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Irrigation Requirements for Seed Production of Two *Eriogonum* Species in a Semiarid Environment

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Abstract**. Seeds of native plants are needed for rangeland restoration in the Intermountain West. Many of these plants are rarely cultivated and relatively little is known about the cultural practices required for their seed production. Irrigation trials were conducted over multiple years for two perennial *Eriogonum* species, *Eriogonum umbellatum* Torr. and *Eriogonum heracleoides* Nutt. The two species grown at the Oregon State University Malheur Experiment Station, Ontario, Ore., received 0, 100, or 200 mm·year^{-1} of drip irrigation. Seed yield responses to irrigation were evaluated by linear and quadratic regression against 1) applied water; 2) applied water plus spring precipitation; 3) applied water plus winter and spring precipitation; and 4) applied water plus fall, winter, and spring precipitation. In general, seed yields responded quadratically to irrigation. For *E. umbellatum*, over 11 years, highest seed yields averaged 260 kg·ha^{-1} and ranged from 207 to 508 kg·ha^{-1}. For *E. heracleoides*, over 6 years, highest yields averaged 353 kg·ha^{-1} and ranged from 168 to 588 kg·ha^{-1}. Adding spring precipitation to applied water improved the accuracy of estimated water requirements for maximum seed production of *E. umbellatum.* For *E. heracleoides*, adding precipitation to applied water did not improve the accuracy of estimated water requirements for maximum seed production. Averaged over 11 years, seed yield of *E. umbellatum* was maximized by 209 mm·year^{-1} of spring precipitation plus irrigation. Averaged over 6 years, seed yield of *E. heracleoides* was maximized by 126 mm·year^{-1} of applied water. Both species required relatively small amounts of irrigation to help assure seed yield, and the irrigation needed for *E. umbellatum* could be adjusted by taking spring precipitation into account.**

In the Intermountain West, native plant communities are being lost because of exotic plant invasions, changing fire regimes, and increasing human population pressure and activities (Balch et al., 2013; Liu and Wimberly, 2015). The National Seed Strategy (Plant Conservation Alliance, 2015) and other recent federal directives emphasize the use of native species to assist the recovery of degraded public lands. Native shrubs and grasses have long been used for revegetation following wildfires and other disturbances. A current priority is the addition of a greater number of native forbs to revegetation plantings that are designed to conserve sage-grouse habitat, increase pollinator populations (Dumroese et al., 2015), and reestablish native communities that are diverse and resilient following wildfire. Increasing the use of *Eriogonum heracleoides* Nutt. and *E. umbellatum* Torr. as well as other common buckwheat species necessitates development of cultural practices required for increase of their seed in agricultural settings, as wildland collections are expensive and generally inadequate to meet revegetation needs. For most forb species where seeds are in demand for restoration use in the Intermountain West, guidelines for seed production practices are not available (Cane, 2008; Shaw and Jensen, 2014).

Eriogonum heracleoides (parsnipflower or Wyeth buckwheat) and *E. umbellatum* (sulphur-flower buckwheat) of the Polygonaceae family are low-growing, taprooted subshrubs that are widespread in the Rocky Mountains and Intermountain West with ivory and yellow flowers, respectively (Reveal, 2012). Both species are mat or clump-forming and produce upright flowering stems that support umbrella-like clusters of flowers. They commonly occur scattered among other vegetation on dry, exposed sites with well-drained soils and are common in rocky and sandy areas. *E. heracleoides* occurs from the sagebrush (*Artemisia* spp. L.) zone through open areas in aspen (*Populus tremuloides* Michx.) and other forested communities, whereas *E. umbellatum* grows in communities from the sagebrush to the subalpine zone (Reveal, 2012; Welsh et al., 1987).

Eriogonum spp. are drought hardy and long-lived. Both species are recommended for plantings to provide pollinator habitat (Ogle et al., 2011). *E. umbellatum* provides food and habitat for sage-grouse (Bunnell et al., 2004; Pyle, 1993). Because of their low palatability, most perennial *Eriogonum* spp. are not considered valuable forage plants for wildlife or domestic livestock, but they are used to some extent in spring and fall when other forage may not be available (USDA Forest Service, 1937). Sheep seek out the flower clusters. *Eriogonum* spp. are useful for low-maintenance landscaping, xeriscaping, and rock garden plantings in urban areas, recreation sites, and along roadsides (Dyer et al., 2005; Parris et al., 2010; Tilley et al., 2007; Young-Mathews, 2012). They are attractive year-around, require little water and are easily maintained. Plants are semievergreen, and flower in early to midsummer after many other natives have completed their flowering cycle. The flowers are long-lasting and remain colorful after drying on the plants (Meyer, 2008).

