i> 'Raptor'	G	1.3 a	—
<i>Festuca longifolia</i> 'Osprey'	G	2.5 cde	—
<i>Festuca ovina</i> VNS	G	4.0 k	—
<i>Festuca rubra</i> var. <i>commutata</i> 'Jamestown II'	G	2.9 defghi	—
<i>Geum triflorum</i>	T	—	4.0 g
<i>Hemerocallis</i> 'Stella d'Oro'	T	1.0 a	—
<i>Ipheion uniflorum</i>	B	1.0 a	—
<i>Iris reticulata</i> 'Joyce'	B	1.0 a	—
<i>Koeleria macrantha</i> 07-901 ND	G	3.3 efg hijk	—
<i>Leptinella squalida</i> 'Platt's Black'	T	1.0 a	—
<i>Linum perenne</i>	T	—	1.8 abc
<i>Lychnis chalcidonica</i>	T	—	1.8 abc
<i>Mentha piperita</i>	T	—	1.9 abcd
<i>Mentha spicata</i>	T	—	1.0 a
<i>Narcissus bulbocodium</i> var. <i>conspicuous</i> 'Golden Bells'	B	1.0 a	—
<i>Narcissus cyclamineus</i> 'Jetfire'	B	1.0 a	—
<i>Narcissus</i> 'Tete e Tete'	B	1.0 a	—
<i>Nectaroscordum siculum</i>	B	1.0 a	—
<i>Nepeta</i> × <i>faassenii</i> 'Kit Cat'	T	1.0 a	—
<i>Panicum virgatum</i>	G	—	3.4 fg
<i>Papaver alpinum</i>	T	—	2.9 def
<i>Pulsatilla vulgaris</i>	T	—	2.8 cdef
<i>Ratibida columnifera</i>	T	—	2.1 abcde
<i>Rudbeckia fulgida</i> 'Goldsturm'	T	1.0 a	—
<i>Salvia verticillata</i> 'Purple Rain'	T	1.3 a	—
<i>Saxifraga</i> × <i>arendsii</i> 'Highlander Rose Shades'	T	—	1.8 abc
<i>Scilla siberica</i>	B	1.0 a	—
<i>Sedum acre</i>	S	3.6 ghijk	—
<i>Sedum album</i> 'Coral Carpet'	S	3.1 efg hijk	—
<i>Sedum album</i> 'Murale'	S	2.1 bcd	—
<i>Sedum</i> 'Blue Lagoon'	S	1.4 ab	—
<i>Sedum</i> 'Blue Spruce'	S	2.8 defg	—
<i>Sedum caudicicola</i> 'Sunset Cloud'	S	3.8 ijk	—
<i>Sedum</i> 'Czar's Gold'	S	4.0 k	—
<i>Sedum dasyphyllum</i> 'Major'	S	1.0 a	—
<i>Sedum ellecombianum</i>	S	4.0 k	—
<i>Sedum forsterianum</i> 'Elegans Silverstone'	S	1.2 a	—
<i>Sedum glaucophyllum</i>	S	1.2 a	—
<i>Sedum hispanicum</i>	S	1.0 a	—
<i>Sedum hispanicum</i> 'Minor Aureum'	S	1.0 a	—
<i>Sedum hybridum</i> 'Immergruchen'	S	3.8 jk	—
<i>Sedum kamschaticum</i> 'Takahira Dake'	S	1.1 a	—
<i>Sedum lineare</i>	S	1.0 a	—
<i>Sedum mexicanum</i>	S	1.0 a	—
<i>Sedum oregonum</i>	S	1.0 a	—
<i>Sedum pulchellum</i>	S	1.0 a	—
<i>Sedum reflexum</i> 'Green Spruce'	S	2.7 def	—
<i>Sedum requienii</i>	S	—	3.4 fg
<i>Sedum rupestre</i> 'Angelina'	S	2.9 defgh	—
<i>Sedum sexangulare</i>	S	3.6 ghijk	—
<i>Sedum spectabilis</i> 'Brilliant'	S	2.6 de	—
<i>Sedum spurium</i> 'Dragon's Blood'	S	3.5 fghijk	—
<i>Sedum spurium</i> 'Fuldaglut'	S	1.7 abc	—
<i>Sedum spurium</i> 'John Creech'	S	3.8 jk	—
<i>Sedum spurium</i> 'Pearly Pink'	S	3.4 fghijk	—
<i>Sedum spurium</i> 'Purple Carpet'	S	2.8 defg	—

