Observations on the survival of 112 plant taxa on a green roof in a semi-arid climate

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Schneider, A., Fusco, M. & Bousselot, J., 2014. Observations on the Survival of 112 Plant Taxa on a Green Roof in a Semi-Arid Climate, Journal of Living Architecture. 1*(5): 10-30. http://greenroofs.org/resources/JOLA2014Volume1(Issue5)Schneider(etal).pdf*

Abstract

The Denver Botanic Gardens (DBG) green roof, built in November 2007, is the first green roof on a city owned building in Denver, Colorado. To date, 112 plant taxa have been trialed, observed, and described on this low water green roof in the high and dry climate of the Colorado Front Range. Plant taxa survival was documented based on the original number of plants installed, and the surviving plants were rated on a scale of 1-4. Additionally, in 2011-2013, plant heights and widths were recorded. The data indicate that taxa can be grouped into categories of perish, survive, and thrive.

Key Words: green roof, semi-arid, plant evaluation

Introduction

Increasing plant taxa richness on a green roof may provide environmental and ecosystem benefits (Cook-Patton and Bauerle 2012, Lundholm et al., 2010). An initial step in increasing taxa richness options available for green roofs is large scale and long-term evaluation of various plant taxa for their suitability on green roofs (Dvorak and Volder 2010). Over the last six growing seasons, 112 plant taxa have been trialed on the DBG green roof.

Despite the fact that water is often limiting on green roofs, select plants can thrive in the semi-arid high elevation of the Colorado Front Range. To demonstrate that green roofs and water conservation can co-exist, the DBG green roof receives less than one inch of additional irrigation per month during the growing season. Most planted landscapes in the semi-arid climate of the Colorado Front Range, are irrigated with larger quantities of water during the growing season. Other researchers have found green roofs grown under dry conditions perform better with diverse plant taxa communities (Nagase and Dunnett 2010).

It is ideal for DBG to evaluate as many plant taxa as possible on the green roof, even those that are considered marginally hardy or may not initially seem ideally suited to a shallow, well-drained substrate. This premise is supported in the literature and pointed out in a literature review (Cook-Patton and Bauerle 2012). The results from European studies indicate how annual variability, especially lack of moisture, can affect overall plant performance (Dunnett et al., 2008, Köhler 2006) and therefore demonstrate the need for long-term evaluation. A list of over one thousand plants will eventually be trialed on the DBG green roof, which fits into the goal of adding to the plant taxa richness available for use on green roofs. Adding more plants to the existing plant palette can help mitigate future issues such as those associated with *Sedum* monoculture green roofs (Sutton et al., 2012).

Plant taxa being considered for planting on a green roof are selected for a variety of characteristics including their rate of establishment, environmental tolerances, commercial availability, aesthetic value and potential to add quality to local wildlife habitat. Increasing functional group diversity, and therefore structural complexity, by plant forms (i.e. woody

shrubs, herbaceous perennials, groundcovers, carpet formers, grasses) is ideal and can theoretically help increase the resilience of the green roof (Cook-Patton and Bauerle 2012, Lundholm et al., 2010). Therefore, the objective of this observational and descriptive study is long term evaluation of numerous plant taxa as potential green roof taxa for use in a high and dry climate.

Materials and Methods

The DBG green roof was installed in the fall of 2007 above a one-story building adjacent to the southeast of the Boettcher Memorial Tropical **Conservatory (Figure 1)**. It is 110 square meters of combined extensive and intensive green roof. Most of the roof has 15 cm of substrate with a gradual rise in depth at the southeast corner of the roof where the substrate reaches a maximum of 45 cm in the form of a small berm. The substrate consists of 80% by volume expanded shale, and 20% by volume of compost and composted bark custom blended for the DBG green roof. Mycorrhizae were added to the substrate at planting in fall of 2007. In spring of 2009, 6.35 mm of locally produced compost (Timberline Gardens, Arvada, CO) was broadcast on the surface of the green roof. No other fertility has been provided to the roof during the time of the evaluation.

Figure 1. The top image is of the Denver Botanic Gardens green roof in spring of 2008 (photo credit: Mark Fusco). The bottom image is of the green roof in summer of 2013 (photo credit: Amy Schneider).

Plants

Between the growing seasons of 2007-2012, a total of 112 plant taxa were installed on the green roof. Many of these plants were propagated onsite at DBG with little additional cost; however, many are also available commercially or as seed. Typically on the DBG green roof, if a plant fails to thrive in its original location, it will be trialed a second time in a different location on the green roof.

