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Irrigation Requirements for Seed Production of Five *Lomatium* 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 for five perennial *Lomatium* species over multiple years. *Lomatium* species grown at the Oregon State University Malheur Experiment Station, Ontario, OR received 0, 100, or 200 mm of irrigation per year. Seed yield responses to irrigation were evaluated by linear and quadratic regression. In general, seed yields from the three species grown for 10 years responded linearly or quadratically to irrigation. To improve the accuracy of estimated irrigation water requirements, regressions were also run on seed yield responses to irrigation plus precipitation during the previous spring; spring and winter; and spring, winter, and fall. 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, respectively. *Lomatium grayi* (J.M. Coult. & Rose) 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. Two of the *Lomatium* species were grown for the last 6 years. The seed yields of *L. nudicaule* (Pursh) J.M. Coult. & Rose did not respond to irrigation. Seed yields of *Lomatium suksdorfii* (S. Watson) J.M. Coult. & Rose responded linearly to irrigation in 2015.**

Seeds of native plants are needed for rangeland restoration in the Intermountain West due to increasing rates of disturbance caused by non-native plant invasions and more frequent wildfires (Balch et al., 2013; Liu and Wimberly, 2015). Postfire restoration can stabilize soils and reduce re-establishment of invasive annuals, although restoration effectiveness depends on techniques and seed mixes (Robichaud et al., 2000). A recent synthesis showed that restoration of forbs (nonwoody perennials) is critical for rehabilitating habitat for pollinators and wildlife, such as the greater sage grouse (Dumroese et al., 2015). A number of promising native forb species have been identified for rangeland restoration purposes, but relatively little is known about the cultural practices required for seed production of these plants (Shaw and Jensen, 2014).

Several members of the genus *Lomatium*, including *L. dissectum* (fernleaf biscuitroot), *L grayi* (Gray's biscuitroot), *L. nudicaule* (barestem biscuitroot), and *L. triternatum* (nineleaf biscuitroot), are recognized as important for use in wildland restoration in the Intermountain West (Dumroese et al., 2015). *Lomatium suksdorfii* is of interest since it is both rare and a potential source of pharmaceutical compounds. These species are native to the western United States and are long-lived perennials with yellow, purple, or green/brown flowers. The shoot develops from the crown of a large taproot in early spring using the natural moisture from snow melt and spring rain. Vegetative growth, flowering, and seed set are complete by late spring to early summer. The leaves dieback after seed set, usually in midsummer. *Lomatium* species are dormant from late summer through winter and do not resume growth with fall rains.

Many *Lomatium* species were used by Native Americans for their food and medicinal properties (Shock et al., 2012a, 2012b; Tilley et al., 2010a, 2010b), and evaluation and use of such species as *L. suksdorfii* (Suksdorf's desertparsley) continue today (Lee et al., 1994). Except for *L. suksdorfii*, which is found only in south-central Washington and north-central Oregon, these species are widespread in the Intermountain West. *Lomatium* species grow in scattered to occasionally dense stands on well-drained coarse- to fine-textured soils and on scablands, rocky slopes, drainages, and open ridges.

Large-statured and widely distributed *Lomatiums* are valued as restoration species because they are among the earliest wildflowers to green up in late winter or spring. They provide a source of forage for wildlife (elk, deer, and antelope) and domestic livestock (sheep and cattle) (Ogle and Brazee, 2009). Barnett and Crawford (1994) reported that sage-grouse hens ate *Lomatium* leaves and stems, while Drut et al. (1994) found that sage-grouse chicks also consumed *Lomatium.* The *Lomatium* species were not identified in either study. *Lomatiums* are also used by birds, small mammals, pollinators, and other insects (Thompson, 1998). *Lomatium* species compete with non-native annuals such as *Bromus tectorum* (cheatgrass) because of their early spring growth and deep taproot system (Parkinson et al., 2013; Tilley et al., 2010a, 2010b).

Commercial seed production of *Lomatium* is needed for use in rangeland restoration plantings in the Intermountain West, but these plants are rarely cultivated, and cultural practices for seed production are largely unknown. A major limitation to economically viable commercial production of *Lomatium* seed is achieving stable and consistent seed production from year to year. In native rangelands, natural variation in spring rainfall and soil moisture results in highly unpredictable water stress at flowering, seed set, and seed development, which for many seed crops is known to compromise seed yield and quality. The seed yield response of *L. dissectum* to irrigation has been reported previously without considering the effect of precipitation (Shock et al., 2012b, 2015).

Native forbs are not well adapted to row crop production practices. Supplemental water can be provided by sprinkler or furrow irrigation systems, but these irrigation systems risk encouraging weeds and fungal pathogens. Subsurface drip irrigation can reduce wetting of the soil surface and could reduce weed and disease pressure.

The trials reported here tested the effects of three low rates of subsurface drip irrigation on the seed yield of five *Lomatium* species. The optimum amount of irrigation for each species was evaluated based not only on the amount of irrigation but also on the amount of seasonal precipitation each year.

