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RESEARCH ARTICLE

Irrigation to Enhance Native Seed Production for Great Basin Restoration

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ABSTRACT: Native shrublands and their associated grasses and forbs have been disappearing from the Great Basin as a result of grazing practices, exotic weed invasions, altered fire regimes, climate change and other human impacts. Native forb seed is needed to restore these areas. The irrigation requirements for maximum seed production of four key native forb species (*Eriogonum umbellatum, Lomatium dissectum, Penstemon speciosus*, and *Sphaeralcea grossulariifolia*) were studied at the Oregon State University Malheur Experiment Station beginning in 2005. Species plots were supplied with 0, 100, or 200 mm of subsurface drip irrigation per year using a randomized complete block design with four replications. Irrigation in each plot was divided into four equal increments applied between bud and seed set with timing dependent upon the flowering and seed set phenology of each species. Seed was harvested in each year of production through 2011, and the optimal irrigation rate was determined by regression. The four native forb species differed in their responses to irrigation. *Lomatium dissectum* seed yields were optimized with 140 mm of irrigation. *Eriogonum umbellatum* seed yields were optimized with 173 to 200 mm of irrigation in dry years and progressively less to no irrigation in the wettest year. *Penstemon speciosus* seed yields were optimized with 107 mm of irrigation in dry years and were reduced by irrigation in wet years. *Sphaeralcea grossulariifolia* seed yields did not respond to irrigation. Water requirements of these species are low, and these results can be used by seed growers to produce native forb seed more economically.

Index terms: Eriogonum umbellatum, fernleaf biscuitroot, gooseberryleaf globemallow, *Lomatium dissectum*, *Penstemon speciosus*, royal penstemon, sagebrush penstemon, sagebrush steppe, *Sphaeralcea grossulariifolia*, subsurface drip irrigation, sulphur-flower buckwheat

INTRODUCTION

Native shrublands and grasslands have been disappearing from the western United States (D'Antonio and Vitousek 1992). The transformation of perennial grassland communities into communities dominated by invasive annual species is evident throughout much of California (D'Antonio and Vitousek 1992; D'Antonio et al. 2000; Seabloom et al. 2003; Germano et al. 2012) and similar transformations are ongoing in shrublands of the arid and semi-arid Intermountain West (D'Antonio and Vitousek 1992; Millennium Ecosystem Assessment 2005; Reynolds et al. 2007; Zald 2008). The loss of native shrublands and grasslands is a worldwide phenomenon (D'Antonio and Vitousek 1992; Seabloom et al. 2003; Millennium Ecosystem Assessment 2005).

Sagebrush-steppe and associated plant communities of the Great Basin are being replaced by invasive exotic grasses, broadleaf weeds, and the expansion of native junipers (Azuma et al. 2005; Miller et al. 2005; Wells 2006; Shock et al. 2007, 2011). Grazing practices have contributed to the spread of exotic annual grasses, which have, in turn, led to catastrophic fires (Miles and Karl 1995; Pellant 1996; Davies et al. 2009, 2010). This transformation in vegetation composition influences other species in the biome due to plant-based food webs.

Restoration of sagebrush steppe vegetation in the Intermountain West is difficult and requires seeding or transplanting native species (James et al. 2013) where native seedbanks have been lost. Commercial seed production is necessary to provide the quantity of grass and forb seed needed for restoration efforts. Most major grass species used for revegetation have long been produced under agricultural conditions, but the forb seed production industry for this region is in its infancy. Major limitations to economically viable commercial production of native forb seed are stable and consistent seed production and reliable seed marketing opportunities. The irrigation of forbs planted for seed might make seed production more consistent. In natural rangelands, wide variation in winter and spring precipitation and soil moisture result in highly unpredictable water stress at flowering, seed set, and seed development, which for other seed crops is known to reduce seed yield and quality.

Both sprinkler and furrow irrigation can provide supplemental water for seed production, but these irrigation systems also encourage weeds by wetting the soil surface. In addition, sprinkler and furrow irrigation can lead to the loss of plant stands and seed production by enhancing fungal pathogens, an extreme economic disadvantage when growing perennial forbs. The trials described here used subsurface drip irrigation. Our goal was to assure flowering and seed set without undue encouragement of weeds or opportunistic diseases by burying drip tapes at 0.3-m depth to avoid wetting the soil surface.

MATERIALS AND METHODS

Plant Establishment

Irrigation trials for *Eriogonum umbellatum* Torr., *Lomatium dissectum* (Nutt.) Mathias & Constance, *Penstemon speciosus* Dougl. ex Lindl., and *Sphaeralcea grossulariifolia* (Hook. & Arn.) Rydb. (USDA NRCS 2014) were initiated in 2005 and 2006 at the Malheur Experiment Station, Oregon State University, Ontario, Oregon (Table 1). Seed from wildland collections was provided by the US Forest Service.