Planting dates varied by taxa over the six growing seasons (Table 1) and five of the taxa were planted during more than one year. At the initial installation in 2007, 53 plant taxa were planted , in 2008 15 more taxa were added, in 2009 five plant taxa were planted, in 2010 20 additional plant taxa were planted, in 2011 17 more were planted, and in 2012 seven plant taxa were added (Table 1). Among the plants trialed, five growth forms are represented and can be used to categorize plant type similar to evaluations done in Halifax, Canada (MacIvor and Lundholm 2011): creeping forb (in our case this only includes non-succulents and had a subcategory of bun formers which are noted), graminoid, woody shrub, and in this study we distinguished non-carpet forming forbs by categorizing them as upright forbs instead of tall forbs and we separated succulents into their own categories due to their unique adaptations to the extremely dry environment (Table 1).

Table 1. Plant information for the 112 taxa included in the evaluation, including growth form category and year(s) planted.

Scientific Name	**Common Name**	**Form**	**Months since planting till Sep 2012[x] (year planted)**
Acantholimon acerosum	acantholimon, spike thrift	creeping forb, bun	53 (2008)
Acantholimon armenum	acantholimon, spike thrift	creeping forb, bun	53 (2008)
Acantholimon litvinovii	acantholimon, spike thrift	creeping forb, bun	53 (2008)
Aethionema schistosum	fragrant Persian stonecress	creeping forb	59 (2007)
Agave parryi	Parry's agave	succulent	53 (2008)
Amorpha fruticosa 'Nana'	dwarf false indigo	woody shrub	41 (2009)
Anacyclus maroccanus	Moroccan chamomile	creeping forb	17 (2011)
Andropogon ternaries	splitbeard bluestem	graminoid	12 (2012)
Andropogon virginicus	broomsedge bluestem	graminoid	12 (2012)
Antennaria parvifolia 'McClintock'	dwarf pussytoes	creeping forb	59 (2007)
Arctostaphylos 'Lauren's Best'	Lauren's Best manzanita	woody shrub	59 (2007)
Arctostaphylos patula	greenleaf manzanita	woody shrub	59 (2007)
Arctostaphylos x*coloradoensis* 'Cascade'	cascade manzanita	woody shrub	59 (2007)
Arenaria alfacarensis	Spanish sandwort	creeping forb	59 (2007)
Artemisia spp.	wormwood	creeping forb	59 (2007)
Atriplex confertifolia	shadescale sagebrush	woody shrub	29 (2010)
Baileya multiradiata	desert marigold	upright forb	41 (2009)
Braya alpine	smooth rockcress	upright forb	29 (2010)
Campanula incurve	Evia bellflower	upright forb	17 (2011)
Campanula kemulariae	bellflower, blue bells	upright forb	29 (2010)

Cercocarpus breviflorus	hairy mountain mahogany	woody shrub	59 (2007)
Chamaebatiaria millefolium	desert sweet	woody shrub	59 (2007)
Chilopsis linearis	desert willow	woody shrub	59 (2007)
Chrysanthemum weyrichii	dwarf chrysanthemum	creeping forb	59 (2007)
Clematis columbiana var. *tenuiloba*	rock clematis	creeping forb	17 (2011)
Cotula hispida	silver cotula	creeping forb	59 (2007), 29 (2010)
Cotyledon orbiculata	pigs ear	succulent	12 (2012)
Cytisus purgans 'Spanish Gold'	Spanish Gold broom	woody shrub	59 (2007)
Delosperma cooperi	hardy ice plant	succulent	59 (2007)
Delosperma 'Kelaidis'	Mesa Verde ice plant	succulent	59 (2007), 53 (2008)
Delosperma nubigenum	yellow ice plant	succulent	59 (2007)
Dianthus anatolicus	Anatolian pink	creeping forb, bun	53 (2008)
Draba hispanica	Spanish draba	creeping forb	59 (2007)
Draba streptocarpa	pretty draba	creeping forb, bun	29 (2010)
Dryas octopetala var. *hookeriana*	Hooker's mountain-avens	creeping forb	29 (2010)
Echinocereus fendleri	Fendler's hedgehog cactus	succulent	41 (2009)
Echinocereus triglochidiatus	kingcup cactus	succulent	59 (2007)
Echinocereus triglochidiatus white sands strain	White Sands kingcup cactus	succulent	59 (2007)
Echinocereus viridiflorus	nylon hedgehog cactus	succulent	59 (2007)
Echium amoenum	red feathers	upright forb	59 (2007)
Ephedra minuta	miniature joint fir	woody shrub	29 (2010)
Ericameria nauseosa ssp. *nauseosa* var. *nauseosa*	rubber rabbitbrush	woody shrub	59 (2007)
Erigeron elatior	tall fleabane	upright forb	17 (2011)
Erigeron leiomerus	rockslide yellow fleabane	creeping forb	17 (2011)
Erigeron vetensis	early bluetop fleabane	creeping forb	29 (2010)

