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An Evaluation of Plant Selections and Irrigation Requirements for Extensive Green Roofs in the Pacific Northwestern United States

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SUMMARY. Extensive green roofs are a challenging environment for most plants, and this has typically limited the available plant palette. However, some functional goals for green roofs such as wildlife habitat require a broader spectrum of plant species from which to choose. In addition, pronounced seasonality in rainfall is a common climatic trait throughout much of the world; yet, few studies have evaluated green roof plant selections or the need for supplemental irrigation in a seasonally dry climate. In a field trial conducted in the Pacific northwestern United States, we evaluated the performance of eight taxa during establishment and under three different water management regimes post establishment: 1) non-irrigated; 2) irrigation based on green roof-specific water conservation guidelines for Portland, OR; or 3) the minimum irrigation required to maintain good plant condition. Plants were regionally available and represented a range of growth forms (succulents, shrubs, grasses, bulbs, and rhizomes) and potential functional attributes (habitat quality, aesthetic quality, and stormwater management proficiency). All eight species had generally high survival over the establishment year, although hardy iceplant (*Delosperma cooperi*) and common woolly sunflower (*Eriophyllum lanatum* var. *lanatum*) experienced some overwinter mortality. Species differed in the timing and absolute amount of growth during establishment. However, when the strong effect of initial size on growth was taken into account using analysis of covariance, there were no remaining differences between species in the relative magnitude of growth during establishment. During the summer following establishment, irrigation regime had significant effects on survival and growth, but these varied across taxa. Irrigation had no effect on survival or growth of the succulents hardy iceplant and 'Cape Blanco' broadleaf stonecrop (*Sedum spathulifolium*) and the bulb small camas (*Camassia quamash*). For the other taxa, plant survival and growth generally decreased with decreasing irrigation and many species did not survive at all without irrigation. Several species, particularly the grass roemer's fescue (*Festuca idahoensis* var. *roemerii*) and the shrub 'Lasithi' cretan rockrose (*Cistus creticus* ssp. *creticus*) suffered aesthetically under low irrigation, partly reflecting adaptive responses to drought stress. Weed pressure was high on bare substrate and was enhanced by irrigation, but weed pressure was negligible following canopy closure across all water regimes. These results suggest that succulents, bulbs, and rhizotomous forbs have potential for use on extensive green roofs in seasonally dry climates even without supplemental irrigation. Designing extensive roofs composed of more diverse growth forms will likely require some amount of supplemental irrigation. This study highlights the need to design context-specific green roofs that match appropriate plant selections with explicit functional goals and management plans. This will improve function and reduce the overall costs associated with maintenance.

Green roofs are subject to extreme environmental conditions, including prolonged periods of drought, high temperatures, and intense wind (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006). In addition, the shallow (<15 cm) and lightweight growing substrates typically used on extensive green roofs do little-to-moderate temperature fluctuations, retain moisture, or allow plants to tap deep moisture reserves (Dunnett and Kingsbury, 2004). Consequently, a rather narrow range of drought-tolerant succulents [particularly stonecrop (*Sedum*) species] have been the dominant plant selections for extensive green roof applications (Getter and Rowe, 2006).

However, expanding the plant palette available for green roofs is desirable. Green roof vegetation composed of diverse growth forms can have higher stormwater and cooling performance relative to less diverse roofs (Lundholm et al., 2010). Also, the use of regionally native plants could help restore wildlife habitat and native biodiversity in the urban environment (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006; Tallamy, 2007). This use of regionally native plants is often an explicit goal of many green roofs, and native species have been successfully used on green roofs where designs incorporate natural soils to enhance their similarity to native habitats (Brenneisen, 2006). Yet, identifying suitable native species is not straightforward because of the unique environmental conditions on roofs and the constraints on substrate composition. Plants that display suitable traits in their native contexts may not do so in the context of an extensive green roof. For instance, many prairie species achieve drought tolerance through their extensive root systems associated with specific microbial symbionts (Snodgrass and Snodgrass, 2006). Alpine plants can tolerate extreme temperature fluctuations; yet, they often cannot tolerate the absolute highs encountered on an urban rooftop.

In addition, regional differences in climate can impose unique constraints on plant functional performance and the associated management requirements. The design of the living component of green roof systems should be tailored to these specific regional differences and to the specific functional goals (Simmons et al., 2008).

Although there has been much work exploring these design relationships for roofs in northern Europe and the eastern United States, we know considerably less about the optimal design strategies for other regions and climate regimes (Dvorak and Volder, 2010). For instance, in temperate regions, current guidelines suggest that irrigation is needed only for plant establishment and that, with proper design (e.g., plant selection, substrate type, and depth) there is no need for permanent irrigation (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Snodgrass and Snodgrass, 2006). However, it is far from clear whether this prescription holds true for green roofs in semiarid and arid climates. These climatic zones cover more landmass than any other climate grouping; yet, we have very little information about proper water management for green roofs under these conditions.