Where adapted, *Eriogonum* spp. can add diversity to native seedings and are particularly valuable because of their ability to establish on disturbed sites resulting from activities including road construction or energy development. Once established, they can provide erosion control due to their mat-forming habit and natural spread. They may also serve as nurse plants that enhance establishment of later arriving species (Meyer, 2008).

Practices that increase the reliability of seed production are needed to reduce grower risk. Although *E. heracleoides* and *E. umbellatum* generally occur in areas receiving low precipitation, recommendations for optimal amounts and timing of irrigation for individual species are needed to improve the reliability of seed production because seed production can be very low in dry years. Research has described the seed yield responses of five species of Intermountain West perennial forbs of the genus *Lomatium* to irrigation and seasonal precipitation (Shock et al., 2016). Sprinkler or furrow irrigation encourages weeds and the spread of fungal pathogens. Subsurface drip irrigation reduces these problems by decreasing surface soil wetting. Reduction of weeds is a critical

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concern when growing native forbs as herbicides have not been approved for use with these species.

We report the effects of three low rates of subsurface drip irrigation on seed yield of *E. heracleoides* and *E. umbellatum*, and how these seed yield responses to irrigation are affected by precipitation. Optimum irrigation for each species was based on the amount of irrigation and seasonal precipitation during each year of production. Seed yield response of *E. umbellatum* to irrigation has been reported for the earlier years of this trial (Shock et al., 2015). Because seed yield can vary between years due to harsh weather, differences in pollination, and many other factors, we report also the effects of the low rates of subsurface drip irrigation on the relative seed yield calculated as the percentage of the yield of the highest yielding treatment for each species for each year.

Methods

Irrigation trials were initiated in 2005 for *E. umbellatum* and in 2009 for *E. heracleoides* at the Malheur Experiment Station of Oregon State University, Ontario, Ore. Ontario is centered at 43°58′42.2″N, 117°1′29.8″W at 689 m elevation. Annual precipitation averaged 257 mm during the study. The field, a Nyssa silt loam (coarse-silty, mixed, mesic, Xeric Haplodurid), was bedded into 76-cm rows and four rows were planted to each species. Most of the field lacked topsoil because of land leveling in the 1950s. The analysis of a soil sample taken on 22 Nov. 2005 indicated a pH of 8.3, 1.09% organic matter, 12 ppm phosphorus (P), 438 ppm potassium, 27 ppm SO_4-S, 4370 ppm calcium, 456 ppm magnesium, 81 ppm sodium, 1.6 ppm zinc (Zn), 0.6 ppm copper, 4 ppm manganese, 3 ppm iron, and 0.6 ppm boron.

Drip tape (T-Tape TSX 515-16-340) was buried at 30-cm depth and spaced 1.52 m apart beneath alternating inter-row spaces. The flow rate for the drip tape was 4.16 L·min^{-1} per 100 m of tape at 55 kPa with emitters spaced 41 cm apart, resulting in a water application rate of 1.7 mm·h^{-1}. Water was filtered through sand media filters. Application durations were controlled automatically as described below.

Seed of *E. umbellatum* was received in Nov. 2004 from the Rocky Mountain Research Station (Boise, ID). Seed of each species came from collections made by U.S. Forest Service employees (Table 1). Excessive rainfall in October prevented planting in the fall of 2004 and planting was postponed to early 2005. To try to ensure germination, the seed was submitted to cold stratification. The seed was soaked overnight in distilled water on 26 Jan. 2005, after which the water was drained and the seed soaked for 20 min in a 10% by volume solution of 13% bleach (sodium hypochlorite) in distilled water. The bleach solution was drained and the seed was placed in thin layers in plastic containers. The plastic containers had lids with holes drilled in them to allow air movement. These containers were placed in a cooler set at ≈1 °C. Every few days, the seed was mixed and, if necessary, distilled water added to maintain seed moisture.

Seed of *E. umbellatum* was planted on 3 Mar. 2005 in four rows spaced 76 cm apart using a custom-made small-plot grain drill with disk openers. Rows of seed were above and 38 cm to each side of the buried drip

Table 1. Source of *Eriogonum* species planted in drip irrigation trials at the Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Common names	Location of seed collection
Eriogonum umbellatum	Sulphur-flower buckwheat	Shoofly Road (ERUM 14), Owyhee Co., ID, 42.710 N, –116.371 W
Eriogonum heracleoides	Parsnipflower buckwheat, Wyeth buckwheat	Mt. Pisgah (ERHE 03), Elko Co., NV, 40.827 N, –116.771 W

Table 2. *Eriogonum* flowering, irrigation, and seed harvest dates by species, 2006–16.