(Continued on next page)

Table 3. (Continued) 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 ^z	Yr 1	Yr 2
<i>Sedum spurium</i> 'Ruby Mantle'	S	3.4 fghijk	—
<i>Sedum spurium</i> 'Summer Glory'	S	2.7 def	—
<i>Sedum spurium</i> 'Tricolor'	S	3.8 ijk	—
<i>Sedum spurium</i> 'Voodoo'	S	1.1 a	—
<i>Sempervivum arachnoideum</i> 'Cebenese'	S	1.0 a	—
<i>Sempervivum arachnoideum</i> 'Stansfieldii'	S	1.0 a	—
<i>Sempervivum calcareum</i> 'Sir William Lawrence'	S	1.0 a	—
<i>Sempervivum</i> sp. 'Maryente'	S	1.0 a	—
<i>Sporobolus heterolepis</i>	G	—	4.0 ghijk
<i>Talinum calycinum</i>	T	—	3.6 fg
<i>Thalictrum kiusianum</i>	T	1.1 a	—
<i>Thymus praecox</i> 'Red Creeping'	T	3.1 efghij	—
<i>Trifolium repens</i> 'Atropurpureum'	T	1.0 a	—
<i>Tulipa humilis</i> 'Violacea'	B	1.0 a	—
<i>Verbena stricta</i>	T	—	2.1 bcde
Survival		2.0 a ^x	2.3 b
ANOVA ^w	Significance		
Species	***		
Year	***		
Type	***		

^zT = temperate nonsucculent perennial; G = grasses; S = succulents, and B = bulbs or geophytes.

^{y,x}Lowercase letters indicate mean separations between species^y or year across species^x using Tukey's honestly significant difference ($P = 0.05$) within a year.

^wDenotes statistical significance as determined by analysis of variance (ANOVA); ***significant at $P \leq 0.001$.

Table 4. Variation in survival scores (4 = 100% survival; 1 = 0% survival), and monthly medium temperatures (°C) and moisture levels (kPa) between blocks for each year and for December through February and for *Sedum* only (all, and only for those that survived in Year I).

Yr	Block number				
	Block 1	Block 2	Block 3	Block 4	All
Year I					
Survival	2.3 b ^z	2.2 ab	2.0 a	2.1 ab	2.2
All <i>Sedum</i> survival	2.6 a	2.5 a	2.2 a	2.3 a	2.4
<i>Sedum</i> (only those that survived (>1.0))	3.6 b	3.3 ab	2.9 a	3.0 ab	3.2
Temp (Dec.–Feb.) only	−6.7 b	−9.2 a	−9.2 a	−8.1 ab	−8.3
Moisture (Dec.–Feb.)	−185 a	−187 ab	−187 ab	−197 b	−189
Year II					
Survival	2.4 ab	2.1 a	2.7 b	2.5 b	2.4
Temp (Dec.–Feb.)	−2.6 b	−9.2 a	−2.9 b	−2.5 b	−4.3
Moisture (Dec.–Feb.)	−175 a	−184 ab	−187 ab	−189 ab	−184
ANOVA					
	Total	Dec.–Feb. only			
Year	NS ^y	NS			
Block	**	***			
Year × block	*	***			

^zLowercase letters indicate mean separation between blocks across species using Tukey's honestly significant difference ($P = 0.05$) following analysis of variance (ANOVA) within a year.