Despite its rainy reputation, the Pacific northwestern United States is dry through most of the summer. For example, Portland, OR, has an annual average rainfall of 37.5 inches, but only an average of 3 inches of this falls during the months of July, August, and September (Hale, 2009). Given typical extensive green roof substrate types and depth, irrigation may be necessary to maintain plants other than the most drought-tolerant sedums. In an effort to provide some guidance and to limit the potential use of irrigation on green roofs, Portland's Bureau of Environmental Services restricts irrigation on all new green roofs seeking to qualify for its floor area ratio (FAR) bonus. The FAR bonus loosens building height restrictions in the Central City District for buildings with green roofs. Building owners—awarded FAR bonuses are required to apply no more than 0.5 inch of irrigation to their extensive green roofs every 10 d during plant establishment and 0.25 inch every 10 d following establishment (T. Liptan, personal communication). These guidelines were established from observations on a single extensive roof setup, and there is a need for more comprehensive data on plant performance across a range of irrigation levels. No studies have investigated the efficacy of

current water management practices in a summer dry environment such as the Pacific northwestern United States or evaluated the performance of green roof plant selections within the context of a specific water management regime.

This study tested the performance of a selection of Pacific northwestern U.S. native and non-native plant species under three different summer irrigation regimes. We also evaluated expected water use and associated management costs under each irrigation regime.

Method and materials

STUDY SITE. The study was conducted on the campus of Oregon State University, Corvallis (lat. 44°30'N, long. 123°17'W, elevation 71 m). Rainfall at Corvallis is strongly seasonal; wet winters boost average annual precipitation to 43.6 inches, but only 2.6 inches of that falls between July and September. Rainfall during the 2007–2008 study period was similar to the long-term average: 40.7 inches, only 1.5 inches of which fell from July through September (Hale, 2009).

TEST BED DESIGN. Twenty-one 4 × 8-ft roof test beds were constructed in a grid at the site. Test beds were oriented with their short length facing south to accommodate the dimensions of the site, and they were positioned away from trees and buildings. Each test bed was lined with a single-ply 1.8-mil thermal polyolefin (TPO) thermoplastic waterproof membrane (Firestone Building Products, Indianapolis, IN). Test beds were 6.5-ft tall and had a uniform lengthwise 2% slope toward a drainage hole. In addition to the impermeous membrane, test beds were topped with a drainage layer and substrate. The drainage layer consisted of 1/4-inch-thick standard drainage mat with a geocomposite fabric bonded to one

side, placed up to provide a filter fabric between substrate and drainage layer (Tremco, Ashland, OH). Growing substrate was a typical extensive green roof type commonly used in the Pacific northwestern United States (Pro-Gro Mixes, Tualatin, OR). Substrate was composed primarily of screened pumice (0.16–0.95 cm), with minor percentages of Fiber Life Compost (byproduct of an anaerobic digestive process) and paper fiber (clean cellulose-based byproduct). The substrate has an estimated field moisture capacity of 732 kg·m⁻³, a saturated bulk density of 1017 kg·m⁻³, and a weight of 546 kg·m⁻³. Substrate was uniformly applied to a depth of 5 inches. No supplemental fertilizer was provided during the course of the study to mimic a typical (and desired) low input system.

Irrigation to the test beds was supplied via short-radius (4 ft) nozzles with head-to-head coverage set to an ACC controller (Hunter, San Marcos, CA). Nine can tests (three cans placed on each roof to collect and measure irrigation amounts) were conducted and averaged to determine that irrigation heads consistently applied 6.63 cm·h⁻¹ at 1.76 kg·cm⁻² force.

PLANT SELECTIONS. Eight plant species were chosen for evaluation that represent three potential functional attributes (Table 1): 1) native Pacific northwestern U.S. species with high potential to provide appropriate floral resources for native pollinators [small camas, common woolly sunflower, yellowleaf iris (*Iris chrysophylla*), idaho blue-eyed grass (*Sisyrinchium idahoense*)]; 2) species with dense root systems and canopies that potentially enhance stormwater retention and evapotranspiration ('Lasithi' cretan rockrose, roemer's fescue); and

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
0.0929	ft ²	m ²	10.7639
3.7854	gal	L	0.2642
40.7458	gal/ft ²	L·m ⁻²	0.0245
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
16.3871	inch ³	cm ³	0.0610
16.0185	lb/ft ³	kg·m ⁻³	0.0624
0.0254	mil	mm	39.3701
28.3495	oz	g	0.0353
0.0703	psi	kg·cm ⁻²	14.2233
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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Table 1. Plant species evaluated in this study for their suitability on extensive green roofs in the Pacific northwestern United States.