		Flowering dates			Irrigation dates		
Species	Yr	Start	Peak	End	Start	End	Harvest
Eriogonum umbellatum	2006	19 May		20 July	19 May	30 June	3 Aug.
	2007	25 May		25 July	2 May	24 June	31 July
	2008	5 June	19 June	20 July	15 May	24 June	24 July
	2009	31 May		15 July	19 May	24 June	28 July
	2010	4 June	12–19 June	15 July	28 May	8 July	27 July
	2011	8 June	30 June	20 July	20 May	5 July	1 Aug.
	2012	30 May	20 June	4 July	30 May	11 July	24 July
	2013	8 May	27 May	27 June	8 May	19 June	9 July
	2014	20 May	4 June	1 July	13 May	24 June	10 July
	2015	13 May	26 May	25 June	29 Apr.	10 June	2 July
	2016	16 May	26 May	25 June	27 Apr.	7 June	1 July
Eriogonum heracleoides	2011	26 May	10 June	8 July	27 May	6 July	1 Aug.
	2012	23 May	30 May	25 June	11 May	21 June	16 July
	2013	29 Apr	13 May	10 June	24 Apr.	5 June	1 July
	2014	20 May	20 May	12 June	29 Apr.	10 June	3 July
	2015	13 May	5 May	17 June	15 Apr.	27 May	24 June
	2016	16 May	6 May	16 June	18 Apr.	31 May	23 June

Table 3. Precipitation and growing degree-days at the Malheur Experiment Station, Ontario, OR.

	Precipitation (mm)				Growing degree-days (10 to 30 °C)
Yr	Spring	Spring + winter	Spring + winter + fall		January to June
2006	86	256	368		707
2007	49	97	157		781
2008	36	81	169		604
2009	103	170	225		671
2010	110	214	298		539
2011	121	235	367		476
2012	66	156	213		682
2013	22	60	135		733
2014	44	130	205		741
2015	82	151	265		895
2016	56	128	255		810
72-year average:	67	147	230	23-year average:	665

tapes. Seed was planted at 12.5-mm depth with 65–100 seeds/m of row.

The trial was irrigated with a minisprinkler system (R10 Turbo Rotator, Nelson Irrigation Corp., Walla Walla, WA) from 4 Mar. to 29 Apr. for even stand establishment. Risers were spaced 7.6 m apart along the flexible polyethylene hose laterals that were spaced 9 m apart. The water application rate was 2.5 mm/hr. A total of 44 mm of water was applied with the minisprinkler system. *E. umbellatum* started emerging on Mar. 29. Starting on 24 June, the field was irrigated with the drip system described above. A total of 95 mm of water was applied with the drip system from 24 June to 7 July 2005. The field was not irrigated further in 2005.

Plant stands for *E. umbellatum* were uneven, and it did not flower in 2005. In early Oct. 2005, more seed was received from the Rocky Mountain Research Station for replanting. The empty lengths of row were replanted by hand on 26 Oct. 2005. In the spring of 2006, the stands exceeded 10 plants/m.

In early Nov. 2009, drip tape was buried as described above in preparation for planting *E. heracleoides.* On 25 Nov. 2009, seed was planted in 76 cm rows using a custom-made small-plot grain drill with disc openers. All seed was planted on the soil surface at 65–100 seeds/m of row. After planting, sawdust was applied in a narrow band over the seed row at 26 $g \cdot m^{-1}$ of row. Following planting and sawdust application, the beds were covered with rowcover. Each rowcover (N-sulate, DeWitt Co., Inc., Sikeston, MO) covered two of the four rows and was applied with a mechanical plastic mulch layer. The field was irrigated for 24 h on 2 Dec. 2009 because of very dry soil conditions.

After *E. heracleoides* emerged, the rowcover was removed in Apr. 2010. The irrigation treatments were not applied to *E. heracleoides* in 2010, and stands were not adequate for yield estimates and very few plants flowered. Gaps in the rows were replanted by hand on 5 Nov. 2010. The replanted seed was covered with a thin layer of a mixture of 50% sawdust and 50% hydroseeding mulch (Hydrostraw LLC, Manteno, IL) by volume. The mulch mixture was sprayed with water using a backpack sprayer.