Eriogonum umbellatum var. *aureum*	sulphur flower buckwheat	creeping forb	59 (2007), 53 (2008)
Erysimum capitatum var. *purshii*	alpine wallflower	upright forb	17 (2011)
Escobaria missouriensis	Missouri foxtail cactus	succulent	59 (2007)
Escobaria vivipara	spinystar	succulent	59 (2007)
Euonymus nanus var. *turkestanicus*	Turkistan burning bush	woody shrub	59 (2007)
Euphorbia polychroma 'Candy'	yellow cushion spurge	upright forb	53 (2008)
Fendlera rupicola var. *wrightii*	Wright's fendlerbush	woody shrub	59 (2007)
Festuca brachyphylla	alpine fescue	graminoid	12 (2012)
Hedeoma clone	pennyroyal	upright forb	17 (2011)
Herniaria glabra	green carpet	creeping forb	59 (2007)
Herniaria glabra 'Sea Foam'	Sea Foam green carpet	creeping forb	53 (2008)
Hesperaloe parviflora	red yucca, hummingbird yucca	succulent	59 (2007), 53 (2008)
Heteropappus spp.	Heteropappus	creeping forb	29 (2010)
Heterotheca jonesii	Jones' false goldenaster	creeping forb	59 (2007)
Hypericum olympicum	Mount Olympus St. John's wort	woody shrub	17 (2011)
Ipomopsis aggregate	scarlet gilia	upright forb	29 (2010)
Ipomopsis rubra	standing cypress	upright forb	53 (2008)
Iris germanica dwarf	dwarf Germanic iris	upright forb	59 (2007)
Leucanthemum atlanticum	daisy (from Morocco)	creeping forb	17 (2011)
Maihuenia poeppigii	chupasangre	succulent	53 (2008)
Muhlenbergia emersleyi	bullgrass	graminoid	12 (2012)
Muhlenbergia Montana	mountain muhly	graminoid	12 (2012)
Nolina microcarpa	beargrass	graminoid	59 (2007)
Olsynium biflorum	grass widow	upright forb	17 (2011)
Opuntia aurea	golden pricklypear	succulent	59 (2007)
Opuntia phaeacantha	tulip pricklypear	succulent	59 (2007)

Opuntia polyacantha	plains pricklypear	succulent	59 (2007)
Panicum virgatum	switchgrass	graminoid	59 (2007)
Paronychia kapela ssp. *Serpyllifolia*	nailwort	creeping forb, bun	59 (2007)
Pediocactus simpsonii	mountain ball cactus	succulent	59 (2007)
Penstemon angustifolius	broadbeard beardtongue	upright forb	29 (2010)
Penstemon caespitosus	mat penstemon	creeping forb	59 (2007)
Penstemon cyananthus	Wasatch beardtongue	upright forb	29 (2010)
Penstemon fendleri	Fendler's penstemon	upright forb	59 (2007)
Penstemon grahamii	Graham beardtongue	creeping forb	29 (2010)
Penstemon linarioides ssp. *Coloradensis*	Colorado narrowleaf beardtongue	creeping forb	59 (2007)
Penstemon pinifolius	pineleaf penstemon	creeping forb	41 (2009)
Petrophytum caespitosum	mat rockspirea	creeping forb	29 (2010)
Phacelia campanularia	California bluebells	upright forb	41 (2009)
Phedimus kamtschaticus/ Sedum kamtschaticum	Russian stonecrop	succulent	59 (2007)
Phemeranthus calycinus	largeflower flameflower	succulent	53 (2008), 17 (2011)
Phlox bifida 'Betty Blake'	cleft phlox	creeping forb	59 (2007)
Physaria bellii	front range twinpod	creeping forb	59 (2007)
Poa fendleriana	muttongrass	graminoid	12 (2012)
Potentilla hyparctica	arctic cinquefoil	creeping forb	59 (2007)
Potentilla nepalensis 'Shogran'	Nepal cinquefoil	creeping forb	29 (2010)
Putoria calabrica	stinking madder	upright forb	17 (2011)
Salvia cryptantha	salvia	upright forb	17 (2011)
Salvia 'Eskihar'	Eskihar sage	creeping forb	17 (2011)
Salvia greggii	autumn sage	woody shrub	53 (2008)
Salvia pachyphylla	mountain desert sage	upright forb	59 (2007)
Scutellaria prostrate	prostrate skullcap	creeping forb	17 (2011)