Common name	Family	Growth form	Native range	Habitat association	USDA zones ^a
Hardy iceplant	Aizoaceae	Succulent	Southern Africa	Short grass prairies and north facing cliffs	6–10
‘Cape Blanco’ broadleaf stonecrop	Crassulaceae	Succulent	Pacific North America	Rocky cliffs, sandy well-drained soil	5–8
‘Lasithi’ cretan rockrose	Cistaceae	Shrub	Eastern Mediterranean	Degraded dense scrub	to 8
Common woolly sunflower	Asteraceae	Shrub	Pacific North America	Prairies, glacial deposits, disturbed sites	5–9
Small camas	Liliaceae	Bulb	Western United States	Grassy meadows, rocky crevices	3–8
Yellowleaf iris	Iridaceae	Rhizome	Oregon, CA	Steep slopes, open coniferous forest	6–9
Idaho blue-eyed grass	Iridaceae	Rhizome	Western United States	Meadows, subalpine forest, wetlands	to 3
Roemer’s fescue	Poaceae	Bunch grass	Pacific North America	Prairies, rangelands	5–9

^aU.S. Department of Agriculture Plant Hardiness Zones (Cathey, 1990).

3) species with known suitability to a green roof environment and that are commonly used in green roof applications (hardy iceplant, ‘Cape Blanco’ broadleaf stonecrop).

Other selection criteria included habitat associations or drought-tolerance attributes that suggested suitability to a green roof environment, aesthetic qualities, and ready availability through the regional nursery trade. Plants were purchased in 4-inch nursery pots from growers in Oregon, WA, and British Columbia.

EXPERIMENTAL DESIGN. On 25 July 2007, 12 replicate roof test beds were planted with individuals of each of the eight species in a complete randomized block design. To evaluate the baseline weed pressure (see below), an additional nine test beds were left unplanted. To assure plant species were equally represented across the known drainage gradient corresponding to the pitch of the test beds, plantings were blocked in four blocks across the gradient. Each block contained one replicate individual of each species ($n = 4$ individuals/species/test bed). All planted test beds were irrigated uniformly for establishment during the first growing season, receiving 0.09 inch every day between 0400 and 0500 HR. The establishment irrigation period lasted from 25 July 2007 to the onset of consistent winter precipitation on 25 Sept. 2007.

On 25 June 2008, three different irrigation treatments were randomly applied to each of the 12 planted test beds ($n = 4$ planted test beds per treatment) and the nine unplanted

weed pressure test beds ($n = 3$ unplanted roofs per treatment): 1) non-irrigated [NON (only natural summer precipitation totaling 1.5 inches)]; 2) Portland FAR bonus regime [PDX (1/8 inch applied every 5 d, totaling 2.25 inches in addition to 1.5 inches ambient summer precipitation)]; and 3) horticultural regime [HOR (our horticultural decision made using roof runoff as a diagnostic tool)]. Irrigation was applied when substrate was dry to the touch in the top 4 inches, ≈ 0.12 inch applied every 2 d for a total of 5.25 inches in addition to 1.5 inches summer moisture. Irrigation treatments lasted 90 d and were consistently applied between 0400 and 0500 HR.

RESPONSE VARIABLES: PLANT PERFORMANCE. Survivorship, size, and number of fully opened flowers of each planted individual were measured monthly during the establishment phase (25 June 2007–25 June 2008) and every 2 weeks during the summer irrigation experiment (25 June–25 Sept. 2008). Aboveground plant sizes were estimated as the volume (cubic centimeters) of idealized spheres: longest width $\times$ longest perpendicular width $\times$ height.

RESPONSE VARIABLES: WEED ABUNDANCE. Test beds were kept weed-free (free of any non-planted species) until the start of the irrigation trials (25 June 2008). Once per month throughout the irrigation experiment (25 July, 25 Aug., and 25 Sept.), all shoots and roots of emerged weeds were collected from each test bed. Weeds were dried at 41 °C until a

constant weight was achieved (≈ 2 d), and total weed dry biomass of each roof was estimated.