The strips of *E. umbellatum* and *E. heracleoides* were divided in Apr. 2006 and 2011, respectively, into twelve 9.1-m-long plots. Each plot contained four rows spaced 76 cm apart. The experimental designs were randomized complete blocks with four replications. The three irrigation treatments were 0 $mm \cdot year^{-1}$ (control), 100 $mm \cdot year^{-1}$, and 200 $mm \cdot year^{-1}$ of additional water. The 100- and 200-mm irrigation treatments received four irrigations, 2 weeks apart, starting at the beginning of flowering. Each irrigation applied 25 mm (100-mm treatment) or 50 mm (200-mm treatment) of water. Flowering dates for each species were recorded and are reported in conjunction with the irrigation dates in Table 2.

Fertilization of the irrigation trial was modest. On 27 Oct. 2006, 56 $kg \cdot ha^{-1}$ of P and 2.2 $kg \cdot ha^{-1}$ of Zn were injected using the drip irrigation system in the *E. umbellatum* plots. Phosphorus was applied as phosphoric acid, and Zn was applied as zinc sulfate. During the first 2 years (2005 and 2006), weeds were controlled primarily with cultivation and hand roguing. Herbicides were screened for their effectiveness and plant tolerance in other trials (Shock et al., 2011). These products are not yet registered for commercial use on *Eriogonum* species. Prowl®(pendimethalin; BASF, Research Triangle Park, NC) at 1.1 $kg \cdot ha^{-1}$ a.i. was broadcast on the soil surface for weed control on 17 Nov. 2006, 9 Nov. 2007, 15 Apr. 2008, 18 Mar. 2009, 4 Dec. 2009, 17 Nov. 2010, 9 Nov. 2011, 7 Nov. 2012, 26 Feb. 2014, and 13 Mar. 2015. Volunteer® (clethodim; Tenkoz, Inc., Alpharetta, GA) was broadcast at 0.07 $kg \cdot ha^{-1}$ a.i. on 18 Mar. 2009, 3 Apr. 2013, and 26 Feb. 2014. Hand roguing of weeds continued as necessary.

Both *E. umbellatum* and *E. heracleoides* started producing seed in the second year after planting (2006 and 2011, respectively). Each year, all seed in the middle 7.5 m of the two center rows of the four-row plots was harvested when seed of each species was mature. Seed was harvested with a small-plot combine (Wintersteiger Nurserymaster; Wintersteiger USA, Salt Lake City, UT) every year, except 2013 and 2016 when the seed was harvested manually. The seed did not separate from the flowering structures in the combine. In 2006, the unthreshed seed of *E. umbellatum* was taken to the U.S. Forest Service Lucky Peak

Table 4. Average seed yields for two *Eriogonum* species over multiple years.

	Avg seed yield by irrigation treatment			
	No irrigation	100 mm/season	200 mm/season	Least significant difference 0.05
Yr		$kg \cdot ha^{-1}$		
Eriogonum umbellatum				
2006	173.9	240.1	373.4	104.0
2007	89.1	184.5	217.1	89.4
2008	135.9	248.1	274.6	57.9
2009	148.2	249.8	268.9	75.5
2010	283.2	291.5	233.8	NS
2011	278.5	153.4	135.5	101.8
2012	68.6	171.6	207.6	94.5
2013	126.8	257.8	246.2	86.8
2014	287.9	494.8	451.0	92.8
2015	152.8	221.6	101.5	NS
2016	205.4	259.7	157.7	NS
Average	177.3	241.8	246.4	25.2
Eriogonum heracleoides				
2011	61.9	80.1	54.9	NS
2012	282.6	354.8	298.3	NS
2013	321.9	578.9	483.5	115.6
2014	188.3	364.8	414.1	85.8
2015	93.6	166.0	136.9	NS
2016	472.2	545.4	489.6	NS
Average	236.7	348.3	312.9	81.2

Table 5. Standard deviations of amount of water applied for maximum seed yield for two *Eriogonum* species.

		Standard deviation of amount of water applied for maximum yield (mm)			
Species	Yr	Water applied	Water applied plus spring precipitation	Water applied plus spring and winter precipitation	Water applied plus spring, winter, and fall precipitation
Eriogonum umbellatum	2006–16	67.7	58.5	75.8	73.6
Eriogonum heracleoides	2011–16	34.2	33.8	53.8	68.9

Table 6. Regression analysis for *Eriogonum umbellatum* seed yield (y, kg·ha^{-1}) in response to irrigation (x, mm/season) using the equation $y = a + b \cdot x + c \cdot x^2$ in 2006–16, and 11-year average. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b \cdot (2c)^{-1}$, where b is the linear parameter and c is the quadratic parameter.