Methods

An irrigation trial for *L. dissectum*, *L. grayi*, and *L. triternatum* was initiated in

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

Species	Common names	Location of seed collection
Lomatium dissectum	Fernleaf biscuitroot	Mann Creek Reservoir, ID (lat. 44.401° N, long. 116.898° W)
Lomatium triternatum	Nineleaf biscuitroot, nineleaf desertparsley	Near US Hwy 395 near Lakeview, OR (lat. 42.111° N, long. 120.319° W)
Lomatium grayi	Gray's biscuitroot, Gray's lomatium	Weiser River Road, ID (lat. 44.260° N, long.116.770° W)
Lomatium nudicaule	Barestem biscuitroot, barestem lomatium	Elko County, NV (lat. 41.119° N, long. 116.510° W)
Lomatium suksdorfii	Suksdorf's desert parsley	Klickitat County, WA (lat. 45°43 to 50′ N, long. 121°1 to 17′ W)

2005 at the Malheur Experiment Station of Oregon State University, Ontario, OR. Ontario is centered at 43°58′ 42.2″ N, 117°1′ 29.8″ at 689 m elevation. Annual precipitation averages 257 mm. The field, a Nyssa silt loam (coarse-silty, mixed, mesic, Xeric Haplodurid), was bedded into 76-cm rows, four rows per bed. Most of the field lacked topsoil due to 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-sulfur, 4370 ppm calcium, 456 ppm magnesium, 81 ppm sodium, 1.6 ppm zinc (Zn), 0.6 ppm copper, 4 ppm manganese, 3 ppm iron (Fe), and 0.6 ppm boron.

Drip tape (T-Tape TSX 515-16-340; T Systems International Inc., San Diego, CA) 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/100 m at 55 kPa with emitters spaced 41 cm apart, resulting in a water application rate of 1.7 $mm \cdot h^{-1}$. Water was filtered through sand media filters. Application durations were controlled automatically.

Seed of *L. dissectum*, *L. grayi*, and *L. triternatum* was planted on 26 Oct. 2005 in four rows 133 m long spaced 76 cm apart using a custom-made small-plot grain drill with disk openers. Seed was planted at 12.5-mm depth with 65–100 seeds/m of row. Seed of each species came from wild collections made by U.S. Forest Service employees (Table 1).

On 25 Nov. 2009, seed of *L. nudicaule* and *L. suksdorfii* was planted in the same field as the other *Lomatium* species in four rows spaced 76 cm apart using the small-plot grain drill. All seed was planted on the soil surface with 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, and the beds were covered with rowcover. Each rowcover (N-sulate Deluxe Plus 1 oz; DeWitt Co., Inc., Sikeston, MO) covered two rows and was applied with a mechanical plastic mulch layer. The field was irrigated for 24 h on 2 Dec. 2009 due to very dry soil conditions.

In April following fall planting, each *Lomatium* strip was divided into twelve 9.1-m-long plots. Each plot contained four rows spaced 76 cm apart. The experimental design was a randomized complete block with four replicates.

The three irrigation treatments were 0 (control), 100, and 200 mm/year. The 100-mm and 200-mm irrigation treatments received four irrigations, 2 weeks apart, starting at the beginning of flowering. Each irrigation applied 25 (100-mm treatment) or 50 mm (200-mm treatment) of water. In 2007, irrigation treatments were inadvertently continued after the fourth irrigation following seed production, doubling the planned irrigation amounts for each treatment. Flowering dates for each species were recorded and are reported in conjunction with the irrigation dates in Table 2.

Table 2. *Lomatium* flowering, irrigation, and seed harvest dates by species, 2006–15.

		Flowering			Irrigation		
Species	Yr	Start	Peak	End	Start	End	Harvest
Lomatium dissectum	2006				19 May	30 June	
	2007				5 Apr.	24 June	
	2008				10 Apr.	29 May	
	2009	10 Apr.		7 May	20 Apr.	28 May	16 June
	2010	25 Apr.		20 May	15 Apr.	28 May	21 June
	2011	8 Apr.	25 Apr.	10 May	21 Apr.	7 June	20 June
	2012	9 Apr.	16 Apr.	16 May	13 Apr.	24 May	4 June
	2013	10 Apr.		25 Apr.	4 Apr.	16 May	4 June
	2014	28 Mar.		21 Apr.	7 Apr.	20 May	2 June
	2015	1 Apr.		24 Apr.	1 Apr.	13 May	26 May and 1 June
Lomatium grayi	2006				19 May	30 June	
	2007	5 Apr.		10 May	5 Apr.	24 June	30 May and 29 June
	2008	25 Mar.		15 May	10 Apr.	29 May	30 May and 19 June
	2009	10 Mar.		7 May	20 Apr.	28 May	16 June
	2010	15 Mar.		15 May	15 Apr.	28 May	22 June
	2011	1 Apr.	25 Apr.	13 May	21 Apr.	7 June	22 June
	2012	15 Mar.	25 Apr.	16 May	13 Apr.	24 May	14 June
	2013	15 Mar.		30 Apr.	4 Apr.	16 May	10 June
	2014	28 Mar.		2 May	7 Apr.	20 May	10 June
	2015	1 Mar.		28 Apr.	1 Apr.	13 May	1 June
Lomatium triternatum	2006				19 May	30 June	
	2007	25 Apr.		1 June	5 Apr.	24 June	29 June and 16 July
	2008	25 Apr.		5 June	10 Apr.	29 May	3 July
	2009	10 Apr.	7 May	1 June	20 Apr.	28 May	26 June
	2010	25 Apr.		15 June	15 Apr.	28 May	22 July
	2011	30 Apr.	23 May	15 June	21 Apr.	7 June	26 July
	2012	12 Apr.	17 May	6 June	13 Apr.	24 May	21 June
	2013	18 Apr.		10 May	4 Apr.	16 May	4 June
	2014	7 Apr.	29 Apr.	2 May	7 Apr.	20 May	4 June
	2015	10 Apr.	28 Apr.	20 May	1 Apr.	13 May	7 and 15 June
Lomatium nudicaule	2011		No flowering				
	2012	12 Apr.	1 May	30 May	18 Apr.	30 May	22 June
	2013	11 Apr.		20 May	12 Apr.	22 May	10 June
	2014	7 Apr.		13 May	7 Apr.	20 May	16 June
	2015	25 Mar.		5 May	1 Apr.	13 May	8 June
Lomatium suksdorfii	2013	18 Apr.		23 May			
	2014	15 Apr.		20 May	7 Apr.	20 May	30 June
	2015	3 Apr.	27 Apr.	10 May	1 Apr.	13 May	23 June

