Push cart used to harvest seed in a trial plot of *Lupinus sericeus*.

Evaluation of thermal, chemical, and mechanical seed scarification methods for 4 Great Basin lupine species

Covy D Jones, Mikel R Stevens, Von D Jolley, Bryan G Hopkins, Scott L Jensen, Dave Turner, and Jason M Stettler

ABSTRACT

Seeds of most Great Basin lupine (*Lupinus* spp. [Fabaceae]) species are physically dormant and thus, difficult to establish in uniform stands in seed production fields. We designed this study to examine 5 seed scarification techniques, each with 11 levels of application (including a non-scarified control), to reduce the physical seed dormancy of longspur lupine (*L. arbustus* Douglas ex Lindl.), silvery lupine (*L. argenteus* Pursh), hairy bigleaf lupine (*L. prunophilus* M.E. Jones), and silky lupine (*L. sericeus* Pursh). These 4 perennial Great Basin lupine species are of interest for both rehabilitation and restoration of degraded rangelands. We evaluated 10 treatments of each of 5 scarification methods, one mechanical, 2 thermal, and 2 chemical (sulfuric acid and sodium hypochlorite) techniques on the above-mentioned species. The sulfuric acid and the mechanical scarification treatments significantly improved germination for both silvery and silky lupine. Additionally, one thermal scarification method (60 s at 95 °C [203 °F]) was effective for silvery lupine. Both sulfuric acid and sodium hypochlorite scarification methods had treatment levels that significantly improved germination of hairy bigleaf lupine. For longspur lupine, all treatments within the 5 scarification methods either decreased or were not a significant improvement of germination as compared with the control, except for the treatment of soaking the seeds for 35 s at 95 °C (203 °F). We found scarification to be an effective tool for reducing physical dormancy in silvery lupine, hairy bigleaf lupine, and silky lupine, thus allowing for a more efficient use of limited seeds.

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KEY WORDS

seed dormancy, physical dormancy, germination, thermal scarification, chemical scarification, mechanical scarification, Fabaceae

NOMENCLATURE

USDA NRCS (2015)

Photos by Covy D Jones

The Great Basin is North America's largest desert, encompassing 54.6 million ha (135 million ac) and spanning a region from the Rocky Mountains to the ranges of the Sierra Nevada. Geographically, the Basin covers much of Utah and Nevada and includes smaller portions of Idaho, Oregon, and California. This vast expanse of territory is exploited for multiple land uses and therefore subject to significant disturbance events. Early settlers of the Great Basin mined precious metals and grazed livestock. A census conducted in 1890 recorded 3.8 million sheep and 0.5 million cattle in Utah alone, with the majority of these animals grazing in the Great Basin during some of the year (Harrison and others 2003). Heavy grazing has reduced native plant diversity and contributed to the spread of exotic weed species.

Cheatgrass (*Bromus tectorum* L. [Poaceae]), an invasive annual, was first identified as early as 1916 in the western US and is currently prolific in the Great Basin and Columbia Basin regions (Morrow and Stahlman 1984). This weedy annual increases fire frequency intervals from historic 30 to 100 y to as often as every 3 to 5 y (Whisenant 1990; Peters and Bunting 1994). These abbreviated fire intervals are detrimental to the native ecosystems of the Great Basin as these inherent ecosystems are not adapted to frequent fires (D'Antonio and Vitousek 1992; Knapp 1996; Brooks and others 2004).

Current restoration efforts in highly invaded Great Basin ecosystems include post-fire reseeding of native plant species. Most native shrub and grass seeds for large-scale restoration projects can be produced and sold at a reasonable price, but native forbs are prohibitively expensive or altogether unavailable (Shaw and others 2005). The Great Basin Native Plant Selection and Increase Project (GBNPSIP) was created in 2000 with the intent to ameliorate this situation. The GBNPSIP is a joint effort between the USDI, Bureau of Land Management and the USDA Forest Service (USDA USFS 2009). The GBNPSIP promotes seed collection and increase of desirable native forb species to meet restoration needs.

Species within the genus *Lupinus* L. (Fabaceae) are an important group of forbs for rehabilitation and restoration projects. The lupines are legumes and are a critical component of shrub-steppe ecosystems, especially given their ability to biologically fix atmospheric nitrogen. Lupines enhance biodiversity, assist in soil stabilization and erosion control, supply wildlife and livestock forage, and are an important pollinator food source (Matthews 1993; Shaw and others 2005; Beuthin 2012; St John and Tilley 2012).

Physical seed dormancy is a barrier to the production of adequate quantities of lupine seeds. Physical dormancy is a survival strategy that ensures the persistence of wildland species

Proliferation of native *Lupinus prunophilus* in a historic fire tract near Emigrant Pass, Nevada.

Lupinus prunophilus intermixed with big sagebrush near Eureka, Utah.

in their native environments (Baskin and Baskin 1998). Dormant seeds can remain viable in the soil profile for long periods. For rangeland species, dormancy helps ensure species survival because ungerminated seeds can pass through periods of disease, drought, fire, or floods that may decimate plant populations. Seed dormancy is characterized as exogenous if caused by factors outside the embryo, or endogenous if caused by factors within the embryo (Nikolaeva 1969). Exogenous dormancy is further characterized as physical, mechanical, or chemical, while endogenous dormancy may be physiological or morphological. Some species express seed dormancy based on combinations of these factors (Jones and Nielson 1992).