The research field, a Nyssa silt loam (coarse-silty, mixed, mesic, Xeric Haplodurid), was leveled more than 70 years ago, and most of the topsoil was removed at that time to fill a natural ravine within the field. Analysis of a soil sample taken on 22 Nov. 2005 indicated a pH of 8.3, 1.09% organic matter, 12 $mg \cdot kg^{-1}$ P_2O_5, 438 $mg \cdot kg^{-1}$ K, 27 $mg \cdot kg^{-1}$ SO_4-S, 4370 $mg \cdot kg^{-1}$ Ca, 456 $mg \cdot kg^{-1}$ Mg, 81 $mg \cdot kg^{-1}$ Na, 1.6 $mg \cdot kg^{-1}$ Zn, 0.6 $mg \cdot kg^{-1}$ Cu, 4 $mg \cdot kg^{-1}$ Mn, 3 $mg \cdot kg^{-1}$ Fe, and 0.6 $mg \cdot kg^{-1}$ B.

The field was bedded to plant the forbs in rows 76 cm apart. Drip tapes (T-Tape TSX 515-16-340) were buried at 30-cm depth and spaced 1.52 m apart beneath alternating inter-row spaces. Emitters were spaced 41 cm apart, and the flow rate for the drip tape was 4.16 $L \cdot min^{-1} \cdot 100\ m^{-1}$ at 55 kPa, resulting in a water application rate of 1.7 mm hr^{-1}. Water was filtered through sand media filters, and application duration was controlled automatically.

Seed of *E. umbellatum*, *L. dissectum, and P. speciosus* was planted on 3 March 2005 using a custom-made small-plot grain drill with disk openers at 1.25-cm depth seeding 65–100 $seeds \cdot m^{-1}$ of row. Due to poor establishment from spring planting, seed was replanted from the same seed lots at 65 seeds m^{-1} using the same planter on 26 October 2005 so that natural, winter vernalization could occur. Excellent stands of all species were obtained in spring 2006. *Sphaeralcea grossulariifolia* was planted 11 April 2006 and was replanted 10 November 2006.

In April 2006, the areas planted to each species were divided into 12 plots, each 9 m long. Each plot contained four rows 0.76 m apart. The experimental design for each species was a randomized complete block with four replicates. The three irrigation treatments were 0 $mm \cdot year^{-1}$(nonirrigated check), 100 $mm \cdot year^{-1}$, and 200 $mm \cdot year^{-1}$. The 100-mm and 200-mm irrigation treatments received four irrigations, applied approximately two weeks apart, starting individually for each species at flowering. The dates of the start, peak, and end of flowering for each species were recorded and are reported in conjunction with the dates of the first and last irrigation in Table 2. Each irrigation delivered 25 mm (100-mm treatment) or 50 mm (200-mm treatment) through the drip system. The amount of water applied was measured by a water meter and recorded. In 2007, irrigation treatments were inadvertently continued after the fourth irrigation, providing additional water after seed set in proportion to the irrigation treatments.

Soil volumetric water content was measured several times each growing season by neutron probe. The neutron probe was calibrated by taking soil samples and probe readings at 0.20-, 0.50-, and 0.80-m depths during installation of the access tubes. The soil water content was determined volumetrically from soil samples taken from each depth and regressed against the neutron probe readings.

Fertilization of the irrigation trials over the six years was minimal. On 27 Oct. 2006, 56 $kg \cdot ha^{-1}$ phosphorus and 2.2 $kg \cdot ha^{-1}$ zinc were injected through the drip tape. On 11 Nov. 2006, 112 $kg \cdot ha^{-1}$ nitrogen as urea was broadcast. On 9 Apr. 2009, 56 $kg \cdot ha^{-1}$ N and 11 $kg \cdot ha^{-1}$ P were applied through the drip irrigation system. On 3 May 2011, 56 $kg \cdot ha^{-1}$ N was applied through the drip irrigation system. Natural precipitation varied considerably from 2006 through 2011 (Table 3, Figure 1).