Fertilization of the irrigation trial over the 6 years was minimal. On 11 Nov. 2006, nitrogen (N) at 112 $kg \cdot ha^{-1}$ as urea was broadcast. The following nutrients were applied as soluble nutrients through the drip irrigation: 27 Oct. 2006: P at 56 $kg \cdot ha^{-1}$ and Zn at 2.2 $kg \cdot ha^{-1}$; 9 Apr. 2009: N at 56 $kg \cdot ha^{-1}$ and P at 11 $kg \cdot ha^{-1}$; 3 May 2011: N at 56 $kg \cdot ha^{-1}$; 13 Apr. 2012: N at 56 $kg \cdot ha^{-1}$, P at 11 $kg \cdot ha^{-1}$, and Fe at 0.012 $kg \cdot ha^{-1}$; 29 Mar. 2013: N at 22 $kg \cdot ha^{-1}$, P at 28 $kg \cdot ha^{-1}$, and Fe at 0.012 $kg \cdot ha^{-1}$; 2 Apr. 2014: N at 22 $kg \cdot ha^{-1}$, P at 28 $kg \cdot ha^{-1}$, and Fe at 0.012 $kg \cdot ha^{-1}$; 15 Apr. 2015: N at 22 $kg \cdot ha^{-1}$, P at 28 $kg \cdot ha^{-1}$, and Fe at 0.016 $kg \cdot ha^{-1}$. Nitrogen was applied as a urea–ammonium nitrate solution, P was applied as phosphoric acid, and Fe was applied as iron chelate.

During the first 2 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., 2011). These products are not yet registered for commercial use on *Lomatium* 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 rouging of weeds continued as necessary.

Seed yield was determined by a manual once-over harvest of all mature seed stalks in the middle 7.5 m of the two center rows of the four-row plots. On a few occasions, the

Table 3. Regression analysis for *Lomatium dissectum* 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 2009–15, and 7-year average. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b/2c$, 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)
2009	56.7	7.6	–0.03	0.6	0.05	535	126
2010	297.7	3.4	–0.011	0.51	0.05	575	161
2011	635.6	14.3	–0.056	0.86	0.001	1,546	127
2012	434.6	1.3	–0.005	0.07	NS	521	132
2013	591.1	6.1	–0.013	0.68	0.01	1,329	242
2014	443.8	5.7		0.83	0.001	1,591	200
2015	703.6	4.4		0.78	0.01	1,583	200
Avg						1,097	
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)
2009	–1,032.6	13.6	–0.029	0.6	0.05	535	231
2010	–199.7	5.7	–0.010	0.51	0.05	575	274
2011	–1,870.0	27.3	–0.054	0.86	0.001	1,546	250
2012	329.2	1.9	–0.005	0.07	NS	521	200
2013	455.8	6.5	–0.012	0.68	0.01	1,329	267
2014	195.7	5.6		0.83	0.001	1,573	244
2015	349.8	4.3		0.78	0.01	1,569	282
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)
2009	–200.4	2.6	–0.0057	0.6	0.05		231
2010	–35.7	1.0	–0.0018	0.51	0.05		274
2011	–124.3	1.8	–0.0036	0.86	0.001		250
2012	63.9	0.4	–0.0009	0.07	NS		200
2013	34.9	0.5	–0.0009	0.68	0.01		267
2014	12.7	0.4		0.83	0.001		244
2015	22.7	0.3		0.78	0.01		282
Avg	–26.93	1.1	–0.0022	0.94	0.001		243

Table 4. Regression analysis for *Lomatium grayi* 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 2007–15, and 9-year averages. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b/2c$, 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})
2007	42.0	0.5		0.26	0.10	149
2008	440.5	14.1	–0.041	0.93	0.001	1,652
2009	424.2	1.8		0.38	0.05	790
2010	1,160.0	4.3	–0.031	0.22	NS	1,309
2011	638.7	1.3	–0.013	0.10	NS	672
2012	259.7	3.1	–0.011	0.66	0.01	468
2013	711.9	2.5		0.25	0.10	1,204
2014	597.0	15.9	–0.059	0.64	0.05	1,654
2015	208.7	8.1	–0.037	0.71	0.01	649
Avg						950
Water applied plus fall, winter, and spring precipitation vs. yield						
Yr	Intercept	Linear	Quadratic	R^2	P	Highest yield (kg·ha^{-1})
2007	–41.0	0.5		0.26	0.10	148
2008	–3,047.6	27.4	–0.040	0.93	0.001	1,652
2009	20.0	1.8		0.38	0.05	784
2010	–2,723.2	21.9	–0.030	0.22	NS	1,309
2011	–1,495.3	10.3	–0.01	0.10	NS	672
2012	–872.2	7.6	–0.011	0.66	0.01	468
2013	385.7	2.4		0.25	0.10	1,197
2014	–5,042.5	39.3	–0.058	0.64	0.05	1,654
2015	–4,458.0	27.2	–0.036	0.71	0.01	649
Water applied plus fall, winter, and spring precipitation vs. relative yield						
Yr	Intercept	Linear	Quadratic	R^2	P	Water applied plus precipitation for highest relative yield (mm/season)
2007	–27.7	0.4		0.26	0.10	357
2008	–188.3	1.7	–0.0025	0.93	0.001	343
2009	2.6	0.2		0.38	0.05	425
2010	–212.6	1.7	–0.0023	0.22	NS	369
2011	–233.1	1.6	–0.00193	0.10	NS	419
2012	–192.6	1.7	–0.0024	0.66	0.01	352
2013	33.2	0.2		0.25	0.10	335
2014	–317.5	2.5	–0.0036	0.64	0.05	341
2015	–690.2	4.2	–0.0056	0.71	0.01	375
Avg	–229.2	1.9	–0.0026	0.59	0.05	358

maturation and harvest of the nonirrigated plants preceded the harvest of the irrigated plants (Table 2). Seed was cleaned from stalks and chaff and was weighed. Seed yield means were compared by analysis of variance and 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