Scutellaria scordifolia	skullcap hyssop	creeping forb	29 (2010)
Sedum lanceolatum	spearleaf stonecrop	succulent	59 (2007)
Sedum rupestre	blue stonecrop	succulent	17 (2011)
Silene schafta	autumn catchfly	creeping forb	29 (2010)
Streptanthus cordatus	heartleaf twistflower	creeping forb	29 (2010)
Teucrium aroanium	gray creeping germander	creeping forb	29 (2010)
Teucrium graphaloides	germander	creeping forb	17 (2011)
Thelesperma ambiguum	Colorado greenthread	upright forb	59 (2007)
Thymus neiceffi	juniper leaf thyme	creeping forb	59 (2007)
Townsendia eximia	Townsend's daisy	upright forb	59 (2007)
Vella spinosa	fine broom, spiny broom	creeping forb	17 (2011)
Veronica liwanensis	Turkish speedwell	creeping forb	59 (2007)
Veronica pectinata	woolly speedwell	creeping forb	59 (2007)
Veronica thymoides	Thyme-leaf speedwell	creeping forb	59 (2007)
Ziziphora bungeana	Ziziphora	upright forb	17 (2011)

[x]The only exception is for the graminoid taxa, which were evaluated in May 2013.

Environmental Conditions

The conditions on the DBG green roof are quite variable both spatially and temporally. Due to the multitude of plant growth forms, several niches are present on the roof, allowing for more complementary resource use (Cook-Patton and Bauerle 2012, Köhler 2006). An example of a niche created is the shade provided by the upright second year growth of the biennial taxa of *Ipomopsis*; other plants benefit from the reduction in transpiration and solar irradiance provided by the additional shade, similar to the survival benefits of shading described in another study that was also located in Denver, CO (Bousselot et al., 2013). Due to the very low moisture conditions present on the green roof, portions of the substrate are exposed and surrounding concrete and glass structures, combined with little air movement, create very high temperature growing conditions during the summer. Winter weather is characterized by warm days where solar gain from surrounding structures heats up the green roof and then drops to freezing temperatures at night. The extreme temperature fluctuations and very low moisture on this green roof make it difficult for a plant to survive. Therefore, if it they do survive on this roof, they are likely to survive on green roofs almost anywhere along the front range of Colorado.

Precipitation in Denver, CO averages only 381 mm annually, thus irrigation was installed on the DBG green roof. Irrigation on the DBG green roof has been variable, with approximately one half of the roof (the majority of the 15 cm depth) irrigated via underground drip irrigation (RainBird XF series with 2.3 lph emitters spaced at 30.5 cm centers); the remaining half of the green roof irrigated via popup sprinkler heads (RainBird 2.8 lph rotary nozzles). During the 2008 and 2009 growing seasons (following the fall 2007 installation), plants were still being established and were irrigated as needed with at least 12.7 mm of automatic irrigation twice each week and 30-45 minutes of hand watering twice each week during the growing season. This agrees with the premise noted by others that plants native to prairie locations need several years for establishment and may require supplemental irrigation (Sutton 2008). Since the spring of 2010, the irrigation regime has varied depending on precipitation but the irrigation system is not turned on until July, and no more than 2.5 cm of water is applied per month, not to exceed 20 cm per growing season.

Data Collection and Analysis

Three data types are collected annually on most of the taxa on the green roof. Survivability was documented based on the original number of plants installed. Visual ratings of the surviving plants are gauged for foliage and overall appearance on a scale of 1-4 with 1 as the lowest (poorest) rating and 4 the highest rating. Additionally, in 2011 and 2012, plant heights and widths were recorded; a growth index was calculated from the plant height and widths similar to Monterusso *et al.* (2005) where (h+w1+w2)/3.

Results and Discussion

Based on survival and visual rating data, plant taxa were grouped into categories of perish, survive, and thrive. Plant taxa in the category of perish had 0% survival, no visual rating and no recordable growth by the summer of 2012, regardless of their planting date. Plant taxa in the category of survive had up to 74% survival rates (slightly stricter than successful overwintering rates described in Bousselot et al., 2010) as well as a visual rating of 1-3. Plant taxa that survived at 75% or greater and had a visual rating of 3-4 were considered to thrive. Growth indices (labeled as size) varied within growth form. Results of plant taxa survival are reported by plant growth form: creeping forb, upright forb, graminoid, shrub, or succulent.