In the Great Basin, some lupine species exhibit physical exogenous dormancy. These species have seedcoats that are impermeable to water, a condition sometimes referred to as "hard seed" (Eldredge 2007; Travlos and others 2007). The degree of dormancy expressed in Great Basin lupine species differs both within and among species. Quinlivan (1970) found that physical dormancy in seeds of 3 lupine species grown in Australia is correlated to the amount of seed moisture at the time of its maturity, with a higher degree of dormancy invoked as seed moisture decreases. In nature, soil fungi, insects, humidity, as well as sharp daily temperature fluctuations have been identified as factors affecting seedcoat permeability or as tools to break physical dormancy (Ceballos and others 2002; Van Assche and others 2003; Eldredge 2007; Jayasuriya and others 2009).

To efficiently cultivate a species, the seeds must be viable and nondormant. Using nondormant seeds, or seeds released from dormancy, allows uniform germination, emergence, and optimal stand establishment. Kurlovich (2002) demonstrated this principle using spring plantings of Washington lupine (*L. polyphyllus* Lindl.), a native to the western US.

Scarification of an impermeable seedcoat allows physically dormant seeds of lupines to imbibe water and subsequently germinate. A number of scarification methods have been found to overcome physical dormancy. Examples of mechanical scarification include various methods of sanding or using tools to chip away the seedcoat. Nonmechanical methods include acids, enzymes, organic solvents, hot water, and other materials to penetrate the seedcoat (Baskin and Baskin 1998). Excessive scarification can be deleterious to the seed embryo. The immediate objective of this study was to determine the efficacy of various scarification treatments to overcome seed dormancy and improve germination of longspur lupine (*L. arbustus* Douglas ex Lindl.), silvery lupine (*L. argenteus* Pursh), hairy bigleaf lupine (*L. prunophilus* M.E. Jones), and silky lupine (*L. sericeus* Pursh). The broad objective of this research is to identify possible techniques to enhance uniform germination, emergence,

and establishment of seed production fields for native western US lupine species.

MATERIALS AND METHODS

In May and June of 2007, 4 collection sites (Table 1; Figure 1) were identified, one for each of 4 lupine species (Figure 2): longspur lupine, silvery lupine, hairy bigleaf lupine, and silky lupine. Seeds were collected in June and July of 2007.

Five seed scarification methods were evaluated on each lupine species: 1) constant temperature thermal treatment; 2) varying temperature thermal treatment; 3) sulfuric acid chemical treatment; 4) sodium hypochlorite chemical treatment; and 5) mechanical scarification treatment using an electric seed scarifier. We had a total of 10 application levels within each scarification method plus an untreated control (Table 2). Control groups consisted of non-scarified seeds from each species that were maintained dry and at ambient conditions (19–21 °C [66–70 °F]) until initiation of germination tests. Twenty-five intact seeds per species were selected for each combination of scarification method/application level. Each treatment level of all methods were replicated twice.

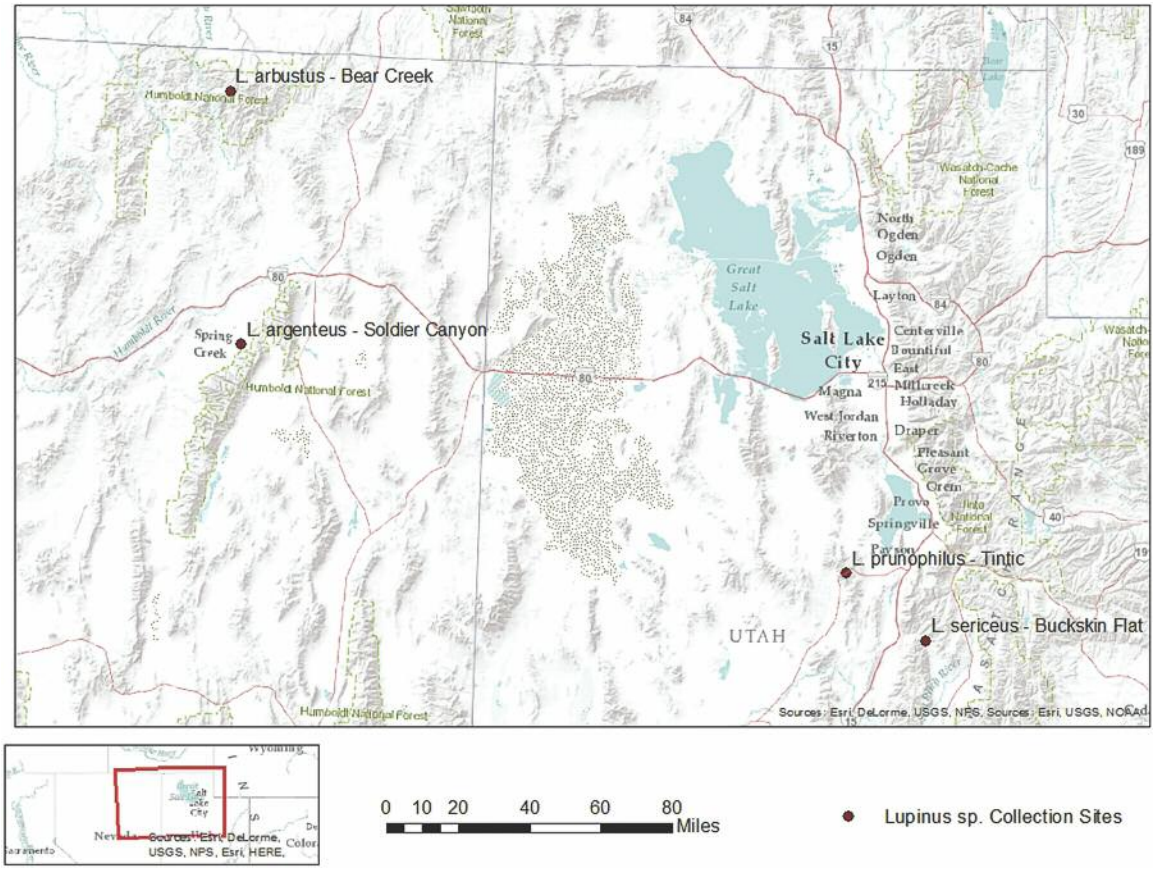

Figure 1. Map of the lupine (*Lupinus* spp.) seed collection locations.