Table 5. Regression analysis for *Lomatium triternatum* 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 2007–15, and 9-year average. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b/2c$, 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)
2007	3.7	0.1		0.52	0.01	31	200
2008	218.7	12.7	–0.030	0.77	0.01	1,557	210
2009	203.4	10.6	–0.039	0.83	0.001	922	135
2010	1,833.6	18.0	–0.046	0.83	0.001	3,580	194
2011	2,220.9	14.1	–0.069	0.45	0.10	2,940	102
2012	267.4	5.4	–0.013	0.52	0.05	822	206
2013	221.4	5.0		0.68	0.01	1,226	200
2014	282.0	7.1		0.97	0.001	1,705	200
2015	362.7	3.1		0.51	0.01	981	200
Avg						1,529	
			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)
2007	–2.9	0.1		0.52	0.01	31	249
2008	–274.5	14.6	–0.029	0.77	0.01	1,557	250
2009	–1,286.1	18.3	–0.038	0.83	0.001	922	241
2010	–656.6	27.6	–0.045	0.83	0.001	3,580	307
2011	–448.3	30.2	–0.067	0.45	0.10	2,940	225
2012	–138.4	7.0	–0.013	0.52	0.05	822	275
2013	114.7	4.9		0.68	0.01	1,211	222
2014	–25.6	7.0		0.97	0.001	1,682	244
2015	114.0	3.0		0.51	0.01	971	282
			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)	
2007	–9.8	0.5		0.52	0.01	249	
2008	–17.7	0.9	–0.002	0.77	0.01	250	
2009	–147.2	2.1	–0.004	0.83	0.001	241	
2010	–18.4	0.8	–0.001	0.83	0.001	307	
2011	–15.3	1.0	–0.002	0.45	0.10	225	
2012	–16.9	0.9	–0.002	0.52	0.05	275	
2013	9.7	0.4		0.68	0.01	222	
2014	–1.5	0.4		0.97	0.001	244	
2015	10.7	0.3		0.51	0.01	282	
Avg	–3.8	0.8	–0.001	0.85	0.001	265	

Table 6. Regression analysis for *Lomatium nudicaule* and *L. suksdorfii* 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 2012–15. For the quadratic equations, the amount of irrigation that resulted in maximum yield was calculated using the formula: $x = -b/2c$, where b is the linear parameter and c is the quadratic parameter. *Lomatium nudicaule* failed to respond to irrigation.

			Water applied vs. yield				
Yr	Intercept	Linear	Quadratic	R^2	P	Highest yield (kg·ha^{-1})	Water applied for highest yield (mm/season)
				L. nudicaule			
2012	60.3	1.5	–0.0074	0.18	NS	139	103
2013	400.5	2.1	–0.0054	0.11	NS	609	196
2014	789.0	–0.6		0.08	NS	789	0
2015	482.3	0.1	–0.0041	0.17	NS	483	16
Avg						505	
				L. suksdorfii			
2014	183.8	0.5	–0.0033	0.01	NS	205	80
2015	844.4	5.6		0.43	0.05	1,967	200
Avg						1,086	

Table 7. Average seed yields for five *Lomatium* species over multiple years.

	Avg seed yield by irrigation treatment (kg·ha^{-1})			
Species	No irrigation	100 mm/season	200 mm/season	$LSD_{(0.05)}$
Lomatium dissectum	403	860	796	171
Lomatium triternatum	703	1,384	1,455	188
Lomatium grayi	498	872	780	254
Lomatium nudicaule	230	349	339	NS
Lomatium suksdorfii	359	309	318	NS

spring precipitation occurred in the same year that yield was determined; fall precipitation occurred the prior 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 $x' = -b/2c$, where a is the intercept, b is the linear parameter, and c is the quadratic parameter. For the linear regressions, the highest seed yield for a species in a given year was based was 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 water required for maximum seed yields for each species. 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.

Results

Lomatium dissectum began flowering and producing seed in 2009, the 4th year after fall planting in 2005 (Tables 2 and 3). Flowering and seed production began for *L. grayi* and *L. triternatum* in the 2nd year (2007), *L. nudicaule* in the 3rd year (2012), and *L. suksdorfii* in the 4th year (2013) after fall planting (Tables 2 and 4–6). Although there were tremendous variations in seed yields over species and years, general tendencies emerged for the mean seed yields for each species and irrigation treatments (Table 7).

Lomatium dissectum, fernleaf biscuitroot. Seed yields of *L. dissectum* exhibited a quadratic response to irrigation amount in 2009–13 (Table 3; Figs. 1–3). The quadratic response to irrigation in 2012 was not statistically significant. Seed yield of *L. dissectum* exhibited linear responses to irrigation rate in 2014 and 2015. The amount of water applied for maximum seed yield, calculated from the regression equations, ranged from 126 to 242 mm per season. Seed yields were estimated to be highest with 200 to 282 mm of total applied water plus spring precipitation. The highest yields averaged 1097 kg·ha^{-1} and ranged from 521 to 1573 kg·ha^{-1}. Averaged over 7 years, relative seed yield was highest with 243 mm of applied water plus spring precipitation (Fig. 3).