Water applied vs. yield

Yr	Intercept	Linear	Quadratic	R^2	P	Highest yield (kg·ha^{-1})	Water applied for highest yield (mm/season)
2006	161.7	1.028		0.52	0.05	367.3	203.2
2007	89.1	1.268	–0.0031	0.69	0.05	217.1	201.8
2008	135.9	1.550	–0.0043	0.73	0.01	276.2	181.0
2009	148.2	1.428	–0.0041	0.60	0.05	271.8	173.2
2010	283.2	0.413	–0.0033	0.08	NS	296.1	62.6
2011	260.6	–0.715		0.58	0.01	260.6	0.0
2012	68.6	1.366	–0.0034	0.65	0.01	207.6	203.6
2013	126.8	2.023	–0.0071	0.62	0.05	413.7	141.9
2014	287.9	3.324	–0.0125	0.76	0.01	508.1	132.5
2015	152.8	1.634	–0.0094	0.55	0.10	223.4	86.4
2016	205.4	1.324	–0.0078	0.47	0.10	261.5	84.7
Average	180.7	1.161	–0.0043	0.75	0.01	259.6	135.9

Water applied plus spring precipitation vs. yield

Yr	Intercept	Linear	Quadratic	R^2	P	Highest yield (kg·ha^{-1})	Water applied plus precipitation for highest yield (mm/season)	Precipitation, spring (mm)
2006	74.6	1.012		0.52	0.05	367.3	289.3	86.1
2007	21.0	1.545	–0.0030	0.69	0.05	217.1	253.8	48.8
2008	75.0	1.827	–0.0041	0.73	0.01	276.2	220.2	36.3
2009	–39.8	2.232	–0.0040	0.60	0.05	271.8	279.3	103.4
2010	199.9	1.109	–0.0032	0.08	NS	296.1	173.5	110.0
2011	345.9	–0.704		0.58	0.01	260.6	121.2	121.2
2012	–34.4	1.774	–0.0032	0.65	0.01	207.6	272.9	66.0
2013	80.6	2.289	–0.0069	0.62	0.05	270.3	165.7	21.6
2014	120.6	4.340	–0.0122	0.76	0.01	508.1	178.6	43.9
2015	–40.0	3.105	–0.0092	0.55	0.10	223.4	169.6	81.8
2016	107.8	2.157	–0.0076	0.47	0.10	261.5	142.5	56.4
Average	79.5	1.727	–0.0041	0.75	0.01	259.6	208.6	65.2

Water applied plus spring precipitation vs. relative yield

Yr	Intercept	Linear	Quadratic	R^2	P	Water applied plus precipitation for highest relative yield (mm/season)
2006	20.0	0.271		0.52	0.05	289.3
2007	9.7	0.712	–0.0014	0.69	0.05	253.8
2008	27.3	0.665	–0.0015	0.73	0.01	220.2
2009	–14.8	0.830	–0.0015	0.60	0.05	279.3
2010	68.6	0.380	–0.0011	0.08	NS	173.5
2011	124.2	–0.253		0.58	0.01	121.2
2012	–16.6	0.854	–0.0016	0.65	0.01	272.9
2013	31.3	0.888	–0.0027	0.62	0.05	165.7
2014	24.4	0.877	–0.0025	0.76	0.01	178.6
2015	–18.0	1.401	–0.0041	0.55	0.10	169.6
2016	41.5	0.831	–0.0029	0.47	0.10	142.5
Average	31.3	0.680	–0.0016	0.75	0.01	208.6

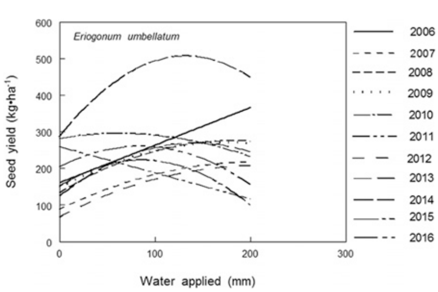

Fig. 1. Seed yield response of *Eriogonum umbellatum* to water applied in 2006–16.