^yDenotes statistical significance as determined by ANOVA; NS, *, **, ***nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

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* performed well (Table 2). Between *Sempervivum* and *Sedum*, *Sempervivum* appears to be less cold tolerant than *Sedum* (personal observation), therefore, it was not surprising that *Sedum* appeared to survive a northern roof (US Hardiness zone 4/5) better than *Sempervivum*. Among *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. caudicola* 'Sunset Cloud', *Sedum* 'Czar's Gold', *S. ellecombianum*, *S. hybridum* 'Immergruchen', *S. requieni*, *S. sexangulare*, and *S. spurium* 'Dragon's Blood', 'John Creech', 'Pearly Pink', 'Ruby Mantle', and 'Tricolor' 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. caudicola*, *S. reflexum* performed well in our study, but performed poorly in other studies (Durhman et al., 2007; Getter and Rowe, 2009; Kozminska et al., 2019). Differences in results may, in part, be related to differences in medium depth. For instance, in a study in on an

unirrigated extensive green roof in southern Michigan (USA), *Sedum* winter 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.

Whether deeper media increases survival because of increased water availability or more moderate media temperature is unclear. Boivin et al. (2001) reported *Sedum* survival on an extensive green roof in Quebec was limited by cold temperatures. In a more recent study, (Kozminska et al., 2019) evaluated the impact of drought on *Sedum* survival on a green roof; they found *S. spurium* and *album* were the most, and least drought tolerant, respectively. Interestingly, *Sedum* species vary in the degree they conduct C3 vs. Crassulacean acid metabolism (CAM) photosynthesis which can influence water

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

^zLowercase letters indicate mean separation between species within a year^z or between years^y using Tukey's honestly significant difference.

^yDenotes statistical significance as determined by analysis of variance (ANOVA). ***Significant at $P \leq 0.001$.

use and survival on a green roof; *Sedum kamschaticum* switched from C3 to CAM photosynthesis on a green roof in a study by Starry et al. (2014), which increased *S. kamschaticum* water use efficiency, however, *S. album* had higher water use efficiency than *S. kamschaticum* 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 6. Best performing species/varieties [both high survival (≥ 3.0) and vigor (≥ 50) scores], and good performing species/varieties [both good survival (≥ 2.5 to < 3.0) and vigor (≥ 25 to < 50)].

Best performing species/varieties	Good performing species/varieties
<i>Allium cernuum</i>	<i>Antennaria dioica</i> 'Rubra'
<i>Allium senescens</i> 'Glaucum'	<i>Aster alpinus</i> 'Dunkle Schone'
<i>Festuca ovina</i> VNS	<i>Festuca longifolia</i> 'Osprey'
<i>Geum triflorum</i>	<i>Festuca rubra</i> var. <i>commutata</i> 'Jamestown II'
<i>Koeleria macrantha</i> 07-901 ND	<i>Papaver alpinum</i>
<i>Panicum virgatum</i>	<i>Pulsatilla vulgaris</i>
<i>Sedum acre</i>	<i>Sedum album</i> 'Murale'
<i>Sedum album</i> 'Coral Carpet'	<i>Sedum</i> 'Blue Spruce'
<i>Sedum cauticola</i> 'Sunset Cloud'	<i>Sedum reflexum</i> 'Green Spruce'
<i>Sedum</i> 'Czar's Gold'	<i>Sedum rupestre</i> 'Angelina'
<i>Sedum ellecombianum</i>	<i>Sedum spectabilis</i> 'Brilliant'
<i>Sedum hybridum</i> 'Immergruchen'	<i>Sedum spurium</i> 'Purple Carpet'
<i>Sedum requienii</i>	<i>Sedum spurium</i> 'Summer Glory'
<i>Sedum sexangulare</i>	
<i>Sedum spurium</i> 'Dragon's Blood'	
<i>Sedum spurium</i> 'John Creech'	
<i>Sedum spurium</i> 'Pearly Pink'	
<i>Sedum spurium</i> 'Ruby Mantle'	
<i>Sedum spurium</i> 'Tricolor'	
<i>Sporobolus heterolepis</i>	
<i>Talinum calycinum</i>	
<i>Thymus praecox</i> 'Red Creeping'	

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 Schone' (native to European Alps with subspecies native in Canada and United States) and *Thymus praecox* 'Red Creeping' (indigenous to palearctic 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 (Bousselot, 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 than 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 Schone' (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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