Lomatium grayi, Gray's biscuitroot. Seed yields of *L. grayi* exhibited quadratic responses

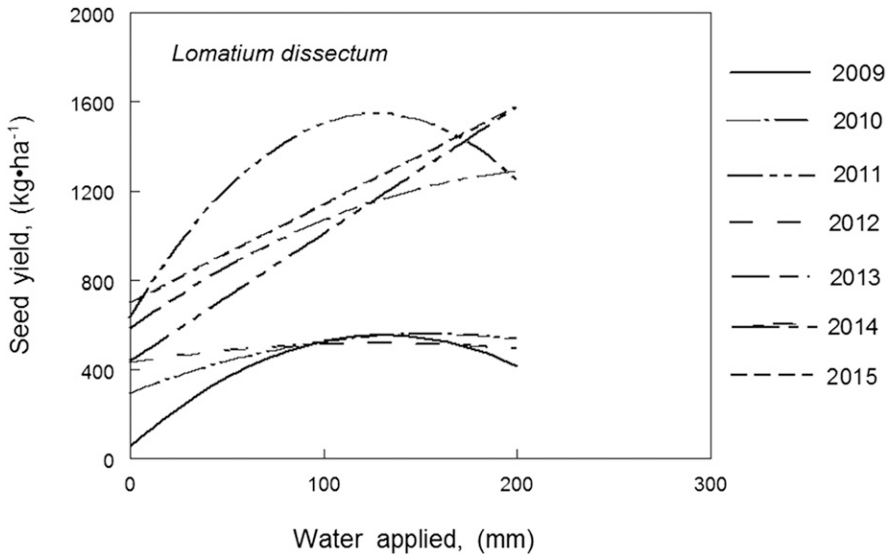

Fig. 1. Seed yield response of *Lomatium dissectum* to water applied in 2009–15.

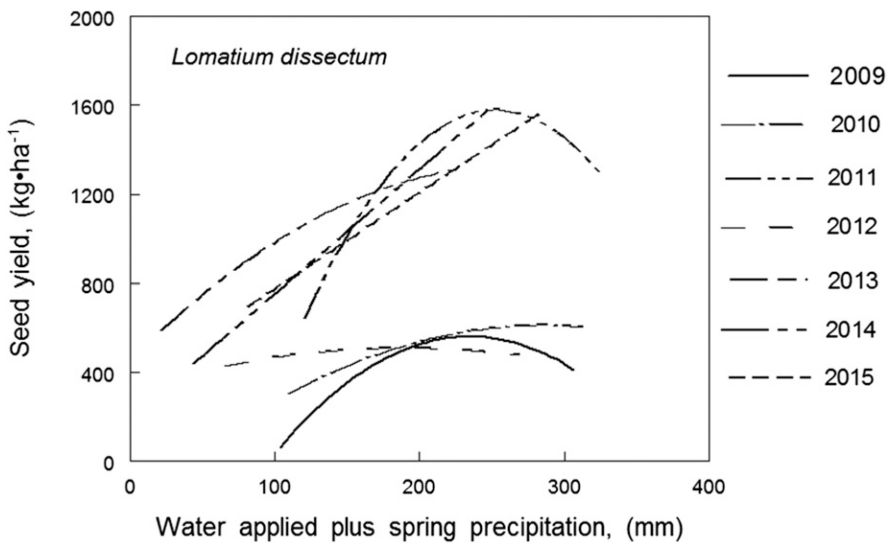

Fig. 2. Seed yield response of *Lomatium dissectum* to water applied plus spring precipitation in 2009–15.

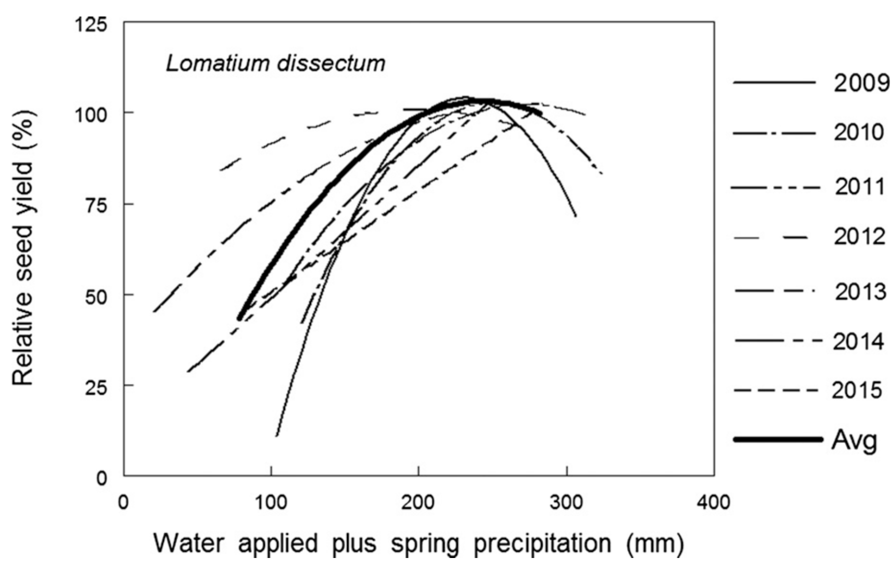

Fig. 3. Relative seed yield response of *Lomatium dissectum* to water applied plus spring precipitation in 2009–15 and the 7-year average relative seed yield response.

to irrigation rate in 2008, 2010, 2011, 2012, 2014, and 2015; linear responses in 2007, 2009, and 2013; and no statistically significant responses in 2010 and 2011 (Table 4; Figs. 4–6). The amount of water applied for the highest yield, calculated from the regression equations, ranged from 51 to 200 mm per season. Seed yields of *L. grayi* were estimated to be highest with 335 to 425 mm of total applied water plus fall, winter, and spring precipitation, depending on the year. These results imply that if a year were very dry, more than 200 mm of irrigation would be required to maximize seed yields. The highest yields averaged 950 kg·ha^{-1} and ranged from 148 to 1654 kg·ha^{-1}, depending on the year. Averaged over 9 years, relative seed yield was highest with 358 mm of total applied water plus fall, winter, and spring precipitation.