Creeping Forbs

For plants in the creeping forb category (Table 2), 28 of 45 plants, or 62%, were placed in the category of perish. While these plants may have merit on green roofs in ecoregions other than the Central High Plains (Dvorak and Volder 2010), they did not survive up to 6 years in Denver's semi-arid, high elevation climate. In time, some plants in this category may be trialed again on the DBG green roof. The majority of the plants in this category (e.g., *Erigeron* spp., *Hernieria* spp. etc.) have taproots, which are ecological adaptations for accessing deep, stable supplies of water. Because extensive green roofs are shallow and do not typically have deep stable supplies

of water, tap-rooted plants may not be ideal candidates for extensive green roof systems (Nagase and Dunnett 2010).

Table 2. Creeping forb relative survival rates, visual ratings, growth index (size), and category type in September 2012.

Scientific Name	**Planted**	**Survive**	**% Survival**	**Rating**	**Size** (cm)	**Category**
Acantholimon litvinovii	5	5	100%	3	12.70	Thrive
Chrysanthemum weyrichii	16	16	100%	4	71.12	Thrive
Draba hispanica	3	mass	>100%	3	12.70	Thrive
Phlox bifida 'Betty Blake'	1	1	100%	4	40.64	Thrive
Physaria bellii	64	mass	100%	4		Thrive
Thymus neiceffi	9	mass	100%	3	13.55	Thrive
Streptanthus cordatus	32	30	94%	3	60.96	Thrive
Penstemon pinifolius	6	5	83%	4	25.40	Thrive
Veronica thymoides	8	6	75%	3	20.32	Thrive
Cotula hispida	9, 21	20	66%	1.5	13.55	Survive
Acantholimon acerosum	4	2	50%	2.5	very small	Survive
Eriogonum umbellatum var. *aureum*	18	9	50%	2	44.03	Survive
Dianthus anatolicus	28	11	39%	3	13.55	Survive
Aethionema schistosum	3	1	33%	3	6.77	Survive
Artemisia spp.	32	10	31%	1	dying	Survive
Acantholimon armenum	5	1	20%	1	small	Survive
Penstemon caespitosus	11	2	18%	2	10.16	Survive
Anacyclus maroccanus	6	0	0%	0		Perish
Antennaria parvifolia 'McClintock'	64	0	0%	0		Perish
Arenaria alfacarensis	16	0	0%	0		Perish
Clematis columbiana var. *tenuiloba*	2	0	0%	0		Perish
Draba streptocarpa	32	0	0%	0		Perish

Dryas octopetala var. *hookeriana*	10	0	0%	0		Perish
Erigeron leiomerus	6	0	0%	0		Perish
Erigeron vetensis	27	0	0%	0		Perish
Herniaria glabra	2	0	0%	0		Perish
Herniaria glabra 'Sea Foam'	18	0	0%	0		Perish
Heteropappus spp.	2	0	0%	0		Perish
Heterotheca jonesii	32	0	0%	0		Perish
Leucanthemum atlanticum	9	0	0%	0		Perish
Paronychia kapela ssp. *serpyllifolia*	16	0	0%	0		Perish
Penstemon grahamii	1	0	0%	0		Perish
Penstemon linarioides ssp. *Coloradensis*	12	0	0%	0		Perish
Petrophytum caespitosum	3	0	0%	0		Perish
Potentilla hyparctica	16	0	0%	0		Perish
Potentilla nepalensis 'Shogran'	3	0	0%	0		Perish
Salvia 'Eskihar'	3	0	0%	0		Perish
Scutellaria prostrata	20	0	0%	0		Perish
Scutellaria scordifolia	4	0	0%	0		Perish
Silene schafta	23	0	0%	0		Perish
Teucrium aroanium	4	0	0%	0		Perish
Teucrium graphaloides	8	0	0%	0		Perish
Vella spinosa	3	0	0%	0		Perish
Veronica liwanensis	9	0	0%	0		Perish
Veronica pectinata	13	0	0%	0		Perish

Plants in the category of survive may be better candidates for retrial or for use on green roofs that receive either greater amounts or more frequent irrigations. Eight of the 45 plants, or 18%, were placed in the category of survive; all of which yielded between 18% and 66% survival with visual ratings of 1-3 on the green roof. Size determined by the growth index showed a variance of two small to measure up to 44.03 cm, with the majority coming in at approximately 12 cm.

Plants in this category are from genera that have shown success in other green roof studies including *Artemisia* (Sutton et al., 2008), *Dianthus* (Dunnett et al., 2008), and *Penstemon caespitosus* (Armstrong 2009). While some taxa have been shown to have very low survival in dry locations, for example *Cotula hispida* (Damas et al., 2010) and *Eriogonum umbellatum* var. *aureum* (Bousselot et al., 2010), *E. umbellatum* var. *aureum* was not unsuccessful when placed in a more protected location (Bousselot et al., 2013). These variable results suggest that taxa should not be entirely discounted just because they fail to thrive in one set of conditions.