DATA ANALYSIS: PLANT PERFORMANCE DURING ESTABLISHMENT PERIOD. Treating test beds as the experimental unit, the percent survivorship of each species on each test bed was calculated for three different periods during the establishment year (summer, winter, and spring). Monthly growth increments for each individual of each species were calculated as follows: monthly growth increment = $\ln S_{t+1} - \ln S_t$, where S_t and S_{t+1} represent the estimated size (cubic centimeters) of individuals in successive monthly surveys. Total increase in size at the end of the establishment year and the summer irrigation experiment were estimated as $\ln S_{1 \text{ year}} - \ln S_{\text{initial}}$ and $\ln S_{\text{exp. end}} - \ln S_{\text{exp. beginning}}$, respectively. Plant growth patterns can differ greatly across functional groups and life history. Consequently, relative growth was compared between species within growth form categories (succulents, shrubs, rhizomes, and bunch grass). The bunch grass and rhizome species were grouped together for growth comparisons. Growth of the bulb small camas was not compared because it entered dormancy and lost all aboveground biomass in mid- to late-July. Initial plant size can have a strong effect on the subsequent growth. To account for this, differences in establishment growth among species within a growth form category were tested using analysis of covariance (ANCOVA) with species as treatment variable and initial plant size as a covariate. Only

those individuals that survived throughout the establishment period were included in the growth analysis.

DATA ANALYSIS: PLANT PERFORMANCE DURING IRRIGATION EXPERIMENT. Average per test bed survivorship of each species across irrigation treatments ($n = 4$ test beds per treatment) was calculated at the end of the irrigation experimental period (25 June to 25 Sept. 2008). Monthly and total growth increments for each individual of each species (excluding small camas) were calculated as for the establishment period (see above). Within species, the effect of irrigation treatment on total growth over the course of the experiment was tested using ANCOVA, with irrigation regime as the treatment factor and initial size at the start of the experiment (25 June 2008) as a covariate. Initial size was log-transformed for analysis. There were no significant irrigation treatment $\times$ log initial size interaction terms, and these were dropped from subsequent models for further analysis. Only those individuals that survived throughout the establishment period were included in the growth analysis. A normalized size index was calculated to help visualize differences in relative growth patterns over the course of the summer irrigation period between species and irrigation treatments. Normalized size was calculated as $S_i/Size_{6/25/08}$.

DATA ANALYSIS: WEED ABUNDANCE. The effect of irrigation regime and planting treatment (planted or substrate only roofs) on mean weed biomass was tested using two-way analysis of variance (ANOVA). Differences in weed biomass were subsequently tested within the substrate only and planted roofs separately using planned comparisons within one-way ANOVA.

Results and discussion

PLANT PERFORMANCE DURING ESTABLISHMENT PERIOD. Overall, plant survival was high during the establishment year (Table 2). Three species (small camas, 'Cape Blanco' broadleaf stonecrop, and idaho blue-eyed grass) experienced no mortality over this period. Yellowleaf iris and 'Lasithi' cretan rockrose experienced minor mortality (6% and 2%, respectively). Two exceptions to the generally high survival were hardy iceplant, which experienced a 25% overwinter (25 Sept. 2007 to 25 Mar. 2008) mortality,

Table 2. Survivorship of eight study species on experimental green roof test beds over one establishment year (25 June 2007 to 25 June 2008).

Common name	Survivorship [mean $\pm$ SE (%)]			
	25 June–25 Sept.	25 Sept.–25 Mar.	25 Mar.–25 June	1 yr
Hardy iceplant	100 $\pm$ 0	75 $\pm$ 7	100 $\pm$ 0	75 $\pm$ 7
'Cape Blanco' broadleaf stonecrop	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0
'Lasithi' cretan rockrose	100 $\pm$ 0	100 $\pm$ 0	98 $\pm$ 2	98 $\pm$ 2
Common woolly sunflower	97 $\pm$ 3	98 $\pm$ 2	82 $\pm$ 7	80 $\pm$ 8
Small camas	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0
Yellowleaf iris	100 $\pm$ 0	96 $\pm$ 3	98 $\pm$ 2	94 $\pm$ 3
Idaho blue-eyed grass	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0
Roemer's fescue	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0	100 $\pm$ 0

Percent survival was estimated for each species on each test bed (four individuals per species per bed) over four different periods during establishment. Values are average per test bed survivorship ($n = 12$ test beds).

and common woolly sunflower, which had an overall mortality of 20%, the bulk of this occurring during the first spring following planting (25 Mar. to 25 June 2008). Cold temperatures probably explain some of the mortality seen in these species. The bulk of hardy iceplant mortality occurred following a 5-d period in which the mean low and high ambient air temperatures ranged from -8.43 to 2.62 °C. This was an atypically long and hard freeze for the region, and the actual temperatures experienced by the plants were likely lower than this, given the exposed position of the roof test beds. Hardy iceplant on green roofs in Portland, OR, also died over Dec. 2008 (T. Liptan, personal communication). While our study reported that the 'Cape Blanco' broadleaf stonecrop was frost hardy, other studies have documented root damage due to freezing in stonecrop species grown on shallower (<7 cm) substrate (Boivin et al., 2001; Getter and Rowe, 2009).