Lomatium triternatum, nineleaf biscuitroot. Seed yields of *L. triternatum* exhibited quadratic responses to irrigation rate in 2008–12 (Table 5; Figs. 7–9). Seed yields in 2007, 2013, 2014, and 2015 showed linear responses to irrigation. Seed yields were estimated to be highest using 102 to 210 mm of applied water depending on the year. Seed yields were estimated to be highest using 222 to 307 mm of applied water plus spring precipitation and ranged from 31 to 3580 kg·ha^{-1}, depending on the year and averaged 1529 kg·ha^{-1}. Averaged over 9 years, relative seed yield was highest with 265 mm of total applied water plus spring precipitation.

Lomatium nudicaule, barestem biscuitroot. Over 4 years of production, seed yields of *L. nudicaule* showed no significant response to water applied (Table 6). Maximum yields averaged 505 kg·ha^{-1} and ranged from 139 to 789 kg·ha^{-1}, depending on the year.

Lomatium suksdorfii, Suksdorf's desertparsley. Seed yields of *L. suksdorfii* did not respond significantly to water applied in 2014, the first year of seed production (Table 6). Seed yields in 2015 showed a linear response to irrigation. Seed yields were estimated to be maximized by 282 mm of total applied water plus spring precipitation in 2015. Maximum yields averaged 1086 kg·ha^{-1} and were 205 kg·ha^{-1} in 2014 and 1950 kg·ha^{-1} in 2015. The higher seed yield in 2015 may be related to advanced plant maturity and greater stature than in 2014.

Discussion

Seasonal precipitation varied greatly among years, as did the amount of water required for maximum seed production. Adding seasonal precipitation to applied water reduced variation in the optimal water requirement for maximum seed production (Table 8). The regression analyses showed high variability in the optimum amount of water for maximum seed yield among years. When precipitation was added to the amount of water applied in the regressions, the variability in the optimum amount of water decreased.

On average, *L. dissectum* started flowering on about 9 Apr., and *L. triternatum* started flowering around 18 Apr. (Table 2). For these

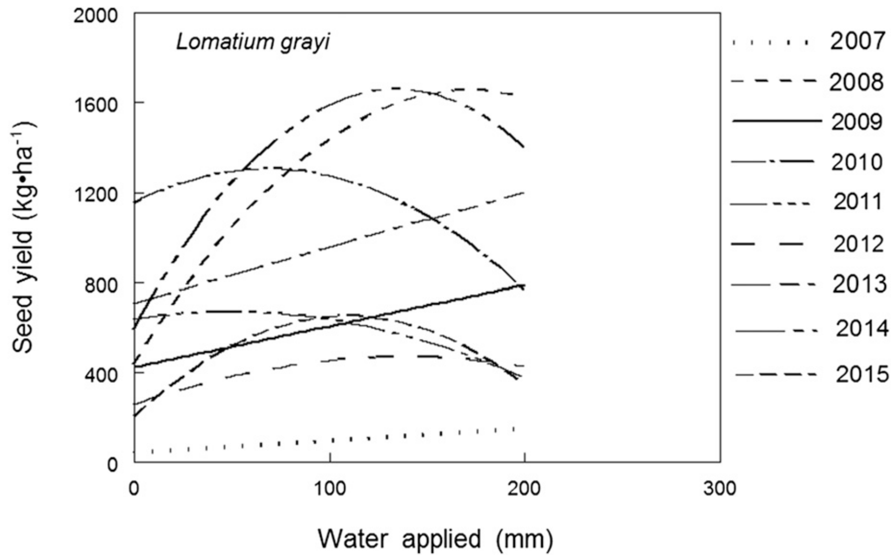

Fig. 4. Seed yield response of *Lomatium grayi* to water applied in 2007–15.

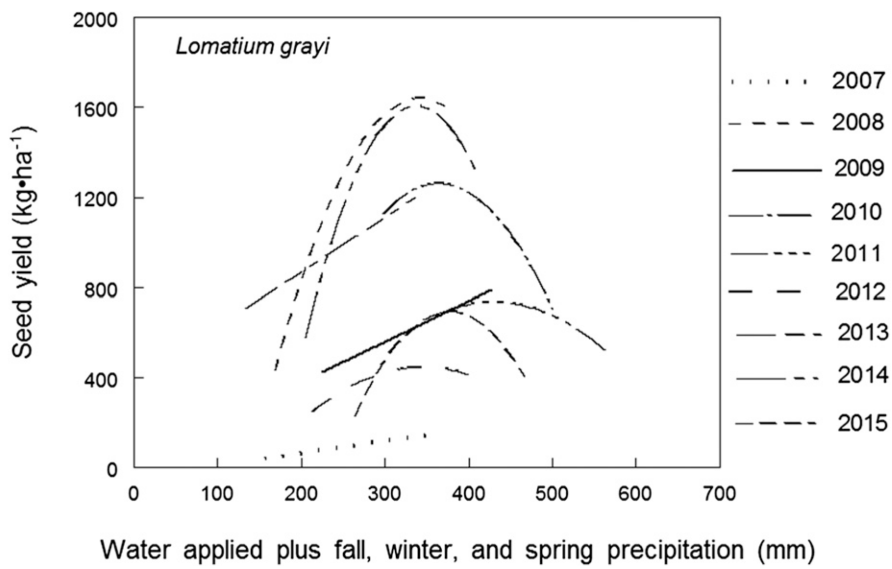

Fig. 5. Seed yield response of *Lomatium grayi* to water applied plus fall, winter, and spring precipitation in 2007–15.