TABLE 1

*Lupine (*Lupinus *spp.) germplasm collection locations in Datum WGS 84.*

Site name	Lupine species	Code	Latitude	Longitude	Elevation (m)	General location
Bear Creek	Longspur lupine (*L. arbustus*)	LUAR3	41.8377537	–115.4565113	2469	North-central NV
Soldier Canyon	Silvery lupine (*L. argenteus*)	LUAR6	40.8012972	–115.3565112	1768	North-central NV
Tintic	Hairy bigleaf lupine (*L. prunophilus*)	LUPR2	39.9632181	–112.0951638	1950	Central UT
Buckskin Flat	Silky lupine (*L. sericeus*)	LUSE4	39.6843129	–111.6769766	1920	Central UT

Note: 1 m = 3.3 ft.

Figure 2. Longspur lupine (*L. arbustus*) (A); silvery lupine (*L. argenteus*) (B); hairy bigleaf lupine (*L. prunophilus*) (C); silky lupine (*L. sericeus*) (D).

Our experimental design for thermal method investigated both varying water bath temperatures for a constant time ("varying temp.") and varying hot water bath exposure time for a constant temperature ("constant temp.") (Table 2). We employed 2 chemical scarification methods (Table 2), each with a range of exposure times to either concentrated sulfuric acid (18 M H_2SO_4) or to sodium hypochlorite (0.39 M NaOCl [commercial bleach]). For mechanical scarification we used a Forsberg electric seed scarifier (Seedburo Equipment, Des Plaines, Illinois) with varying exposure times (Table 2).

Following mechanical scarification, seeds were separated from the seedcoat chaff in preparation for germination tests. For treatments requiring wetting, the seeds were thoroughly rinsed with cold tap water to reduce seed temperature and (or) to remove chemical residue. Similar to the common practices of planting "primed seed" with a mechanical seeder, seeds were dried overnight at ambient conditions on blotter paper. Primed seeds can be dried and stored, as long as the radicle has not emerged, and then planted at a later date (Hill 1999). The following morning we placed all treated and control seeds in Petri plates on moist blotter paper to imbibe water and germinate. Plates were placed in a clear plastic bag to prevent sample desiccation. Bags were enclosed in a cardboard box and left in ambient conditions (19–21 °C [66–70 °F]) for the duration of the study.

Data Collection and Analysis

The Association of Official Seed Analysts (AOSA) germination protocols for allied lupine species suggest that germination should be monitored for 18 d. In this study, germination was monitored for 22 d. Germination counts were completed 3 times during that period.

We analyzed the germination data separately for each of the 4 species using the GLM model in SAS 9.2 (SAS Institute Inc, Cary, North Carolina). Response variables included scarification method, application level, and the interaction between the

TABLE 2

Tukey-Kramer adjustments for multiple comparisons of the interaction between 5 scarification methods and 11 treatment levels within each method applied to 4 lupine species.

Mean % germination after scarification treatment														
Constant temp. (95 °C [203 °F])			Varying temp. (1 min)			Sulfuric acid (18 M H_2SO_4)			Sodium hypochlorite (0.39 M NaOCl)			Forsberg electric seed scarifier		
Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value
Longspur lupine (*L. arbustus*)														
Cont.	68		Cont.	68		Cont.	68		Cont.	68		Cont.	68	
15 s	**14**	**0.0254**	50 °C [122 °F]	**10**	**0.0091**	1 min	**16**	**0.0411**	15 min	**14**	**0.0254**	1 s	4	0.9717
20 s	**19**	**0.0254**	55 °C [131 °F]	**8**	**0.0053**	2 min	**10**	**0.0091**	30 min	**14**	**0.0254**	2 s	**12**	**0.0154**
25 s	**16**	**0.0411**	60 °C [140 °F]	22	0.1510	3 min	**4**	**0.0018**	45 min	**8**	**0.0053**	3 s	24	0.2192
30 s	**10**	**0.0091**	65 °C [149 °F]	30	0.5330	4 min	22	0.1510	60 min	**6**	**0.0031**	4 s	**10**	**0.0091**
35 s	**80**	**0.0053**	70 °C [158 °F]	50	1.0000	5 min	38	0.9320	75 min	**6**	**0.0031**	5 s	22	0.1510
40 s	24	0.2192	75 °C [167 °F]	34	0.7709	6 min	**4**	**0.0018**	90 min	50	1.0000	6 s	**16**	**0.0411**
45 s	36	0.8652	80 °C [175 °F]	18	0.0652	7 min	**2**	**0.0010**	105 min	44	0.9977	7 s	**10**	**0.0091**
50 s	22	0.1510	85 °C [185 °F]	68	1.0000	8 min	**12**	**0.0154**	120 min	46	0.9996	8 s	28	0.4135
55 s	22	0.1006	90 °C [194 °F]	42	0.9907	9 min	**12**	**0.0154**	135 min	46	0.9996	9 s	**12**	**0.0154**
60 s	**14**	**0.0254**	95 °C [203 °F]	**16**	**0.0411**	10 min	26	0.3071	150 min	42	0.9907	10 s	18	0.0652
Silvery lupine (*L. argenteus*)														
Cont.	52		Cont.	52		Cont.	52		Cont.	52		Cont.	52	
15 s	62	1.0000	50 °C [122 °F]	50	1.0000	1 min	72	0.9927	15 min	38	1.0000	1 s	76	0.9098
20 s	66	1.0000	55 °C [131 °F]	66	1.0000	2 min	66	1.0000	30 min	52	1.0000	2 s	84	0.3571
25 s	56	1.0000	60 °C [140 °F]	56	1.0000	3 min	66	1.0000	45 min	60	1.0000	3 s	84	0.3571
30 s	60	1.0000	65 °C [149 °F]	52	1.0000	4 min	76	0.9098	60 min	54	1.0000	4 s	86	0.2359
35 s	70	0.9990	70 °C [158 °F]	70	0.9990	5 min	**92**	**0.0487**	75 min	62	1.0000	5 s	84	0.3571
40 s	70	0.9990	75 °C [167 °F]	52	1.0000	6 min	82	0.5050	90 min	42	1.0000	6 s	88	0.1467
45 s	86	0.9999	80 °C [175 °F]	56	1.0000	7 min	82	0.5050	105 min	40	1.0000	7 s	86	0.2359
50 s	68	0.9999	85 °C [185 °F]	58	1.0000	8 min	80	0.6627	120 min	62	1.0000	8 s	**96**	**0.0139**
55 s	62	1.0000	90 °C [194 °F]	74	0.9688	9 min	78	0.8053	135 min	44	1.0000	9 s	90	0.0865
60 s	**92**	**0.0487**	95 °C [203 °F]	70	0.9990	10 min	68	0.9999	150 min	44	1.0000	10 s	78	0.8053