An additional nine plants of the 45 creeping forbs, or 20%, were considered in the thrive category, all of which yielded between 75% and >100% survival with visual ratings of 3-4 on the green roof. Three of the genera have been published in green roof evaluations, *Draba* (Boivin et al., 2001), *Thymus* (Bousselot et al., 2011, Schroll et al., 2009), and *Veronica* (Dunnett et al., 2008). Only two taxa of the nine that thrived on the DBG green roof have even been documented as being used in the context of green roofs: *Penstemon pinifolius* (Bousselot et al., 2011) and *Phlox bifida* (Sutton et al., 2012). This illustrates that some plant taxa have proven to be successful in difficult climates, such as that of Denver, CO, but these taxa have not been widely evaluated in green roof trials in other ecoregions, thus supporting the need for additional plant taxa evaluations on green roofs in more ecoregions (Dvorak and Volder 2010).

The subcategory of bun forming creeping forbs yielded a noteworthy number of plants that survived or thrived, specifically five out of six (Tables 1 and 2). *Acantholimon litvinovii* and *Draba hispanica* thrived, while *Dianthus anatolicus* and both *Acantholinum acerosum*, and *A. armenum* were categorized as survive. Only one taxa of the group of bun formers in this evaluation, *Paronychia kapela* ssp. *serpyllifolia,* perished. These results suggest that bun forming creeping forbs are likely good candidates for taxa that may survive on extensive green roofs, especially in semi-arid climates. However, their extremely small size and slow horizontal growth rates may limit their large-scale adoption for use in systems that cover large areas of rooftop.

Upright Forbs

Twenty three taxa of upright forbs have been evaluated on the DBG green roof. Sixteen of those 23 plants, or 70%, have perished. This may indicated that upright forbs have limited use on extensive green roofs in low irrigation locations. Two of the taxa, or 9%, *Campanula incurva* and *Penstemon angustifolius* had marginal survival rates (33% and 50%, respectively) and are therefore in the survive category. No size or rating was recorded on *C. incurva*, which indicates that the two remaining plants were barely viable. Two plants of *P. angustifolius* were installed and even though only one survived, it is large (60.69 cm) with a high visual rating of 4, therefore, it may be a good candidate for additional trial.

Table 3. Upright forb relative survival rates, visual ratings, growth index (size), and category type in September 2012.

Scientific Name	**Planted**	**Survive**	**% Survival**	**Size** (cm)	**Rating**	**Category**
Echium amoenum	4	4	100%	21.17		Thrive
Ipomopsis aggregata	18	Reseeded	>100%	71.12	4	Thrive
Ipomopsis rubra	16	Reseeded	>100%	71.12	4	Thrive
Iris germanica dwarf	26	26+	>100%	40.64	3	Thrive
Thelesperma ambiguum	32	Mass	100%		3.5	Thrive
Penstemon angustifolius	2	1	50%	60.96	4	Survive
Campanula incurva	6	2	33%			Survive
Baileya multiradiata	seed	0	0%			Perish
Braya alpina	12	0	0%			Perish
Campanula kemulariae	1	0	0%			Perish
Erigeron elatior	8	0	0%			Perish
Erysimum capitatum var. *purshii*	31		0%			Perish
Euphorbia polychroma 'Candy'	mass	0	0%			Perish
Hedeoma clone	3	0	0%			Perish
Olsynium biflorum	4	0	0%			Perish
Penstemon cyananthus	6	0	0%			Perish
Penstemon fendleri	8	0	0%			Perish
Phacelia campanularia	seed	0	0%			Perish
Putoria calabrica	32	0	0%			Perish
Salvia cryptantha	5	0	0%			Perish
Salvia pachyphylla	3	0	0%			Perish
Townsendia eximia	24	0	0%			Perish
Ziziphora bungeana	17	0	0%			Perish

Only four, or 17%, of the upright forbs thrived, none of which can be found in the literature associated with green roofs. Their relatively large size (range of 21.17-71.12cm) and high visual ratings suggest that these upright forbs are good candidates for green roofs. However, with just over a quarter of the upright taxa qualifying in the survive or thrive categories, it may need to be considered what types of upright taxa are ideally suited to the environment on a green roof. Two of the taxa, both in the genus *Ipomopsis*, reseed and therefore may be good examples of the type of upright plants suitable for use on green roofs; their ability to move around the roof to where resources are available may benefit their long term survivability, similar to observances noted during a 20 year evaluation of the alternation of taxa with a portion of them reseeding on two rooftops in Berlin, Germany (Köhler 2006).