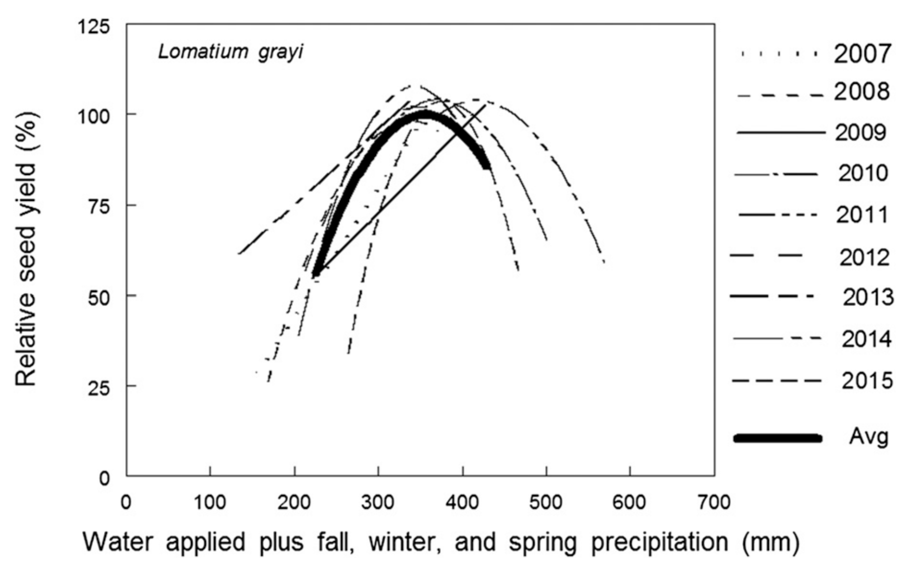

Fig. 6. Relative seed yield response of *Lomatium grayi* to water applied plus fall, winter, and spring precipitation in 2007–15 and the 9-year average relative seed yield response.

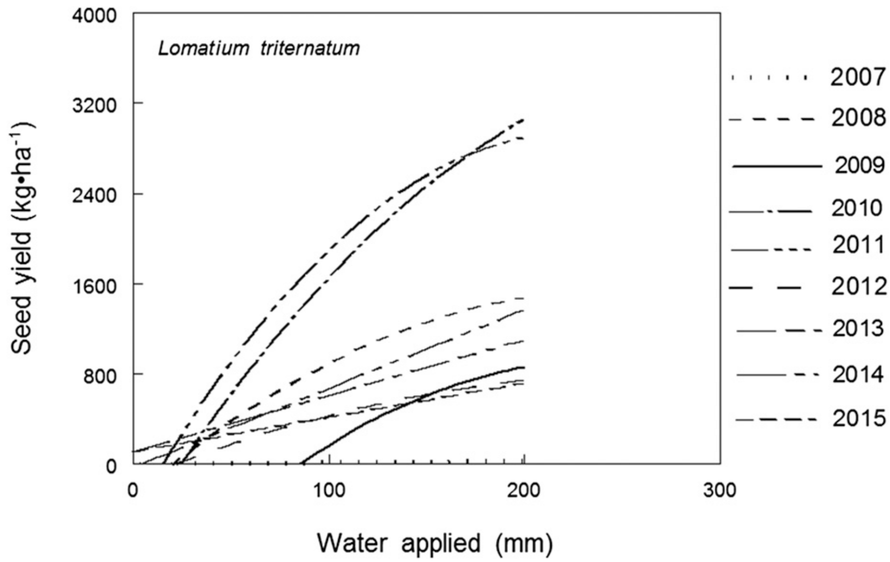

Fig. 7. Seed yield response of *Lomatium triternatum* to water applied in 2007–15.

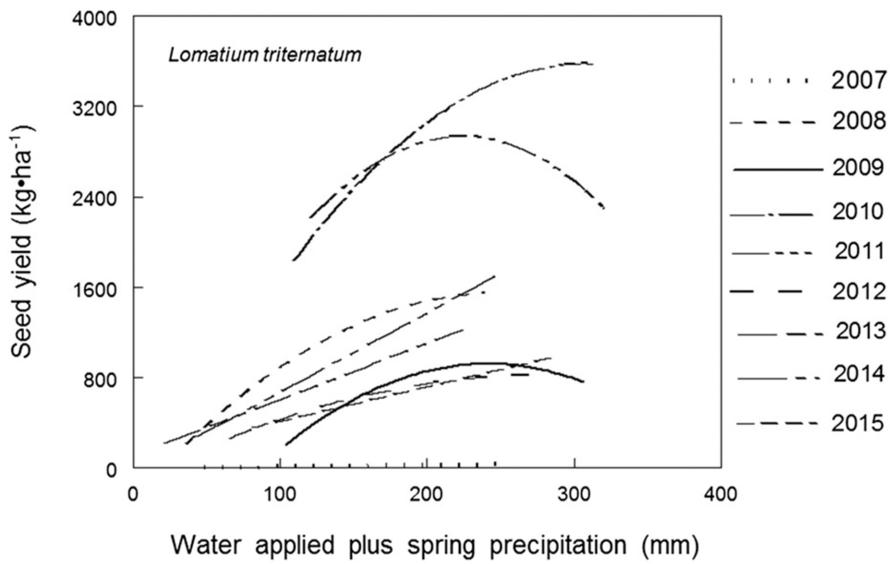

Fig. 8. Seed yield response of *Lomatium triternatum* to water applied plus spring precipitation in 2007–15.