(continued)

TABLE 2 *(continued)*

Tukey-Kramer adjustments for multiple comparisons of the interaction between 5 scarification methods and 11 treatment levels within each method applied to 4 lupine species.

Mean % germination after scarification treatment														
Constant temp. (95 °C [203 °F])			Varying temp. (1 min)			Sulfuric acid (18 M H_2SO_4)			Sodium hypochlorite (0.39 M NaOCl)			Forsberg electric seed scarifier		
Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value	Treat.	%	*P* value
Hairy bigleaf lupine (*L. prunophilus*)														
Cont.	32		Cont.	32		Cont.	32		Cont.	32		Cont.	32	
15 s	44	1.0000	50 °C [122 °F]	22	1.0000	1 min	74	0.4402	15 min	16	1.0000	1 s	56	0.9993
20 s	66	0.8649	55 °C [131 °F]	12	1.0000	2 min	62	0.9682	30 min	8	0.9993	2 s	60	0.9885
25 s	62	0.9682	60 °C [140 °F]	30	1.0000	3 min	80	0.1765	45 min	12	1.0000	3 s	58	0.9967
30 s	50	1.0000	65 °C [149 °F]	20	1.0000	4 min	84	0.0821	60 min	16	1.0000	4 s	54	0.9999
35 s	44	1.0000	70 °C [158 °F]	8	0.9993	5 min	74	0.4402	75 min	14	1.0000	5 s	46	1.0000
40 s	46	1.0000	75 °C [167 °F]	44	1.0000	6 min	82	0.1220	90 min	**92**	**0.0136**	6 s	40	1.0000
45 s	68	0.7767	80 °C [175 °F]	34	1.0000	7 min	**90**	**0.0219**	105 min	68	0.7767	7 s	50	1.0000
50 s	72	0.5543	85 °C [185 °F]	54	0.9999	8 min	62	0.9682	120 min	72	0.5543	8 s	42	1.0000
55 s	54	0.9999	90 °C [194 °F]	46	1.0000	9 min	76	0.3362	135 min	56	0.9993	9 s	26	1.0000
60 s	60	0.9885	95 °C [203 °F]	58	0.9967	10 min	82	0.1220	150 min	50	1.0000	10 s	30	1.0000
Silky lupine (*L. sericeus*)														
Cont.	22		Cont.	22		Cont.	22		Cont.	22		Cont.	22	
15 s	68	0.2526	50 °C [122 °F]	20	1.0000	1 min	74	0.0845	15 min	22	1.0000	1 s	62	0.5606
20 s	32	1.0000	55 °C [131 °F]	10	1.0000	2 min	**94**	**0.0006**	30 min	22	1.0000	2 s	**80**	**0.0227**
25 s	36	1.0000	60 °C [140 °F]	6	1.0000	3 min	**84**	**0.0086**	45 min	4	1.0000	3 s	74	0.0845
30 s	46	0.9994	65 °C [149 °F]	36	1.0000	4 min	**82**	**0.0141**	60 min	2	1.0000	4 s	**86**	**0.0052**
35 s	26	1.0000	70 °C [158 °F]	30	1.0000	5 min	**98**	**0.0002**	75 min	16	1.0000	5 s	64	0.4465
40 s	36	1.0000	75 °C [167 °F]	42	1.0000	6 min	12	1.0000	90 min	18	1.0000	6 s	64	0.4465
45 s	34	1.0000	80 °C [175 °F]	42	1.0000	7 min	10	1.0000	105 min	46	0.9994	7 s	58	0.7815
50 s	56	0.8684	85 °C [185 °F]	34	1.0000	8 min	22	1.0000	120 min	38	1.0000	8 s	60	0.6758
55 s	46	0.9994	90 °C [194 °F]	34	1.0000	9 min	12	1.0000	135 min	20	1.0000	9 s	50	0.9889
60 s	58	0.7815	95 °C [203 °F]	46	0.9994	10 min	0	0.9999	150 min	26	1.0000	10 s	66	0.3420

Notes: All significant interactions are identified in bold text. Means comparison in each case is against the control within the same treatment method and species.

TABLE 3

Scarification method means across treatment levels for each of 4 lupine species and analyzed using REGWQ groupings.