With the exception of idaho blue-eyed grass, all species increased in aboveground size over the course of the establishment year. In absolute terms, this growth was quite variable across species. Roemer's fescue had the greatest average absolute increase ($169,693$ cm³), yellowleaf iris had the least (2644 cm³), while idaho blue-eyed grass decreased to an average of 9053 cm³. However, absolute growth depended significantly on the initial size of the planted individuals (Table 3). Initially larger individuals grew relatively less than smaller ones during establishment. Initial size varied both as a consequence of innate growth form differences across species and

individual variation within a species. When the influence of initial size was taken into account using ANCOVA and when analyzed within growth form categories, there were no differences between species in establishment growth (Table 3).

Most of the species evaluated did not grow until the spring following the establishment year. However, species varied in the specifics of this growth. 'Lasithi' cretan rockrose and 'Cape Blanco' broadleaf stonecrop maintained their initial size for much of the establishment period, increasing in size at the start of the following spring (10 Mar. 2008). Hardy iceplant and common woolly sunflower lost aboveground biomass during the winter months before growing at the start of spring (25 Mar. 2008). Roemer's fescue, yellowleaf iris, and idaho blue-eyed grass declined in size during the initial summer and winter after planting before eventually growing the following spring. Yet, the aboveground size of idaho blue-eyed grass was still smaller than its initial size by the end of the establishment year. Yellowleaf iris was the latest to begin spring growth on 10 May 2008.

The generally high-establishment survival and the broadly equivalent relative growth rates observed for the species in our study suggests that they are all generally suited to the substrate and temperature conditions of typical green roofs in the Pacific northwestern United States. However, the supplemental irrigation provided during establishment undoubtedly was an important factor in this success. Thuring et al. (2010) documented higher establishment survival for green roof plants

when supplemental irrigation was provided. Although we did not explicitly test how irrigation influenced establishment, it seems likely (given the results of the subsequent irrigation portion of this study) that overall establishment mortality would have been considerably higher without supplemental irrigation. Also, most species did not increase in above-ground biomass until near the end of the establishment year. During this period, the large proportion of bare substrate coupled with ample irrigation made the roofs susceptible to weed establishment, which necessitated persistent weeding. These results suggest that maintenance (irrigation management and weeding) during establishment are likely critically important for the ultimate success of green roofs, particularly in seasonally dry environments. More work is needed to identify optimal establishment protocols that minimize water inputs and the need for weed removal.

PLANT PERFORMANCE, IRRIGATION EXPERIMENT. Overall plant health was good at the start of the irrigation experiment. Planted test beds had an average of 83% vegetative cover, and plant roots had become well integrated into the substrate profile. The German Landscape Research, Development and Construction Society (FLL) standards for extensive green roofs call for 90% coverage for groundcovers (FLL, 2002). As the dry season progressed, irrigation regime had a strong influence on plant survivorship, but this effect varied across species (Table 4). Irrigation regime had no effect on the survival of the succulents hardy iceplant and 'Cape Blanco' broadleaf stonecrop or the Pacific northwestern U.S. native bulb small camas. Despite receiving just 1.5 inches of summer precipitation, these species had 100% survivorship. These results support other studies and much practical experience indicating that succulents are good choices for non-irrigated green roof applications because they are reliably drought tolerant even when grown on shallow substrate depths (Dvorak and Volder, 2010; Getter and Rowe, 2006; Thuring et al., 2010). However, there is other evidence that stonecrop species may not generally perform well in water-stressed environments that have warmer nighttime temperatures than are commonly seen in the Pacific northwestern

Table 3. Analysis of covariance testing for differences in growth among species on experimental extensive green roof test beds during the first year of establishment.

	<i>F</i>	<i>P</i>	<i>df</i>
Succulents			
Species	2.209	0.141	1
Initial size	3.962	0.050	1
Initial size × species	2.035	0.157	1
Error			82
Shrubs			
Species	0.005	0.942	1
Initial size	28.628	<0.001	1
Initial size × species	0.010	0.919	1
Error			82
Rhizomes and bunch grass			
Species	0.594	0.554	2
Initial size	30.666	<0.001	1
Initial size × species	0.163	0.850	2
Error			135

The analysis tests for differences in growth between species within growth form categories accounting for initial size of transplanted individuals as a covariate. Species in each growth form category are succulents (hardy iceplant, 'Cape Blanco' broadleaf stonecrop), shrubs ('Lasithi' cretan rockrose, common woolly sunflower), rhizomes, and bunch grass (yellowleaf iris, idaho blue-eyed grass, roemer's fescue). Growth of the bulb small camas was not analyzed. Establishment period was 25 June 2007 to 25 June 2008. Establishment growth was estimated as $\ln(\text{size}_{25 \text{ June } 2008}) - \ln(\text{size}_{25 \text{ June } 2007})$. Above ground plant sizes were estimated as the volume (cubic centimeters) of idealized spheres: longest width × longest perpendicular width × height; 1 cm³ = 0.0610 inch³.