Nursery (Boise, ID) and run through a dewinger to separate seed. The seed was further cleaned in a Clipper Office Tester (Clipper Separation Technologies, Blufton, IN). In subsequent years, the unthreshed seed of both species was run through a manually operated meat grinder to separate the seed. The seed was further cleaned in a small clipper.

Seed yield responses to irrigation were evaluated by linear and quadratic regression. Seed yield for each species each year was regressed separately against 1) applied water; 2) applied water plus spring precipitation; 3) applied water plus winter and spring precipitation; and 4) applied water plus fall, winter, and spring precipitation. Winter and spring precipitation occurred in the same calendar year that the yield was determined; fall precipitation occurred the previous year.

Seed yield (y, kg·ha^{-1}) in response to irrigation or irrigation plus precipitation (x, mm/season) was estimated by the equation $y = a + b \cdot x + c \cdot x^2$. For the quadratic equations, the amount of irrigation (x') that resulted in maximum yield (y') was calculated using the formula $x' = -b \cdot (2c)^{-1}$, where a is the intercept, b is the linear parameter, and c is the quadratic parameter and the maximum yield was considered the "highest" yield. For the linear regressions, the highest seed yield for a species in a given year was based on the highest measured average seed yield.

Adding the seasonal precipitation to the irrigation response equation would have the potential to provide a closer estimate of the amount of irrigation water actually required for maximum seed yield for each species each year. Regressions of seed yield for each species each year were calculated on all the sequential seasonal amounts of precipitation and irrigation, but only some of the regressions are reported below. For each species, the period of precipitation plus applied water that had the lowest standard deviation for irrigation plus precipitation over the years was chosen as the most reliable independent variable for predicting seed yield. To compare yield responses over years, regressions were also made on the relative seed yields compared with irrigation plus precipitation.

Relative seed yield for each plot was calculated as the percentage of the yield of the highest yielding treatment for each species for each year. Regressions were also made relating seed yield to growing degree-days.

Results

E. umbellatum and *E. heracleoides* began flowering and producing seed in the second year after planting (Table 2). On average, *E. heracleoides* started flowering 5 d earlier and had a flowering duration 8 d shorter than *E. umbellatum*. Both precipitation and growing degree-days had large year-to-year variation (Table 3). Large year-to-year variations in seed yields also occurred for both species (Table 4). Although there were tremendous variations in seed yields over species and years, general trends emerged for the mean seed yields for each species and irrigation treatment. Variations in seed yields over years were not related to growing degree-days.

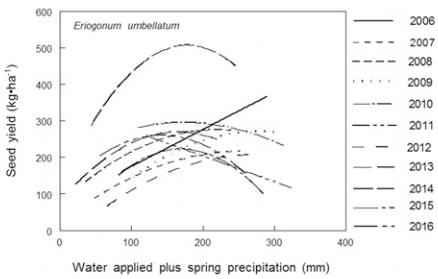

Fig. 2. Seed yield response of *Eriogonum umbellatum* to water applied plus spring precipitation in 2006–16.

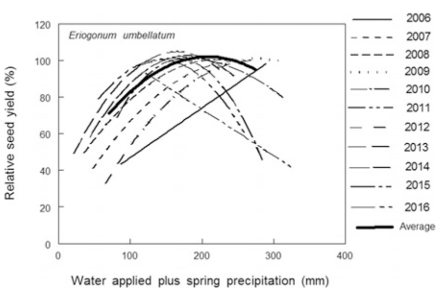

Fig. 3. Relative seed yield response of *Eriogonum umbellatum* to water applied plus spring precipitation in 2006–16 and the 11-year average relative seed yield response.

Eriogonum umbellatum, sulphur-flower buckwheat. Adding spring precipitation to applied water reduced the variation in estimate of the optimal irrigation requirement for maximum seed production of *E. umbellatum*, but addition of the earlier fall and winter increments of precipitation increased the variation in the estimated optimal water requirement (Table 5). Seed yields of *E. umbellatum* had quadratic responses to irrigation amount in 2007–10 and 2012–16 (Table 6; Figs. 1–3). The quadratic response to irrigation in 2010 was not statistically significant, and in 2011, the response to irrigation was linear and negative. Over the 11 years of testing, the years 2011 and 2010 had the highest and second highest spring precipitation and the lowest and second lowest growing degree-days, respectively (Table 3). Seed yield of *E. umbellatum* exhibited a positive linear response to irrigation rate in 2006. The amount of water applied plus spring precipitation for maximum seed yield, calculated from the regression equations, ranged from 0 water applied plus 120 mm of spring precipitation yielding 261 $kg \cdot ha^{-1}$ in 2011 to 203 mm of water applied plus 86 mm of spring precipitation yielding 367 $kg \cdot ha^{-1}$ in 2006. The highest yields averaged 260 $kg \cdot ha^{-1}$ and ranged from 207 to 508 $kg \cdot ha^{-1}$. Averaged over 11 years, relative seed yield was highest with 208 $mm \cdot year^{-1}$ of applied water plus spring precipitation (Table 6; Fig. 3).