	Mean % germination			
Scarification method	Longspur lupine (*L. arbustus*)	Silvery lupine (*L. argenteus*)	Hairy bigleaf lupine (*L. prunophilus*)	Silky lupine (*L. sericeus*)
Control	68.0 a	52.0 d	32.0 d	22.0 c
Constant temperature	18.0 cd	67.6 c	56.8 b	44.0 b
Varying temperature	30.0 b	60.4 c	32.8 d	30.0 c
Sulfuric acid	14.8 d	76.4 b	76.8 a	48.8 b
Sodium hypochlorite	27.6 bc	50.0 d	40.4 cd	21.6 c
Mechanical	19.2 cd	85.2 a	46.4 c	66.4 a

Note: Within each species, means with the same letters are not significantly different.

two. We also ran a REGWQ *post hoc* multiple comparison procedure for an overall evaluation of scarification methods, and a Tukey-Kramer *post hoc* multiple comparison procedure to evaluate the interaction between scarification method and application level. Loess smoothing functions were used to generate figures in R statistical package 2.13.1 (The R Foundation, Vienna University of Economics and Business, Austria) in order to illustrate germination trends across treatment application levels.

RESULTS

Longspur lupine (*L. arbustus*)

For longspur lupine, 68% of the untreated control seeds germinated. We found that the scarification method, application level, and method × application level interaction all were significant with *P* values of 0.0009, <0.0001, and 0.0007, respectively. All scarification methods reduced germination, as compared to the control, for this species (Table 3). When comparing scarification methods, the control had significantly higher germination than any method with a mean of 68%. The method that was closest to the control for germination was sodium hypochlorite scarification at 27.6%. The scarification method that reduced germination the most was sulfuric acid with a mean of 14.8% (Table 3). Constant thermal scarification for 35 s at 95 °C (203 °F) significantly (*P* value 0.0053 [Table 2]) improved germination over the control with 80% germination.

Silvery lupine (*L. argenteus*)

Fifty-two percent of the silvery lupine untreated control seeds germinated. The scarification method, application level, and method × level interaction were all significant for silvery lupine, with *P* values of <0.0001, <0.0001, and 0.0277, respectively. The mechanical scarification method produced significantly higher germination rates than any other method with a mean of 85.2% (Table 3). The sulfuric acid scarification method produced a mean of 76.4%, which was significantly higher than the remaining 3 methods (Table 3). There were 3 levels within scarification treatments that had significantly higher germination than the controls (Table 2). Mechanical scarification for 8 s produced a very high 96% germination rate (*P* value 0.0139 [Table 2]). The 5 min sulfuric acid treatment and the 1 min at 95 °C (203 °F) treatment both had a 92% germination rate and were significantly higher than the control (*P* value 0.0487). There were no other obvious means contributing to the significant method × treatment level interaction (Table 2).

Hairy bigleaf lupine (*L. prunophilus*)

Thirty-two percent of the control seeds of hairy bigleaf lupine seeds germinated. The scarification method, treatment level, and the method × level interaction were all significant (*P* values <0.0001) for this species. The highest germination percentage was the result of sulfuric acid scarification with a mean of 76.8%, followed by constant temperature with a mean of 56.8%, which was also significantly higher than the remaining methods (Table 3). There were 2 levels within scarification treatments that significantly increased hairy bigleaf lupine seed germination. These were the 7-min sulfuric acid treatment and the 90-min sodium hypochlorite treatment with 90% and 92% germination and *P* values of 0.0219 and 0.0136, respectively (Table 2).

Silky lupine (*L. sericeus*)

A total of 22% of the silky lupine control seeds germinated. Similar to hairy bigleaf lupine, the scarification method, treatment level, and the method × level interaction were all significant (*P* values <0.0001) for silky lupine. The scarification method with the significantly highest germination was the