While bulbs and similar types of plants have had little published evaluation on green roofs, besides *Allium* spp., their belowground carbohydrate and water storage adaptations are ideally suited to the difficult conditions on an extensive green roof. Many *Iris* spp. have the additional benefit of a horizontally spreading habit, as is the case with the cultivar included in this study. Species tulips were trialed on this green roof, however, since none of them emerged, they were not included in this evaluation.

Graminoids

While the majority of the graminoid taxa being evaluated in this study have only recently been incorporated into the evaluation, they show early promise. Of the eight graminoid taxa being evaluated, six of them were planted in 2012, and were therefore not included in the evaluation of plant size or rating. However all six of the new graminoid taxa, plus *Nolina microcarpa* (planted in 2007) have demonstrated 100% survival as of May 2013, therefore they have been categorized under thrive. The remaining graminoid taxon, *Panicum virgatum*, has had half of the original 2007 planting survive.

The relative success of graminoids as a group is consistent with results found previously (MacIvor and Lundholm 2011) where graminoid taxa had the highest growth rates of all the lifeforms they evaluated in Halifax, Canada. Additionally, nine of the 15 most dominant taxa (i.e. found most consistently over the years) during a 20 year evaluation on a non-irrigated and non-sedum extensive green roof in Berlin, Germany, were graminoid taxa. While others have also had success evaluating graminoid taxa on extensive green roofs (Bousselot et al., 2010, Simmons et al., 2008, Sutton 2008), grasses remain largely ignored compared to succulents for use on extensive green roofs.

Table 4. Graminoid relative survival rates, visual ratings, growth index (size), and category type in May 2013.

Scientific Name	**Planted**	**Survive**	**% Survival**	**Size** (cm)	**Rating**	**Category**
Andropogon ternarius	10	10	100%			Thrive

Andropogon virginicus	10	10	100%			Thrive
Festuca brachyphylla	64	64	100%			Thrive
Muhlenbergia emersleyi	10	10	100%			Thrive
Muhlenbergia montana	64	64	100%			Thrive
Nolina microcarpa	3	3	100%	40.64	3	Thrive
Poa fendleriana	64	64	100%			Thrive
Panicum virgatum	6	3	50%	49.11		Survive

Shrubs

The woody shrubs in this evaluation were concentrated primarily on or near the bermed portion of the green roof, which reached a depth of 45cm. Several genera among these shrubs are used in steep bank stabilization (*Cystisus* spp., *Ericameria* spp., *Euonymus* spp., etc.), which can be a rough equivalent to an intensive green roof with shallow soils and low moisture content of the soil. Overall they had good survivability, with only two of the 15 woody shrubs, or 13%, in the category of perish; while five, or 33%, of the 15 shrubs were categorized as survive. Their relative sizes were small for woody plants ranging from 13.55-60.69cm and visual ratings of 2-2.5.

Eight, or 53%, of the 15 taxa thrived. This group of plants was larger (range of 30.48-152.40cm) and visual ratings of 3-4. Two of these taxa have even begun to reseed, *Amorpha fruticosa* 'Nana' has had three seedlings become established and *Ericameria nauseosa* spp. *nauseosa* var. *nauseosa* has had several seedlings emerge around the roof. Despite the success of these taxa, few mentions have been made in the literature about these genera in reference to green roofs only *Amorpha* (Armstrong 2009, Sutton et al., 2012), *Arctostophylos* (Sutton et al., 2012) and *Euonymus* (Köhler 2006). The only two taxa included in green roof literature are *Chilopsis linearis* (Dakin et al., 2013) and *Salvia greggii* (Simmons et al 2008).

Table 5. Shrub relative survival rates, visual ratings, growth index (size), and category type in September 2012.

Scientific Name	**Planted**	**Survive**	**% Survival**	**Size** (cm)	**Rating**	**Category**
Amorpha fruticosa 'Nana'	3	4	133%	33.02	4	Thrive
Cercocarpus breviflorus	3	3	100%	91.44	3	Thrive
Chamaebatiaria millefolium	3	3	100%	119.38	3	Thrive
Chilopsis linearis	2	2	100%	152.40	4	Thrive
Ericameria nauseosa ssp.	5	seeded	>100%	30.48	3	Thrive

nauseosa var. *nauseosa*						
Euonymus nanus var. *turkestanicus*	5	5	100%	60.96	3	Thrive
Salvia greggii	5	5	100%	81.28	3	Thrive
Ephedra minuta	6	5	83%	30.48	3	Thrive
Arctostaphylos 'Lauren's Best'	1	1	100%	60.96	2	Survive
Arctostaphylos patula	2	2	100%	14.39	2	Survive
Arctostaphylos x *coloradoensis* 'Cascade'	2	2	100%	60.96	2	Survive
Atriplex confertifolia	6	2	33%	13.55	2.5	Survive
Cytisus purgans 'Spanish Gold'	3	1	33%	27.09	3	Survive
Fendlera rupicola var. *wrightii*	64	0	0%			Perish
Hypericum olympicum	4	0	0%			Perish