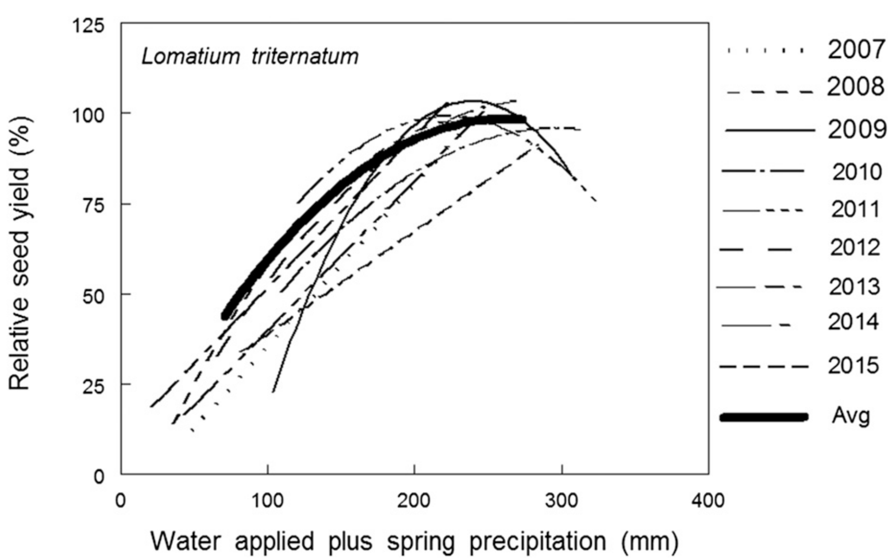

Fig. 9. Relative seed yield response of *Lomatium triternatum* to water applied plus spring precipitation in 2007–15 and the 9-year average relative seed yield response.

two species, the addition of spring precipitation to applied irrigation water resulted in the lowest standard deviation of the amount of water applied for maximum yield according to the quadratic equations for 2007–15 (Table 9). For *L. grayi*, the addition of fall, winter, and spring precipitation to applied irrigation water resulted in the lowest standard deviation of the amount of water applied for maximum yield according to the regression equations for 2007–15 (Table 9; Figs. 4–6). *Lomatium grayi* usually started flowering in early to mid-March (Table 2), possibly explaining why it might have responded more to fall, winter, and spring precipitation than *L. dissectum* and *L. triternatum*.

Other studies that examined responses of xerophytic plants to irrigation found similar responses within the ranges of irrigation in our study. In Tucson, AZ, with annual precipitation of 293 mm, native grass and native woody plant establishment from seed was optimum with 187 to 210 mm of irrigation plus precipitation (Roundy et al., 2001). In the Chihuahuan Desert in New Mexico, with annual precipitation of 211 mm, only 6 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* (fourwing saltbush) did not respond to either 400 mm of irrigation in one year or 200 mm of irrigation the next year. In the Owens Valley, CA, with annual precipitation of 113 mm, *Sarcobatus vermiculatus* (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, all *Lomatium* species tested, except *L. nudicaule*, responded to irrigation with increased seed yields. For the three species tested for 7–9 years (*L. dissectum*, *L. grayi*, and *L. triternatum*), seed yields were increased significantly by irrigation. Seed yields of *L. suksdorfii* also increased by irrigation in 2015. The amount of irrigation and precipitation needed for maximum *Lomatium* seed yields in this study (200–400 mm/year) was substantially lower than irrigation plus precipitation requirements for row crops in the Treasure Valley of Oregon (500–800 mm/year, AgriMet, 2016). Although *Lomatium* species are perennials, they complete their cycle from sprouting to seed harvest by mid-June, thus their irrigation requirements would be expected to be lower. However, irrigation requirements for *Lomatium* are low even when compared with an early season crop such as winter wheat (*Triticum aestivum*), which has an average water requirement of 633 mm in the Treasure Valley.

Studies of cultural practices for native plants are critical to increasing seed production and availability of plant material used in

Table 8. Precipitation and growing degree-days at the Malheur Experiment Station, Ontario, OR, 2006–15. Fall: 22 Sept. to 21 Dec.; winter: 22 Dec. to 21 Mar.; and spring: 22 Mar. to 21 June.

	Precipitation (mm)			Growing degree-days (10–30 °C)
Yr	Spring	Spring + winter	Spring + winter + fall	January–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
		71-year avg		22-year avg
	67	147	230	654

Table 9. Standard deviations of amount of water applied for maximum seed yield for three *Lomatium* species.

		Standard deviation of amount of water applied for the highest seed yield (mm)			
Species	Years	Water applied	Water applied plus spring precipitation	Water applied plus winter and spring precipitation	Water applied plus fall, winter, and spring precipitation
Lomatium dissectum	2009–15	47.2	29.4	35.8	61.9
Lomatium grayi	2007–15	56.6	42.9	47.9	34.0
Lomatium triternatum	2007–15	38.9	28.9	43.8	58.4

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.

Conclusions

The seed yields of four of the five *Lomatium* species (*L. dissectum*, *L grayi*, *L. triternatum*, and *L. suksdorfii*) responded significantly to subsurface drip irrigation. The irrigation requirements for seed production of *L. dissectum* and *L. triternatum* were best estimated by a quadratic response to irrigation plus spring precipitation. The irrigation requirements for seed production of *L. grayi* were best estimated by a quadratic response to irrigation plus precipitation during the fall, winter, and spring. Additional trials are needed for *L. suksdorfii* to better define its seed yield response to precipitation plus applied water.

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