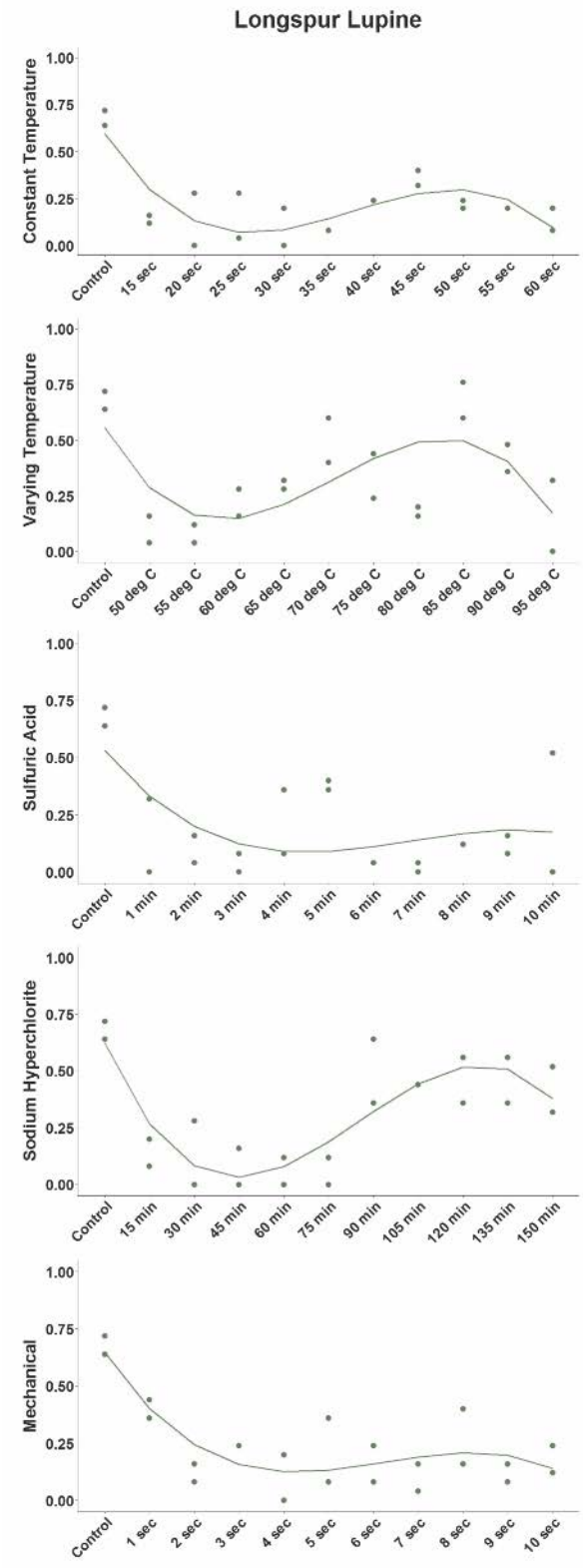

Figure 3. Percentage of germination trends of longspur lupine (*L. arbustus*) for 5 methods of scarification and 11 treatment levels (including control). Germination fraction, or percentage, is on the *y* axis and application levels are on the *x* axis. Each dot in the figures represents the actual data point. Level varies by scarification method as outlined in Table 2. Data are shown with a Loess smoothing function trend line.

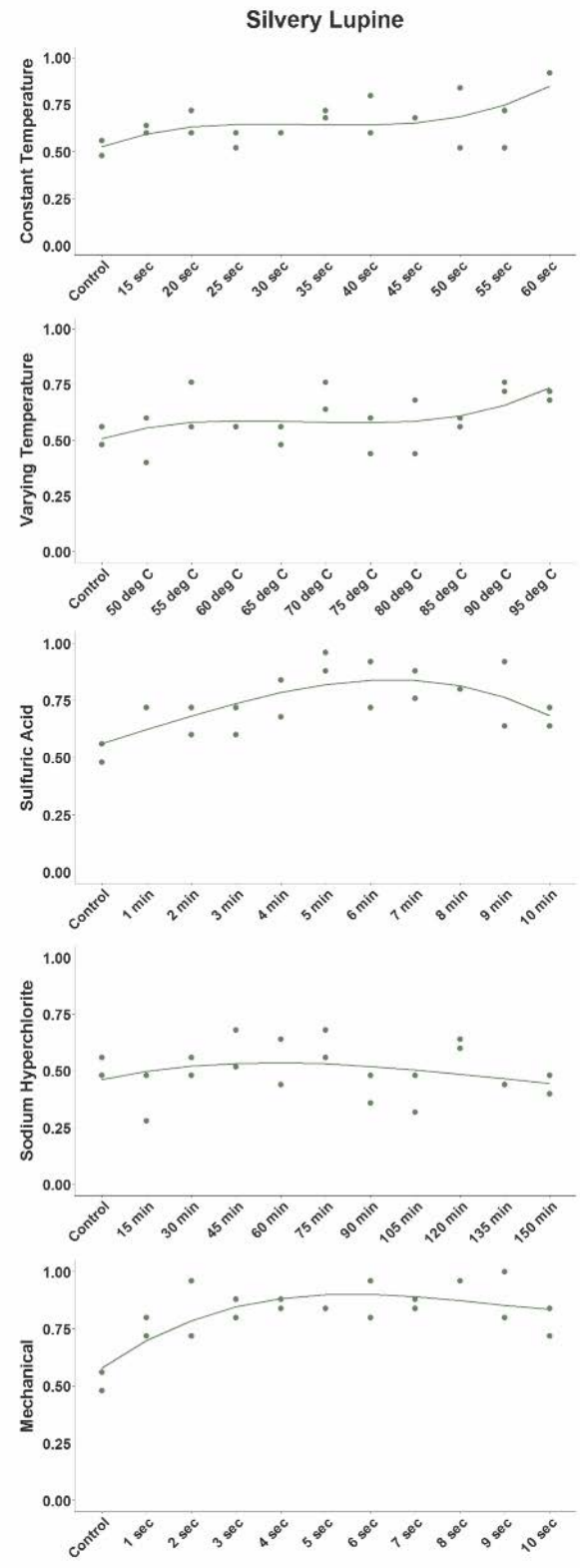

Figure 4. Percentage of germination trends of silvery lupine (*L. argenteus*) after 5 methods of scarification and 11 treatment levels. Germination fraction, or percentage, is on the *y* axis and treatment levels are on the *x* axis. Each dot in the figures represents the actual data point. Level varies by scarification method as outlined in Table 2. Data are shown with a Loess smoothing function trend line.