During the first two years (2005 and 2006), weeds were controlled primarily with cultivation and hand rouging. Herbicides were screened for their effectiveness and plant tolerance in other trials (Shock et al. 2010). Even though they are not yet registered for use, we broadcasted Prowl® (pendimethalin) at 1.1 kg $ai \cdot ha^{-1}$ on the soil surface for weed control on 17 Nov. 2006, 9 Nov. 2007, 15 Apr. 2008, 18 Mar. 2009, 4 Dec. 2009, and 17 Nov. 2010. Volunteer® (clethodim) was broadcast at 0.57 $L \cdot ha^{-1}$ on 18 Mar. 2009. Hand rouging of weeds

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

Species	Common names	Plant source location	Plant source state
Eriogonum umbellatum	sulphur-flower buckwheat	Shoofly Road, Owyhee Co.	Idaho
Penstemon speciosus	royal penstemon, sagebrush penstemon	Leslie Gulch, Malheur Co.	Oregon
Lomatium dissectum	fernleaf biscuitroot	New Plymouth, Payette Co.	Idaho
Sphaeralcea grossulariifolia	gooseberryleaf globemallow	Cherry Creek, Juab County	Utah

Table 2. Native forb flowering, irrigation, and seed harvest dates by species in 2006–2011, Malheur Experiment Station, Oregon State University, Ontario, OR.

		Flowering			Irrigation		
Species		Start	Peak	End	Start	End	Seed harvest
Eriogonum umbellatum	2006	19-May		20-Jul	19-May	30-Jun	3-Aug
	2007	25-May		25-Jul	2-May	24-Jun	31-Jul
	2008	5-Jun	19-Jun	20-Jul	15-May	24-Jun	24-Jul
	2009	31-May		15-Jul	19-May	24-Jun	28-Jul
	2010	4-Jun	12-19 Jun	15-Jul	28-May	8-Jul	27-Jul
	2011	8-Jun	30-Jun	20-Jul	20-May	5-Jul	1-Aug
Penstemon speciosus	2006	10-May	19-May	30-May	19-May	30-Jun	13-Jul
	2007	5-May	25-May	25-Jun	19-Apr	24-Jun	23-Jul
	2008	5-May		20-Jun	29-Apr	11-Jun	17-Jul
	2009	14-May		20-Jun	19-May	24-Jun	10-Jul
	2010	14-May		20-Jun	12-May	22-Jun	22-Jul
	2011	25-May	30-May	30-Jun	20-May	5-Jul	29-Jul
Lomatium dissectum	2006				19-May	30-Jun	
	2007				5-Apr	24-Jun	
	2008				10-Apr	29-May	
	2009	10-Apr		7-May	20-Apr	28-May	16-Jun
	2010	25-Apr		20-May	15-Apr	28-May	21-Jun
	2011	8-Apr	25-Apr	10-May	21-Apr	7-Jun	20-Jun
Sphaeralcea grossulariifolia	2006						
	2007	5-May	25-May	5-Sep	16-May	24-Jun	3 times[a]
	2008	5-May		15-Jun	15-May	24-Jun	21-Jul
	2009	1-May		10-Jun	22-May	24-Jun	14-Jul
	2010	10-May	4-Jun	25-Jun	28-May	8-Jul	20-Jul
	2011	26-May	15-Jun	14-Jul	20-May	5-Jul	29-Jul

[a]Seed harvested three times in 2007: 20 June, 10 July, and 13 August.

Table 3. Annual precipitation (2006-2011) and the long term average (66 years) at the Malheur Experiment Station, Oregon State University, Ontario, OR.

	Precipitation (mm)	
Year	Jan–June	April–June
2006	229	79
2007	79	48
2008	74	30
2009	147	99
2010	211	109
2011	211	99
66-year average	147	69

continued throughout the study.

Seed production of *P. speciosus* was susceptible to losses from *Lygus* Hahn. (lygus bugs). *Penstemon speciosus* was sprayed with Aza-Direct® at 0.006.9 g ai·ha^{-1} on 14 and 29 May 2007 and Capture® 2EC at 112 g ai·ha^{-1} on 20 May 2008 for lygus control.

Flowering, Harvesting, and Seed Cleaning

Floral phenology was monitored annually for each species (Table 2). Seed harvests were timed to coincide with seed matura-