Table 4. The influence of three irrigation treatments on survivorship of eight species growing on experimental extensive green roof test beds during the summer following establishment (25 June–25 Sept. 2008).

Common name	Survivorship [mean ± SE (%)]		
	Horticultural	Portland	Non-irrigated
Hardy iceplant	100 ± 0	100 ± 0	100 ± 0
'Cape Blanco' broadleaf stonecrop	100 ± 0	100 ± 0	100 ± 0
'Lasithi' cretan rockrose	94 ± 6	75 ± 10	0 ± 0
Common woolly sunflower	88 ± 7	31 ± 12	6 ± 6
Small camas	100 ± 0	100 ± 0	100 ± 0
Yellowleaf iris	88 ± 7	13 ± 7	0 ± 0
Idaho blue-eyed grass	100 ± 0	88 ± 7	0 ± 0
Roemer's fescue	100 ± 0	94 ± 6	0 ± 0

Values are per test bed percent survivorship ($n = 4$ test beds per treatment). All test beds received ambient summer precipitation totaling 1.5 inches. Irrigation treatments were non-irrigated, horticultural (≈ 0.12 inch applied every 2 d for a total of 5.25 inches), and Portland (1/8 inch applied every 5 d totaling 2.25 inches); 1 inch = 25.4 mm.

United States, such as Australia or inland Mediterranean climate zones (Williams et al., 2010). Our results also support those of other studies suggesting that bulbs may be good plant selections for non-irrigated green roofs (Snodgrass and Snodgrass, 2006). Small camas is a Pacific northwestern U.S. native bulb that grows well in moist areas, and it was not necessarily expected to survive without any supplemental summer irrigation; yet, it had 100% survival across all irrigation treatments. This summer dormant bulb emerges early to mid-March and has a full growth period before going dormant mid- to late-July.

Survivorship of the other five species generally declined across the treatment gradient in applied water (Table 4). For these species, the lack of summer irrigation resulted in complete or nearly complete mortality. However, roemer's fescue, idaho blue-eyed grass, and 'Lasithi' cretan rockrose did maintain relatively high survivorship in the low-irrigation Portland regime. Idaho blue-eyed grass and roemer's fescue are both facultative wetland species that are adapted to seasonally dry conditions (Darris et al., 2007; U.S. Department of Agriculture, 2008), whereas rockrose is a drought-tolerant shrub (Page, 2006). Other studies have also identified that non-irrigated

green roofs can be a challenging environment to non-succulent perennials, particularly on shallow (<10 cm) substrate depths. Without irrigation, many herbaceous perennials suffer drought stress on extensive green roofs even in ecoregions that experience more equitable seasonal rainfall patterns (Monterusso et al., 2005; Rowe et al., 2006). Increasing substrate depth or irrigation amount broadens the range of species that can survive on a roof (Dvorak and Volder, 2010). In this study, providing relatively minimal irrigation allowed representatives of other non-succulent growth forms to persist in the face of prolonged drought on a shallow substrate.

In contrast to the establishment period, initial plant size had no significant influence on subsequent growth over the irrigation experiment for most species. The one exception was Idaho blue-eyed grass, where growth was negatively related to initial size (ANCOVA: initial size $F_{1,27} = 16.70$, $P < 0.001$). Irrigation treatment significantly influenced plant growth, but this effect also depended on species. Some, but not all, species exhibited significantly greater growth rates under higher irrigation (Fig. 1). The exceptions were 'Cape Blanco' broadleaf stonecrop, roemer's fescue, common woolly sunflower, and yellowleaf iris, which grew slowly or even decreased in aboveground size over the course of the experiment irrespective of irrigation treatment [Fig. 1 (irrigation treatment factors in ANCOVA: 'Cape Blanco' broadleaf stonecrop, $F_{2,44} = 2.65$, $P = 0.08$; roemer's fescue, $F_{1,28} = 0.04$, $P = 0.85$; common woolly sunflower, $F_{1,9} = 4.33$, $P = 0.06$; yellowleaf iris, $F_{1,11} < 0.001$, $P = 0.99$]. Irrigation treatment did have a significant effect on the growth of hardy iceplant (ANCOVA: irrigation treatment, $F_{2,32} = 8.03$, $P < 0.001$), Idaho blue-eyed grass (ANCOVA: irrigation treatment, $F_{1,27} = 16.70$, $P < 0.001$), and 'Lasithi' cretan rockrose (ANCOVA: irrigation treatment, $F_{1,23} = 11.42$, $P = 0.003$). The succulent hardy iceplant appeared to be able to use small and infrequent summer rain events. After experiencing a steady decline in aboveground biomass under the non-irrigated treatments, individuals experienced a growth spurt following a 0.77-inch rain event between 10 and 25 Aug. These results suggest that, following establishment, a low