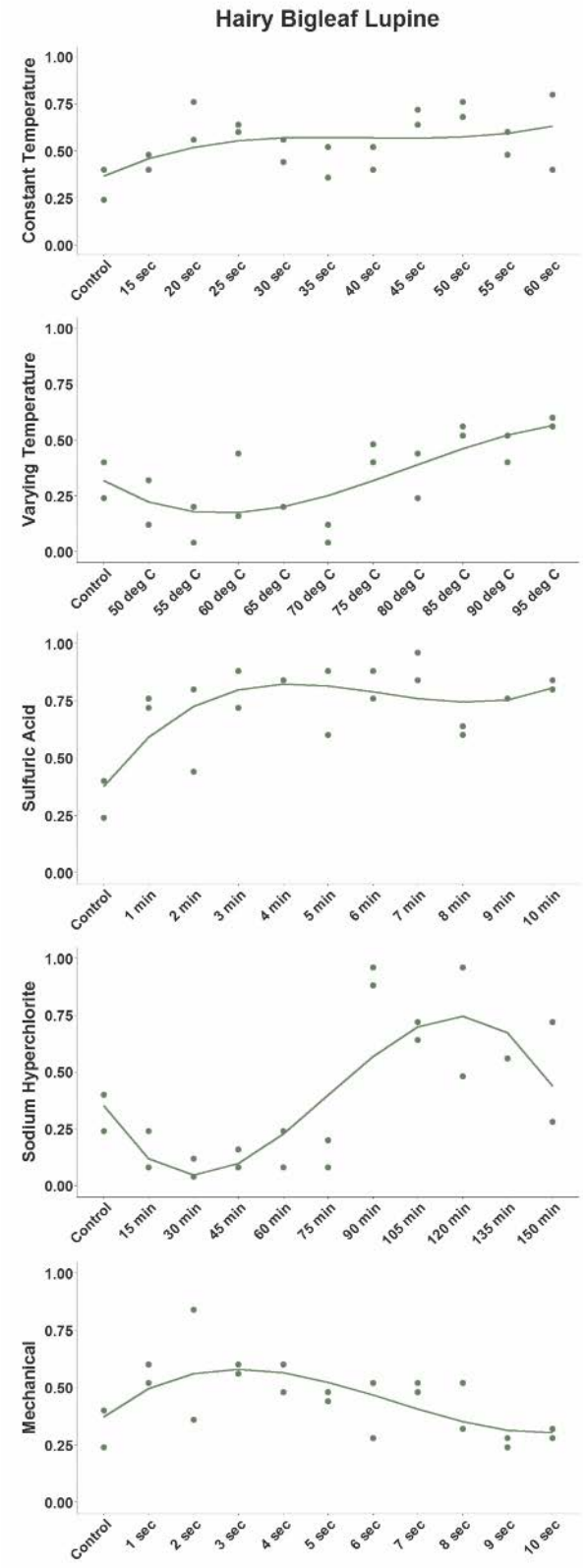

Figure 5. Percentage of germination trends of hairy bigleaf lupine (*L. prunophilus*) after 5 methods of scarification and 11 treatment levels. Germination fraction, or percentage, is on the *y* axis and treatment levels are on the *x* axis. Each dot in the figures represents the actual data point. Level varies by scarification method as outlined in Table 2. Data are shown with a Loess smoothing function trend line.

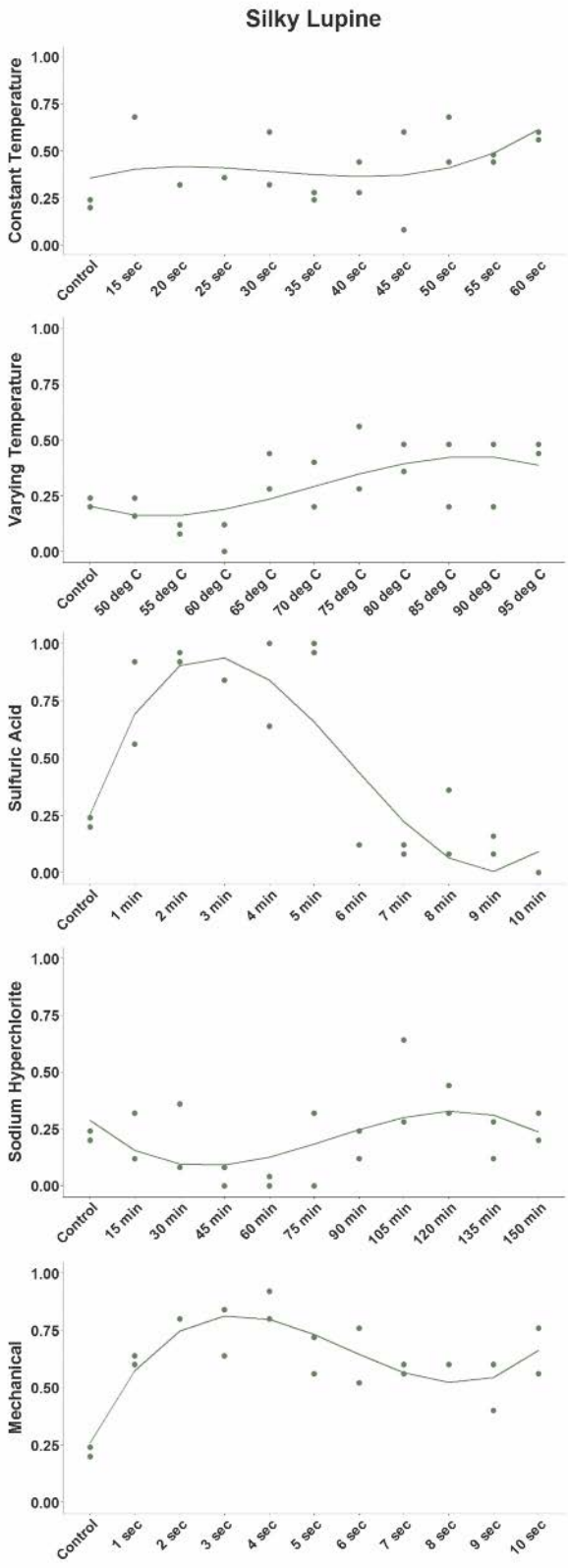

Figure 6. Percentage of germination trends of silky lupine (*L. sericeus*) after 5 methods of scarification and 11 treatment levels. Germination fraction, or percentage, is on the *y* axis and treatment levels are on the *x* axis. Each dot in the figures represents the actual data point. Level varies by scarification method as outlined in Table 2. Data are shown with a Loess smoothing function trend line.

mechanical method with a mean of 66.4% (Table 3). This method was followed by the constant temperature and the sulfuric acid methods with means of 48.8% and 44%, respectively (not significantly different from each other). There were several levels within scarification treatments that were significantly higher than the control (Table 2); all of which were treatments within the sulfuric acid and mechanical methods. Sulfuric acid treatments of 2, 3, 4, and 5 min had mean germination of 94%, 84%, 82%, and 98% with *P* values of 0.0006, 0.0086, 0.0141, and 0.0002, respectively. The 2 mechanical treatments were 2 and 4 s with mean germination of 80% and 86% with *P* values of 0.0227 and 0.0052, respectively (Table 2).