Eriogonum heracleoides, parsnipflower buckwheat. For *E. heracleoides*, only applied water is reported in evaluating yield responses to irrigation. Adding spring precipitation to applied water had a negligible effect on reducing the year to year variation in the optimal water requirement for maximum seed production in the regression analysis (Table 4). Neither winter plus spring precipitation nor fall, winter, plus spring precipitation reduced the year-to-year variation in estimating the optimal water requirement for maximum seed production.

From 2011–16, seed yields of *E. heracleoides* responded to irrigation only in 2013 and 2014, the 2 years with the lowest spring precipitation (Table 7; Figs. 4 and 5). From the quadratic responses to irrigation, seed yields were estimated to be highest with 123 $mm \cdot year^{-1}$ of total applied irrigation water yielding 588 $kg \cdot ha^{-1}$ in 2013 and 189 mm of total applied irrigation water yielding 415 $kg \cdot ha^{-1}$ in 2014. The highest treatment yields averaged 353 $kg \cdot ha^{-1}$ and ranged from 168–588 $kg \cdot ha^{-1}$, depending on the year. Considering the results over 6 years, relative seed yields showed a quadratic response to irrigation and were maximized at 353 $kg \cdot ha^{-1}$ by 126 $mm \cdot year^{-1}$ of total applied water.

Discussion

Seasonal precipitation varied greatly among years, as did the amount of irrigation water required for maximum seed production. The regression analyses showed large differences in the optimum mm of water for maximum seed yield among years. There was more variability in seed yield within and between years for *E. heracleoides* than for *E. umbellatum*. When precipitation was added to the amount of water applied in the regressions, the variability in the optimum amount of water decreased for *E. umbellatum*, but not for *E. heracleoides.* The graphs of the relative seed yield of the *Eriogonum* species in

Table 7. Regression analysis for *Eriogonum heracleoides* seed yield (y, $kg \cdot ha^{-1}$) in response to irrigation (x, mm/season) using the equation $y = a + b \cdot x + c \cdot x^2$ in 2011–16 and 6-year averages. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b \cdot (2c)^{-1}$, where b is the linear parameter and c is the quadratic parameter.

Water applied vs. yield								
Yr	Intercept	Linear	Quadratic	R^2	P	Highest yield ($kg \cdot ha^{-1}$)	Water applied for highest yield (mm/season)	Precipitation, spring (mm)
2011	61.9	0.401	–0.0022	0.16	NS	80.3	92.0	121.2
2012	282.6	1.367	–0.0064	0.01	NS	355.1	106.1	66.0
2013	321.9	4.332	–0.0176	0.64	0.05	588.1	122.9	21.6
2014	188.3	2.400	–0.0064	0.85	0.001	414.9	188.8	43.9
2015	93.6	1.232	–0.0051	0.29	NS	168.3	121.3	81.8
2016	472.2	1.376	–0.0065	0.06	NS	545.7	106.8	56.4
Average	236.7	1.851	–0.0074	0.57	0.05	353.3	125.9	70.5

Water applied vs. relative yield						
Yr	Intercept	Linear	Quadratic	R^2	P	Water applied for highest relative yield (mm/season)
2011	77.2	0.500	–0.00272	0.16	NS	92.0
2012	79.6	0.385	–0.00181	0.01	NS	106.1
2013	55.6	0.748	–0.00304	0.64	0.05	122.9
2014	45.5	0.580	–0.00154	0.85	0.001	188.8
2015	56.4	0.742	–0.00306	0.29	NS	121.3
2016	86.6	0.252	–0.00118	0.06	NS	106.8
Average	68.0	0.531	–0.00211	0.57	0.05	125.9

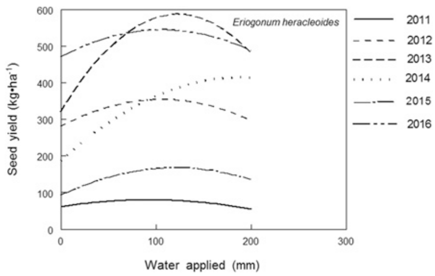

Fig. 4. Seed yield response of *Eriogonum heracleoides* to water applied in 2011–16.