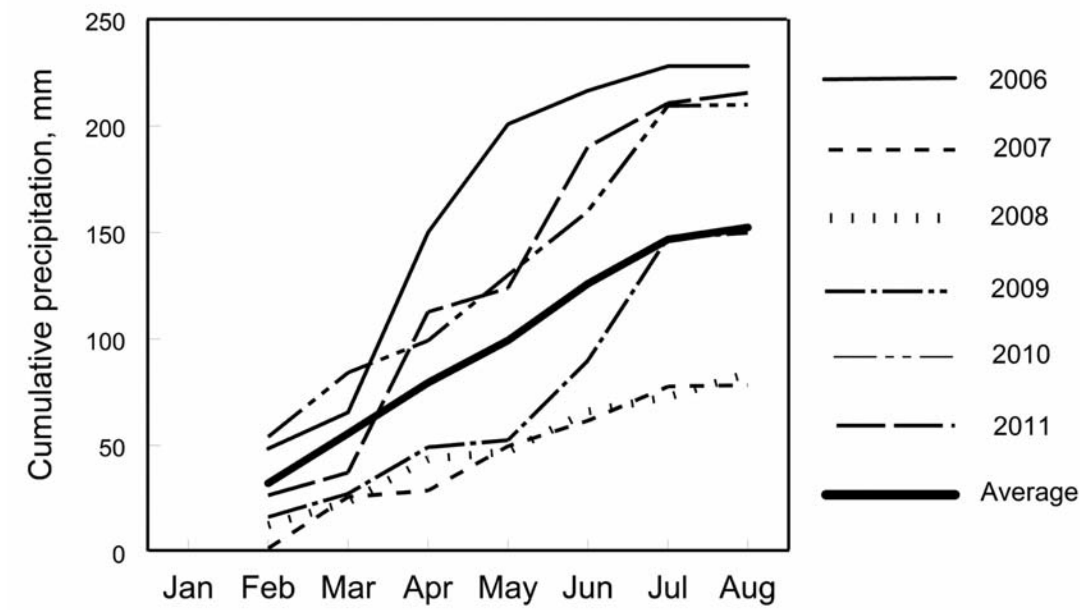

Figure 1. Cumulative annual and 6-year average precipitation from January through July at the Malheur Experiment Station, Oregon State University, Ontario, OR.

tion, which varied among species and years (Table 2). Seed from the middle 7.5 m of the two center rows in each plot was harvested and cleaned. Seed harvesting and cleaning methods differed by species (Table 4). Seed of *E. umbellatum*, *P. speciosus,* and *S. grossulariifolia* was harvested by combine. The seed of *E. umbellatum* and *S. grossulariifolia* required extra threshing. Seed of *L. dissectum* was harvested by hand and did not require additional threshing. Seed was cleaned prior to yield measurements; seed quality was not determined. Seed yield means were compared by protected analysis of variance, LSDs were calculated, and nonlinear regression of seed yield was calculated against applied water.

RESULTS

Soil Volumetric Water Content

Soil volumetric water content responded to the irrigation treatments for each species and varied each year with precipitation and winter snow pack (data not shown).

Flowering and Seed Set

Eriogonum umbellatum and *P. speciosus* produced seed in 2006, in part from plants that had emerged in the spring of 2005. There were few *S. grossulariifolia* plants in 2006, but this species flowered and set seed in 2007 after the November 2006 replanting. *Lomatium dissectum* did not flower and produce seed in quantity until 2009.

Table 4. Native forb seed harvest and cleaning by species, Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Number of harvests/year	Harvest method	Pre-cleaning	Threshing method	Cleaning method
Eriogonum umbellatum	1	combine[a]	none	dewinger[b]	mechanical[c]
Penstemon speciosus[d]	1	combine[e]	none	combine	mechanical[c]
Lomatium dissectum	1	hand	hand	none	mechanical[c]
Sphaeralcea grossulariifolia	1 – 3	hand or combine[e]	none	combine	none

[a] Wintersteiger Nurserymaster small-plot combine with dry bean concave.
[b] Specialized seed threshing machine at USDA Lucky Peak Nursery used in 2006. Thereafter, an adjustable hand-driven corn grinder was used to thresh seed.
[c] Clipper seed cleaner.
[d] Harvested by hand in 2007 and 2009 due to poor seed set.
[e] Wintersteiger Nurserymaster small-plot combine with alfalfa seed concave. For the *S. grossulariifolia* , flailing in the fall of 2007 resulted in more compact growth with the result that only one combine harvest was required in 2008, 2009, and 2010.

Penstemon speciosus had poor seed set in 2007, partly due to a heavy lygus bug infestation that was not adequately controlled by the applied insecticides. In the Treasure Valley, the first hatch of lygus bugs occurs when 250 degree-days calculated at 52 °F base are accumulated. Data collected by an AgriMet weather station adjacent to the field indicated that the first lygus bug hatch would have occurred on 14 May 2006, 1 May 2007, 18 May 2008, 19 May 2009, and 29 May 2010. The average lygus bug hatch date for 1995–2010 was 18 May. *Penstemon speciosus* begins flowering in early to mid-May. The earlier lygus bug hatch in 2007 probably resulted in harmful levels of lygus bugs being present during a larger part of the *P. speciosus* flowering period than normal. Lower seed set for *P. speciosus* in 2007 was also related to poor vegetative growth compared to 2006 and 2008. In 2009, all plots of *P. speciosus* again showed poor vegetative growth and seed set. Root rot affected the wetter plots of *P. speciosus* in 2009, but the stand partially recovered due to natural reseeding. Reseeding of *P. speciosus* resulted in its long term productivity, but also increased the generations of seed increase between wild collection of seed and seed use in range restoration.