Succulents

Due to the large scale adoption and investigation of succulents on extensive green roofs throughout North America (Dvorak and Volder 2010, Snodgrass and Snodgrass 2006), predictably, the succulents as a group did very well in this observational evaluation. Only one, or 5%, of the 21 succulents, *Cotyledon orbiculata*, failed to survive overwintering on the DBG green roof, most likely due to the fact that it is not winter hardy in Denver's climate. This concurs with what others have noted that plant hardiness zones remain the same even if winters seem warmer on rooftops (Snodgrass and Snodgrass 2006).

Seven, or 33%, of the 21 succulents were categorized as survive; six of those are slow growing cacti which prefer little competition for resources; size ranged from 4.23-24.55cm and ratings of 1.5-3. *Delosperma* 'Kelaidis' survived but will likely do better as more shade develops on the green roof as it prefers partial shade in the high elevation and high solar radiation environment of Denver. The remaining fourteen succulents, or 62%, thrived. They had high visual ratings of 3-4 and large growth indexes 15.24-132.08cm. The only *Agave parryi* to perish was simply due to the fact that it bloomed and parent plants of *Agave* die after blooming. The genera of *Delosperma* (Bousselot et al., 2010, Bousselot et al., 2011, Schroll et al., 2011) *Opuntia* (Bousselot et al., 2010, Monterusso et al., 2005), *Phemeranthus* (formerly *Talinum* spp.; Getter et al., 2009, Snodgrass and Snodgrass 2006) and of course the frequently used *Sedum* have been evaluated for use on green roofs but rarely *Agave*, *Echinocereus*, or *Hesperaloe parvifolia* (Simmons et al., 2008). While it is well-known that succulents thrive on green roofs, it was speculated that they may not need to be irrigated, even in this very dry environment.

Table 6. Succulent relative survival rates, visual ratings, growth index (size), and category type in September 2012.

Scientific Name	**Planted**	**Survive**	**% Survival**	**Size** (cm)	**Rating**	**Category**
Delosperma cooperi	12	mass	100%	45.72	3	Thrive
Delosperma nubigenum	21	21	100%	62.65	4	Thrive
Echinocereus fendleri	mass	6	100%	15.24	4	Thrive
Echinocereus triglochidiatus white sands strain	2	2	100%	19.47	3	Thrive
Hesperaloe parviflora	8, 5	13	100%	101.60	3	Thrive
Opuntia aurea	mass	all	100%	101.60	4	Thrive
Opuntia phaeacantha	mass	all	100%	132.08	4	Thrive
Opuntia polyacantha	mass	all	100%	60.96	4	Thrive
Phedimus kamtschaticus/Sedum kamtschaticum	5	mass	100%	60.96	4	Thrive
Phemeranthus calycinus	12	reseeded	>100%			Thrive
Sedum lanceolatum	64	mass	>100%			Thrive
Sedum rupestre	31	mass	>100%			Thrive
Agave parryi	4	3	75%	60.96	4	Thrive
Echinocereus viridiflorus	11	8	73%		2	Survive
Escobaria missouriensis	mass	6	50%	4.23	1.5	Survive
Pediocactus simpsonii	10	5	50%	5.08	2	Survive
Escobaria vivipara	20	9	45%	6.77	2	Survive
Echinocereus triglochidiatus	18	8	44%	24.55	3	Survive
Maihuenia poeppigii	27	6	22%	10.16	2	Survive
Delosperma 'Kelaidis'	40, 8	2 masses	20%	9.31	2	Survive
Cotyledon orbiculata	5	0	0%			Perish

In conclusion, the lifeform that displayed the greatest survival in this observational evaluation on the DBG green roof was the succulents, however, both woody shrubs and graminoids performed very well. Upright and creeping forbs, as groups, had less success; if taprooted plants are avoided, then those lifeforms may result in better survival on a shallow green roof. Individual species within each lifeform group performed well, similar to an evaluation done in Germany (Köhler 2006), and these should be considered for use on extensive green roofs. Long term evaluation of these 112 taxa and more will continue, similar to evaluations done in Germany (Köhler 2006), as evaluation of potential green roof taxa is still a major need (Dvorak and Volder 2010).

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