Fig. 1. Influence of three irrigation treatments on relative growth of eight species on experimental extensive green roof test beds during the summer following establishment. All test beds received ambient summer precipitation totaling 1.5 inches. NON, non-irrigated; HOR, ≈ 0.12 inch applied every 2 d for a total of 5.25 inches; PDX, 1/8 inch applied every 5 d totaling 2.25 inches. Values are mean $\pm$ SE above ground size (cubic centimeters) normalized to the size at the start of the irrigation trial ($size_t/size_{t=6/25}$). Aboveground plant sizes were estimated as the volume (cubic centimeters) of idealized spheres: longest width $\times$ longest perpendicular width $\times$ height. Sample sizes vary across sample dates and species due to mortality; 1 inch = 25.4 mm, 1 $cm^3 = 0.0610$ inch³.

irrigation regime such as Portland's FAR bonus guidelines can maintain a relatively diverse range of species on an extensive green roof at performance levels (in terms of survival and growth) comparable to those under more excessive watering.

However, many species suffered aesthetically under the low water regimes even if they had high survivorship

or maintained positive growth. For instance, the center of many 'Cape Blanco' broadleaf stonecrop developed areas of necrosis under the low and no irrigation treatments. This browning out may have been a result of an incompatible interface between the nursery production substrate in which transplants arrived and the highly aggregate green roof substrate.

This effect appears to be amplified with less water. Irrigation amounts that are sufficient to saturate the green roof substrate are often insufficient to resaturate the highly organic nursery production substrate, partly because of the hydrophilic nature of organic matter (Caron and Riviere, 2003). Similar die-out issues have been observed with green roof plants installed in 4-inch square nursery containers on a Portland roof (T. Liptan and E. Snodgrass, personal communication). This suggests that nursery container stock may not be the ideal planting material for green roofs that experience severe dry conditions.

'Lasithi' cretan rockrose and roemer's fescue also suffered aesthetically under low irrigation; many leaves turned brown, dropped, and in the case of 'Lasithi' cretan rockrose the branch ends became bare. Leaf drop or leaf rolling are documented drought responses in both species (Grammatikopoulos, 1999; White et al., 1992). Although desirable from a water use perspective, many drought-dormant and semidormant species may be poor choices for green roof applications because they create large amounts of flammable litter, which can be a fire hazard, or they compromise the aesthetics of the roof (Getter and Rowe, 2006). However, some drought-dormant species may have more desirable qualities. In our study, the native bulb small camas had a strong summer-dormant growth pattern, but created relatively little dry biomass and did little to detract from roof aesthetics after dormancy began. Similarly, the rhizomatous idaho blue-eyed grass had strong seasonal growth patterns, but did not experience strict summer dormancy, maintaining some aboveground biomass through the summer. These and similar species could be used to augment native habitat functions such as floral resources for native pollinators and to provide seasonal aesthetic accents.

Other species that are drought tolerant in their native contexts may not be so under the unique conditions of an extensive green roof. This may have been the case for the common woolly sunflower in our study. In the Willamette Valley, OR, common woolly sunflower is associated with vascular-arbuscular mycorrhizal fungi (VAMF) (Ingham and Wilson, 1999). VAMF and other rhizosphere

microorganisms are known to be associated with drought tolerance in plants under water-restricted conditions (Gianinazzi et al., 2010).

IRRIGATION MANAGEMENT. The three different irrigation regimes in this study produced markedly different results in terms of overall plant performance. While our specific results are idiosyncratic to the particular substrate depth, species, and weather conditions, the results highlight the need to develop irrigation guidelines that are region and function specific. In our study, the intent of the horticultural regime was to keep a diverse range of plants alive on a shallow substrate with high aesthetic value using the least amount of applied water. Our approach for determining this irrigation amount was simple but effective. Green roof managers could similarly determine site-specific irrigation needs by monitoring the amount of water applied until runoff occurs and applying this amount before the green roof substrate dries out completely. Of course, the use of soil moisture or evapotranspiration (ET) sensors and rain shut-off valves could increase efficiency and reduce management effort.

The applied irrigation totals can be used to estimate relative water usage for each of the irrigation regimes in this study. Water use for the Portland FAR regime totaled 0.69 L·m⁻² per day. Extrapolated to the size of a typical commercial installation (the 1668.4 m² Portland Building green roof, 1120 SW fifth Street, Portland, OR), the regime would require a total of 105,457 L of water over 90 d or 1172 L per day. Given existing water rate charges of \$2.07/2832 L, this equates to a water bill of \$77 during the 90-d irrigation season. In contrast, the Horticultural regime used 0.163 L·m⁻² per day of water. For the Portland building example, this equates to 262,132 L of irrigation water over a 90-d period and an estimated cost of \$192, more than twice the cost of the low irrigation regime. Therefore, there can be considerable monetary incentive to optimize irrigation inputs relative to the desired functional goals.