Sphaeralcea grossulariifolia exhibited prolonged flowering in 2007, its first seed production year (early May through September), possibly due to the extra irrigation water that was applied. Multiple manual harvests were necessary in 2007 because the seeds were rapidly dispersed from the capsules once they matured. Following harvest the flailing of the *S. grossulariifolia* vegetation was initiated in the fall of 2007 and thereafter was repeated annually to induce a more concentrated flowering period for a single mechanical harvest. Precipitation in June of 2009 and 2010 was substantially higher than average. Rust (*Puccinia sherardiana* Korn.) infected *S. grossulariifolia* in June of 2009 and 2010, causing substantial leaf loss and reduced vegetative growth.

Seed Yields

Eriogonum umbellatum

In 2006, seed yield of *E. umbellatum* increased with increasing water application up to 200 mm, the highest amount tested (Table 5, Figure 2). In 2007–2009, seed yield showed a quadratic response to irrigation rate. Based on the quadratic equations, seed yields were maximized by 202 mm of water applied in 2007, 181 mm in 2008 and 173 mm in 2009. In 2010, there was no significant difference in seed yield among the irrigation treatments. In 2011, seed yield was highest with no irrigation. The 2010 and 2011 seasons were unusually cool and wet (Table 3, Figure. 1). Accumulated precipitation during April through June of these years was among the highest over the years of the trial (Table 3). The relatively high seed yield of *E. umbellatum* in the nonirrigated treatment in 2010 and 2011 seemed to be related to the high January to March precipitation followed by high April to June precipitation. Irrigation in these two years might also have exacerbated the rust infections observed in the 100- and 200-mm treatments and contributed to the lower yields. Averaged over six years, seed yield of *E. umbellatum* increased with increasing water applied up to 200 mm, the highest amount tested (Figure 2). The shape of the quadratic seed yield responses observed in most years suggested that additional irrigation above 200 mm would not be beneficial. *Eriogonum umbellatum* responded to 173 to 200 mm of irrigation in the first year and in years with less than 300 mm of precipitation from January through June. In wetter years seed yield responses were negative.

Penstemon speciosus

From 2006 to 2009, the seed yield of *P. speciosus* showed a quadratic response to total irrigation (Figure 3, Table 5). Seed yields were maximized by 106–108 mm of applied water in 2006, 2007, 2008, and 2009, years when there was less than 90 mm of precipitation from May through June. Seed yields did not increase with irrigation in years when rainfall from May through June was above 90 mm. In 2010 and 2011, seed yield did not differ significantly among irrigation treatments. Seed yield was low in 2007, probably due to lygus bug damage, as mentioned above. Seed yield in 2009 was low due to stand loss from root rot. The plant stand recovered somewhat in 2010 and 2011, due largely to natural reseeding, especially in the nonirrigated plots. The plant lifespan of *P. speciosus* was around three years in our agronomic setting, suggesting that long-term seed yields will depend upon replanting to the same or different fields.

Lomatium dissectum

Lomatium dissectum exhibited very slow vegetative growth in 2006–2008, and produced very few flowers in 2008. The species was affected by *Alternaria* sp. Nees. fungus, and this infection might have delayed *L. dissectum* plant development and reduced its seed yield. Vegetative growth and flowering for *L. dissectum* were greater in 2009. Seed yield exhibited a linear response to irrigation in 2009 (Table 5; Figure 4). Seed yield for the 100-mm irrigation treatment was significantly higher than for the nonirrigated check, but the 200-mm irrigation rate did not result in a significant increase above the 100-mm rate. In 2010 and 2011, seed yields of *L. dissectum* showed a quadratic response to irrigation rate and were maximized by 161 mm of applied water in 2010 and 127 mm in 2011. Averaged over the three years, seed yield showed a quadratic response to irrigation rate and was estimated to be maximized by 140 mm of applied water (Shock et al. 2012).

Sphaeralcea grossulariifolia

In 2007–2011, seed yield did not vary significantly among irrigation treatments for *S. grossulariifolia* (Table 5). This forb was well adapted to produce moderate seed yield regardless of the natural variations of rainfall or irrigation at Ontario, Oregon.