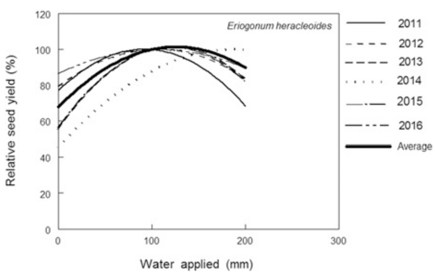

Fig. 5. Relative seed yield response of *Eriogonum heracleoides* to water applied in 2011–16 and the 6-year average relative seed yield response.

the present study show a consistency of relative seed yield responses for each species over years (Figs. 3 and 5). *Eriogonum umbellatum* was more responsive to irrigation than *Eriogonum heracleoides* in this study. This might be related to the differences in native habitat of the two species. The habitat ranges of *E. heracleoides* and *E. umbellatum* overlap, but *E. heracleoides* typically occupies sites with lower elevation and lower precipitation than *E. umbellatum* (USDA/NRCS, 2007). The seed yield of *E. umbellatum* had no significant yield response to irrigation in 2010, a wet year, and actually declined with irrigation in 2011, the year with the highest rainfall. The positive yield response of *E. umbellatum* to irrigation in 2006, another wet year, could have been because it was the first year of production and the plants receiving less irrigation were proportionally smaller in 2006.

The irrigation requirements for the *Eriogonum* species in this study were comparable with the results for three *Lomatium* species grown at the same site (Shock et al., 2016). Over multiple years, *Lomatium dissectum* (Nutt.) Mathias & Constance and *L. triternatum* (Pursh) J.M. Coult. & Rose seed yields were best estimated by a quadratic response to irrigation plus spring precipitation with highest yields at 243 and 255 mm·year^{-1}, respectively. *Lomatium grayi* (J.M. Coult. & Rose) seed yields were best estimated by a quadratic response to irrigation plus precipitation during the fall, winter, and spring with highest yields at 358 mm·year^{-1}.

Other studies that examined irrigation responses of xerophytic plant establishment and growth found similar responses within the ranges of irrigation in our study. In Tucson, Ariz., with annual precipitation of 293 mm, native grass and native woody plant establishment from seed was optimum with 187–210 mm of irrigation plus precipitation (Roundy et al., 2001). In the Chihuahuan Desert in New Mexico, with annual precipitation of 211 mm, only six of 15 species increased vegetative growth in response to 338 mm of annual irrigation (Gutierrez and Whitford, 1987).

There are few published studies examining seed production of native plants in response to irrigation in arid regions. In a west-central Texas area that receives 530 mm of annual precipitation, Petersen and Ueckert (2005) found that seed production of *Atriplex canescens* (Prush) Nutt. (fourwing saltbush) did not respond to either 400 mm of irrigation in 1 year or 200 mm of irrigation the next year. In the Owens Valley, CA, with annual precipitation of 113 mm, *Sarcobatus vermiculatus* (Hook.) Torr. (greasewood) seed yields were significantly higher when irrigated (Breen and Richards, 2008). These studies were not designed to determine optimum amounts of irrigation for seed yield.

In this study, both *Eriogonum* species tested responded to irrigation with increased seed yields many years, increasing the reliability of seed production. The amount of irrigation and precipitation needed for maximum *Eriogonum* seed yields (100–300 mm·year^{-1}) was substantially lower than irrigation plus precipitation requirements for row crops in the Treasure Valley of eastern Oregon (evapotranspiration of 500–800 mm·year^{-1}, AgriMet, 2016; Feibert and Shock, 2016). Although *Eriogonum* species are perennials, they complete their cycle from sprouting to seed harvest by early July; thus, their irrigation requirements would be expected to be lower than those for row crops. However, irrigation requirements for *Eriogonum* are low even when compared with an early season crop such as winter wheat (*Triticum aestivum* L.), which has an average water requirement of 633 mm in the Treasure Valley (Feibert and Shock, 2016).

Studies of cultural practices for native plants are essential to increase seed production and availability of plant material used in restoration of ecosystems in the Intermountain West. As restoration needs increase, the economic opportunities for native plant seed growers will also increase. Developing in-depth knowledge on seed production practices will support the native seed industry in the future. Precise irrigation can help assure seed yield and reduce grower risk.

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