WEED MANAGEMENT. There was an effect of both irrigation treatment (two-way ANOVA: $F_{2,15} = 6.70$, $P = 0.008$) and planting treatment [Fig. 2 (two-way ANOVA: $F_{1,15} = 146.75$,

Fig. 2. Influence of irrigation and vegetation on dry weight of weed biomass collected from planted and substrate-only green roof test beds three times during Summer 2008 (25 July, 25 Aug., and 25 Sept.). Values are means $\pm$ SE. All test beds received ambient summer precipitation totaling 1.5 inches. NON, non-irrigated; HOR, ≈ 0.12 inch applied every 2 d for a total of 5.25 inches; PDX, 1/8 inch applied every 5 d totaling 2.25 inches. Within a planting treatment, different letters indicate a significant difference in mean weed biomass between irrigation treatments using planned comparisons within a one-way analysis of variance ($P < 0.05$, $df = 15$); 1 inch = 25.4 mm, 1 g = 0.0353 oz.

$P < 0.0001$) on weed abundance. Unplanted roofs had an average of 23.1 ± 6.4 g (mean $\pm$ SE) of weed biomass compared with only 0.4 ± 0.1 g for planted roofs. In the complete two-way model, there was no significant interaction between irrigation and planting treatments ($F_{2,15} = 2.10$, $P = 0.157$). However, when planted and unplanted roofs were analyzed separately, irrigation treatment had a significant effect on weed biomass only on the unplanted roofs (Fig. 2). These results suggest that after the establishment period, irrigation patterns have little direct impact on weed management. However, we did not test how plant mortality on the low irrigation roofs influenced weed establishment in the following season. It seems likely that roof designs composed of plant selections that perform poorly with respect to the irrigation environment would be susceptible to weed establishment over the long term.

Conclusions

Overall, our results confirm that the succulents commonly used in

existing green roof applications have broad suitability for use on roofs in seasonally dry environments such as the Pacific northwestern United States with little or no supplemental irrigation. Bulbs and rhizomatous species that experience some form of drought dormancy also appear to be good candidates, particularly when used as functional accents with other species. However, grasses and shrubs that display drought tolerance in their native contexts may not be good choices on extensive green roofs with little or no supplemental irrigation. This may be because their drought tolerance mechanisms do not operate properly in a green roof environment with shallow non-native soils, or because drought dormancy results in poor aesthetics, or because the accumulation of senescent biomass during dry periods causes a potential fire hazard. These interactions can constrain the ability to design roofs composed of plant assemblages native to particular ecoregions. In the Pacific northwestern United States, most species associated with grassland and forest ecosystems where many of the major urban centers are located would likely be inappropriate for use on extensive green roofs without supplemental irrigation. A continuing irrigation management plan as well as adjustments to substrate composition and depth would be required if a native ecoregion roof design was a priority.

Our results provide some broad criteria to inform a more comprehensive screening program. Functional groups that should be targets of screening include other bulb and rhizomatous species native to the western United States, such as fritillaries (*Fritillaria* spp.) and shootingstars (*Dodecatheon* spp.); native succulents such as pricklypears and chollas (*Opuntia* spp.) and liveforevers (*Dudleya* spp.); and some perennial shallow rooted species that are associated with dry rocky habitats and that produce relatively little aboveground biomass such as purple leptotaenia (*Lomatium columbianum*) and gray's biscuitroot (*Lomatium grayi*). While it may be difficult to reconstruct representative native assemblages on extensive green roofs, incorporating more regionally native (although not ecoregion native or consistent) species could still provide improved habitat quality over the more traditional stonecrop dominant designs.

We found that weeds are likely to become established in bare substrate and that weed establishment is enhanced by irrigation. Weed management should be a top management priority during the establishment phase when there is much bare substrate, planted individuals grow slowly, and supplemental irrigation is high. However, once plants establish and attain high amounts of cover, weed pressure is negligible even for roofs that receive higher amounts of irrigation.

Integrated green roof design requires a more comprehensive analysis of costs and benefits, including the costs associated with weeding, plant loss, or irrigation along with the specific plant-associated benefits of biodiversity, storm-water management, energy savings, or aesthetics. Designers should identify the project's specific functional goals and constraints, as well as explicitly incorporate management requirements and planning into the design. Coupling this approach with plant evaluations that identify suitable species beyond the traditionally used stonecrops will result in more regionally appropriate and better performing green roofs.

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