DISCUSSION

The four forb species reported in our trials differed greatly in their seed yield response to irrigation, varying from *L. dissectum*, an early season flowering species, which responded to irrigation in every year, to *S. grossulariifolia,* which failed to respond to irrigation in any year, regardless of natural precipitation. *Eriogonum umbellatum* and *P. speciosus* responded to irrigation in dry years and displayed little or no seed yield

Table 5. Native forb seed yield response to irrigation rate (mm/season) 2006–2011 at the Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Year	Irrigation rate 0 mm	100 mm	200 mm	LSD (0.05)
		----- Yield (kg·ha^{-1}) -----			
Eriogonum umbellatum [a]	2006	173.9	240.1	416.2	104
	2007	89.2	184.6	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	233.9	NS
	2011	278.5	153.3	135.5	101.8
	Average	184.8	227.9	257.7	38.6
Penstemon speciosus [a]	2006	183.1	387.7	239.2	150.4
	2007	2.8	10.4	5.9	5.3 [b]
	2008	105.3	411	309.7	201.2
	2009	7.6	18	10.1	6.7 [b]
	2010	164.9	83.2	78.1	NS
	2011	415.6	367.6	390.4	NS
	Average	146.6	213	172.2	NS
Lomatium dissectum [c]	2006	------ no flowering ------			
	2007	------ no flowering ------			
	2008	--- very little flowering ---			
	2009	56.7	359	367.1	220
	2010	297.7	609.1	559.6	223.6
	2011	635.6	1503.9	1247.5	202.6
	4- to 6-yr average	330	824	724.7	219.2
Sphaeralcea grossulariifolia [d]	2006	-------- few plants --------			
	2007	495.7	363.8	394.1	NS
	2008	308.3	205.3	200.1	NS
	2009	303.2	334.8	366.2	NS
	2010	347.8	393.1	388.2	NS
	2011	250.9	293.3	165.9	NS
	2- to 6-yr average	341.2	318.1	302.9	NS

[a] Planted March 2005, areas of low stand replanted by hand in October 2005.

[b] LSD (0.10).

[c] Planted March 2005, all plots replanted in October 2005.

[d] Planted spring 2006, all plots replanted in November 2006.

response in wet years.

This range of responses is consistent with the findings of other authors for seed yields of other plants native to arid and semiarid lands. At the Owens Lake playa in California, *Sarcobatus vermiculatus* (Hook.) Torr. (greasewood) seed yield was enhanced by supplemental irrigation (Breen and Richards 2008). Pol et al. (2010) demonstrated that a wide range of perennial C_3 and C_4 grasses responded to rainfall events with increased seed productivity in the arid grasslands of Mendoza Province, Argentina. In contrast, Fisher et al. (1988) found that irrigation of *Larrea tridentata* (DC.) Coville (creosote bush) was detrimental to fruit production in the northern Chihuahuan Desert rangelands of New Mexico. In west Texas, Petersen and Ueckert (2005) found that seed yields of *Atriplex canescens* (Pursh) Nutt. (fourwing saltbush) failed to respond to irrigation. To date, literature on irrigation impacts