Germination Trends across Scarification Treatments Levels

There were no trends in the germination data for longspur lupine. All scarification methods dramatically and significantly decreased germination over the control (Table 2; Figure 3).

Trends for silvery lupine showed all scarification methods except sodium hypochlorite increased germination (Table 2; Figure 4). These trends are most discernible with the sulfuric acid and mechanical methods. Although, both thermal scarification methods also gradually increased germination with either increasing time exposure to a steady 95 °C (203 °F) or at a constant time of 1 min with temperatures ranging from a low of 50 °C (122 °F) to the most germination at 95 °C (203 °F).

Hairy bigleaf lupine showed increasing germination trends for all methods except mechanical scarification (Table 2; Figure 5). Germination trends for both thermal scarification methods showed a 20% increase over the control. Sulfuric acid scarification increased germination from 0 to 4 min exposure times then plateaued with increasing time up to our maximum of 10 min. For the sodium hypochlorite treatment regime, germination steadily increased until peak germination was reached at 120 min followed by a decrease for longer treatments. The overall trend for the mechanical method was an increase in germination at the 2 s exposure followed by a decrease in germination for longer exposures.

The most notable trend we observed in silky lupine was with the sulfuric acid treatment (Table 2; Figure 6). Germination sharply increased to 94% at the 2 min exposure and then decreased sharply to 0% at 10 min of soaking in H_2SO_4.

DISCUSSION

Before we determined to do this scarification study we attempted to cultivate the 4 lupine species used in this study. In these early field trials we found that both silvery lupine and hairy bigleaf lupine were physically dormant whereas longspur lupine and silky lupine did not express physical dormancy. We added longspur lupine and silky lupine to this study to identify if scarification would significantly improve their germination. Increased germination and uniform plant emergence would reduce the costs of producing seeds for these lupine species. In this study, we found that only the 35 s soaking at 95 °C (203 °F) significantly improved the germination of longspur lupine whereas all other levels of any other method either did not significantly improve germination over the untreated control or actually significantly diminished germination (Table 2). As a result, our data suggest that longspur lupine does indeed lack physical dormancy. Percentage of seed germination of the second species with questionable physical dormancy, silky lupine, was significantly improved by at least 4 treatment levels of sulfuric acid and 2 levels of mechanical scarification (Table 2). Clearly, this species does have some physical dormancy. Scarification of silky lupine seeds may provide some economic benefit during cultivation.

In general, we found mechanical scarification to be the most efficient and practical way to process large quantities of seeds for 2 species. This method exhibited comparable results to that of chemical scarification with silvery lupine and silky lupine without the complex procedures and added dangers of using hazardous chemicals. Travlos and others (2007) found mechanical scarification to be more effective than sulfuric acid scarification on the marama bean (*Tylosema esculentum* (Burch) L. Schreib [Fabaceae]), a physically dormant African legume. The Forsberg electric seed scarifier was too abrasive for the other 2 species; even the shortest exposure times physically damaged the seed embryo of both hairy bigleaf lupine and longspur lupine.

Despite the associated time and hazard constraints, both the sulfuric acid and sodium hypochlorite scarification methods included treatment levels that yielded significant improvement in germination for hairy bigleaf lupine (Table 2). Another option for this species might be to use a less aggressive mechanical scarifier. Dreesen (2004) used a rock tumbler with pea gravel and water to clean and scarify New Mexico olive (*Forestiera pubescens* Nutt. var. *pubescens* [Oleaceae]). This less abrasive mechanical scarification treatment may take more time but would be less likely to damage the seed embryo and may be more desirable than the use of sodium hypochlorite or the more hazardous sulfuric acid. Further research is needed for alternative mechanical methods that result in less embryo damage than occurs with the Forsberg scarifier.

We do not know of any other studies that have used sodium hypochlorite treatment to scarify legume seeds. This chemical is commonly used to scarify the physically dormant seeds of the wild relatives of tomato (*Solanum lycopersicum* L. [Solanaceae]), many of which (such as *S. galapagense* S.C. Darwin & Peralta) will not germinate without this treatment (Rick and Hunt 1961; Gordillo and others 2008). Although sodium hypochlorite is easy to acquire and safer to use than sulfuric

acid, it produced significant improvements in germination for only one species at only one treatment level (hairy bigleaf lupine, at 90 min). No other treatment level × species interaction was significant for this chemical. There appeared to be no perceptible physical seedcoat degradation from this treatment. Further studies are needed to determine if increased exposure time and (or) concentration might be an effective scarification method. Tomato seeds are typically treated at approximately 0.4 M concentration for 30 min (Rick and Hunt 1961; Gordillo and others 2008).

Thermal scarification methods were unpredictable and did not improve germination compared with the control for any of the 4 lupine species tested. Thus, despite the long-term use of thermal scarification with blue lupine (*L. pilosus* L.) (Hootman 1941), thermal scarification cannot be recommended for these 4 lupine species unless further work at higher temperatures and (or) exposure levels shows significant and consistent improvements in germination.

CONCLUSIONS AND APPLICATION

We found scarification to be an effective tool for reducing physical dormancy in 3 of the 4 native lupine species we tested, thus allowing for a more efficient use of limited quantities of seeds. In general, germination of longspur lupine was either reduced or not significantly improved with the scarification treatments for the methods we tested. The other 3 species responded similarly to those reported by Dittus and Muir (2010) who found several scarification treatments to be effective for treating seeds of similar legume species. When used appropriately, scarification will improve establishment and reduce the cost of seed production for silvery lupine, hairy bigleaf lupine, and silky lupine. By following the recommendations for optimal germination for each of these species, seed producers will be able to increase the germination, emergence, and field establishment of these Great Basin lupine species.

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