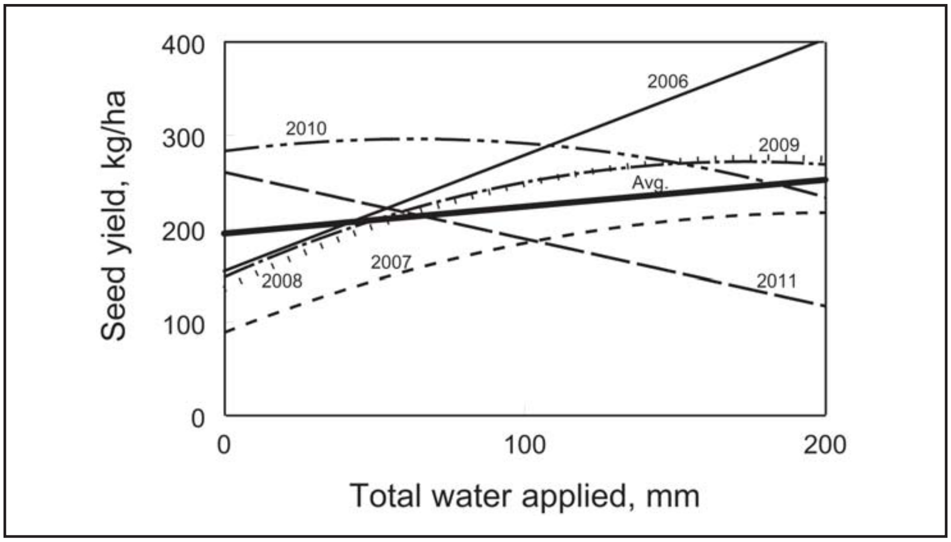

Figure 2. Average and annual *Eriogonum umbellatum* seed yield response to irrigation water applied in each of 6 years, Malheur Experiment Station, Oregon State University, Ontario, OR. Regression equations: 2006, Y = 154.5 + 1.244X, R^2 = 0.68, *P* = 0.02; 2007, Y = 89.12 + 1.268X – 0.003143X^2, R^2 = 0.69, *P* = 0.02; 2008, Y = 135.9 + 1.550X – 0.004283X^2, R^2 = 0.73, *P* = 0.005; 2009, Y = 148.2 + 1.428X – 0.004124X^2, R^2 = 0.60, *P* = 0.02; 2010, Y = 283.2 + 0.4127X – 0.003299X^2, R^2 = 0.08, *P* = NS; 2011, Y = 260.7 – 0.7252X, R^2 = 0.58, *P* = 0.004; 6-year average, Y = 194.8 + 0.2880X, R2 = 0.48, *P* = 0.01.

on seed production of forbs native to the Intermountain Region remains extremely limited (Shock et al. 2012).

All of the seed yield responses reported in our trials were for forbs grown without competition with weeds or associated species. In a natural setting, these forbs would compete for resources with other sagebrush steppe plants in their immediate vicinity. As a result, the supplemental water required for high seed yield for these species may be substantially different in natural settings. In addition, plants were grown on soil with modest nutrient content, with minimal fertilization in 2006, 2009, and 2011. These supplements should have contributed to plant health. Native forbs were susceptible to disease and insect pests. Seed yields can be reduced by pests and diseases and labeling of fungicides, insecticides, and herbicides for these seed crops would be beneficial for commercial seed production.

In the present trials, forb plant stands from spring plantings were generally poor while those from fall plantings were considerably better, an observation which may be useful both for the establishment of commercial seed production fields and rangeland restoration projects. Seed production for range restoration should include documentation of the original seed source and tests of seed viability. Restoration efforts may have greater chances of success if the percent of viable seed is known to help guide planting densities.

CONCLUSIONS

Subsurface drip irrigation systems were tested for native seed production because they have two potential strategic advantages: (1) efficient, precise, and uniform water application, and (2) the buried drip tape provides water to the plants at depth, precluding stimulation of weed seed germination on the soil surface and keeping water away from native plant tissues, which typically are not adapted to a wet environment.

Due to the semi-arid environment at the seed production location, supplemental irrigation may often be required for successful flowering and seed set of some forbs because soil water reserves may be exhausted before seed formation. The total irrigation requirements for these arid-land species were low and varied by species (Table 6). *Lomatium dissectum* required approximately 140 mm of irrigation for optimal seed yield. *Penstemon speciosus* and *E. umbellatum* responded quadratically to irrigation in dry years with the optimum of 173 to 200 mm and 106 to 108 mm, respectively, but irrigation in wet years provided no advantage and could be detrimental. Seed production of *S. gros-*

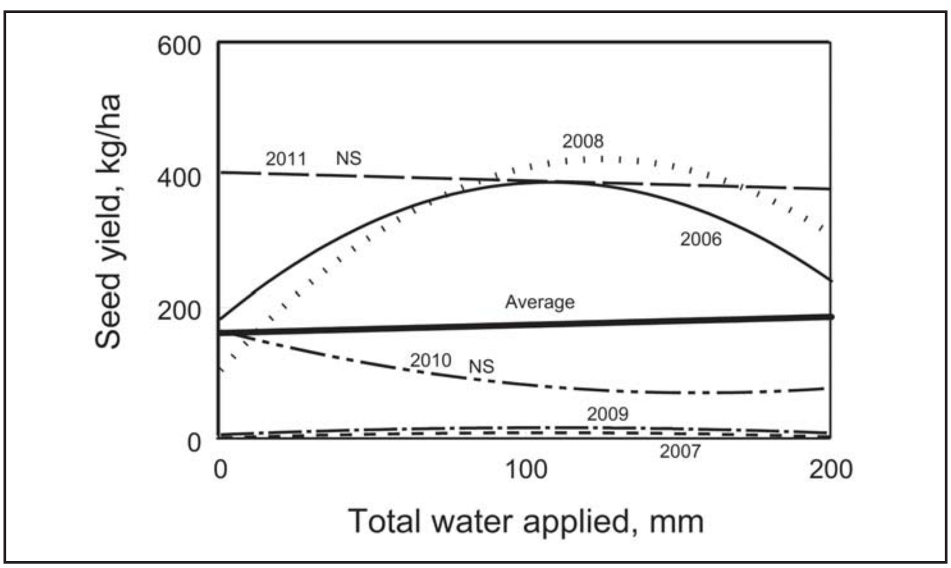

Figure 3. Annual and 6-year average *Penstemon speciosus* seed yield response to irrigation water, Malheur Experiment Station, Oregon State University, Ontario, OR. Regression equations: 2006, Y = 183.1 + 3.812X – 0.01767X^2, R^2 = 0.66, *P* = 0.01; 2007, Y = 2.797 + 0.1444X – 0.0006839X^2, R^2 = 0.48, *P* = 0.05; 2008, Y = 105.3 + 5.092X – 0.02035X^2, R^2 = 0.56, *P* = 0.04; 2009, Y = 7.628 + 0.1962X – 0.0009186X^2, R^2 = 0.54, *P* = 0.03; 2010, Y = 164.9 – 1.199X + 0.003826X^2, R^2 = 0.35, *P* = 0.13 (NS); 2011, Y = 403.8 – 0.1261X, R^2 = 0.01, *P* = NS; 6-year average, Y = 161.5 + 0.1218X; R^2 = 0.46, *P* = 0.06.

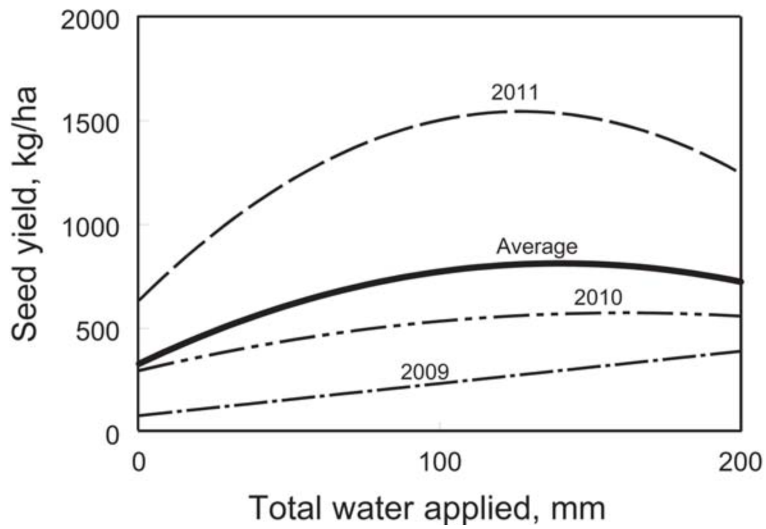

Figure 4. Annual and 3-year average *Lomatium dissectum* seed yield response to irrigation water, Malheur Experiment Station, Oregon State University, Ontario, OR. Regression equations: 2009, Y = 80.32 + 1.552X, R^2 = 0.30, *P* = 0.07; 2010, Y = 297.7 + 3.441X – 0.01066X^2, R^2 = 0.51, *P* = 0.04; 2011, Y = 635.6 + 14.31X – 0.05623X^2, R^2 = 0.86, *P* = 0.0001; 3-year average, Y = 330.0 + 6.905X – 0.02466X^2, R^2 = 0.72, *P* = 0.003.

sulariifolia did not respond to irrigation in our trials, suggesting that natural rainfall was sufficient to maximize seed production in the absence of weed competition with this species. Such variation in seed yield response among species may be expected because native forbs of the Great Basin exhibit a wide array of plant traits (e.g., growth habit, root structure, and phenology).

Seed of native forbs is required to restore diverse native communities in the Great Basin. However, growers are reluctant to attempt production of new species without knowledge of the necessary cultural practices and potential seed yields. Delayed seed production, differences in plant sizes and growth requirements, pollinator needs, and technology and equipment required to produce each species are among the multiple challenges encountered when bringing these species into agronomic production. Elucidating irrigation requirements to maximize seed production of individual native forbs provides growers with key data required to select and economically produce seed. Increased use of native forbs will necessitate additional research on basic biology and agronomic requirements of individual species.

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Table 6. Amount of irrigation water for maximum native forb seed yield, years to seed set, and life span under the agronomic conditions at Ontario. A summary of multiyear research findings, Malheur Experiment Station, Oregon State University, Ontario, OR.

Species	Optimum amount of irrigation (mm/growing season)	Years to first seed set from fall planting	Life span (years)
Eriogonum umbellatum	0 in wet years, 173–200 mm in the first year and years with less than 300 mm of rain from January through June	1	6+
Penstemon speciosus	0 in wet years, 106–108 mm in years with less than 90 mm of rain from May through June	1	3
Lomatium dissectum	127–160 mm, 140 mm averaged over years	4	6+
Sphaeralcea grossulariifolia	no response	1	5+

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