Chapter 7

Evaluation of Herbicide Efficacy, Injury, and Yield in White Lupin (*Lupinus albus* L.)

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/61708

Abstract

White lupin is of increasing interest in the southeastern United States (US) as a winter legume cover crop or as mid-winter forage for ruminants. White lupins are poor weed competitors during early establishment, making effective weed control necessary; however, only three herbicides are currently registered for use in lupin. An experiment was conducted at two Alabama sites in 2007 and 2008 to evaluate herbicide efficacy provided by ten preemergence (PRE) and nine postemergence (POST) herbicides as well as lupin injury and yield. Overall, PRE applied herbicides, particularly imazethapyr, linuron, and flumioxazin, caused less crop injury than POST herbicides while providing ≥ 86% control of annual bluegrass, corn spurry, heartwing sorrel, henbit, and lesser swinecress six weeks after application. Grass-active herbicides, fluazifop and sethoxydim, provided greater than 95% of annual bluegrass control without causing unrecoverable lupin damage. Imazethapyr applied POST controlled shepherd's purse (96% to 98%), cutleaf evening-primrose (81% to 96%), and wild radish (71% to 99%) without lupin injury. POST-directed spray applications of glyphosate and flumioxazin provided good weed control of corn spurry (80% to 98%) and winter vetch (71% to 95%) but caused significant crop injury due to drift. In general, grain yields were only reduced with the use of chlorimuron, diclosulam, glyphosate, and thifensulfuron. This research suggests there are several herbicides not currently registered that could be beneficial for use in US lupin production.

Keywords: Alternative nitrogen source, cover crop, weed contro

1. Introduction

Conventional agriculture depends on synthetic nitrogen (N) fertilizers and herbicides for high crop performance [1]. Alternative N sources are available in the form of leguminous crops such as *Lupinus* spp. White lupin is of major interest in the southeastern US because new cultivars exhibit differential vernalization requirements similar to wheat (*Triticum aestivum* L.) and can be utilized as mid-winter forage. White lupin has been utilized in the southeastern US as a livestock feed, for human consumption and as a winter cover crop in conservation agriculture [2, 3]. Since its introduction in the 1930s, until the 1950s the US lupin production reached over 1 million ha; however, production declined with the loss of government support, cold-weather damage to seed nurseries, and the increased availability of inorganic fertilizers [3-5].

Lupinus spp. are poor weed competitors during early establishment since canopy development is slow, facilitating light penetration and subsequent weed seed germination and yield loss due to competition. Lupin reaches maximum vegetative growth during flowering when it can successfully compete with newly emerging weeds [6]. Effective weed control is necessary to ensure lupin success under competition with weed species for water, nutrients, and light [6, 7].

Previous research has been conducted to compare the effectiveness of herbicides on weed control and potential for crop injury in lupin. A successful preemergence (PRE) herbicide treatment resulting in no crop damage is pendimethalin alone, or in combination with metribuzin [8, 9]. Pendimethalin use in white lupin provided 100% control of Russian thistle (*Salsola tragus* L.) and prostrate knotweed (*Polygonum aviculare* L.) [10]. The use of PRE applied metolachlor and alachlor, primarily in mixes with other herbicides, successfully controlled annual grasses and some broadleaf weed species greater than 90% in spring-type white lupin [11, 12]. Additionally, metolachlor, alone or mixed with linuron, did not cause white lupin injury [13].

Knott [8] found that lupin are especially sensitive to postemergent (POST) herbicides. Fluazifop, as a POST application, provided ≥98% control of wheat (*Triticum aestivum* L.), triticale (x Triticosecale Wittm ex A. Camus), and annual ryegrass (*Lolium multiflorum* Lam.) without causing injury to the lupin crop [8, 14]. POST application of imazethapyr provided good weed control but resulted in 15% to 24% crop injury and yield reduction [13]. Similarly, Penner et al. [12] found that the use of imazethapyr, as either PRE or POST, caused crop damage of 35% to 60%. Hashem et al. [15] showed that interrow weed control in narrow-leaf lupin provided by paraquat plus diquat increased yields compared to glyphosate alone, glyphosate plus metrabuzin, and glyphosate followed by paraquat plus diquat.

Currently, only three herbicides are registered for use in lupin: S-metolachlor, carfentrazone-ethyl, and glyphosate [16]. Therefore, the objective of this experiment is to investigate the use of chemical weed management practices in white lupin and evaluate their effect on weed control, crop injury, and lupin grain yield.

2. Materials and methods

Experimental treatment and design. A two-year experiment was established at two test sites on the E.V. Smith Research and Extension Center of the Alabama Agricultural Experiment Station in October 2007 and 2008, respectively. The experiment was a 2 (year) x 2 (location) x 3 (cultivar) x 4 (block) x 24 (weed control) factorial treatment arrangement. The experiment design was a randomized complete block design (r = 4) nested within each year x location x cultivar combination. The weed control factor had 20 levels: one nontreated control, ten PRE-applied herbicides, and nine POST-applied herbicides (Table 1). The two locations of the experiment were the Field Crops Unit (FCU), near Shorter, AL (32.42 N, 85.88 W) and the Plant Breeding Unit (PBU), Tallassee, AL (32.49 N, 85.89 W). At FCU, the experiment was established on a Compass soil; a coarse-loamy, siliceous, subactive, thermic Plinthic Paleudults with a loamy sand surface structure. At PBU, the experiment was conducted on a Compass Soil: a fine-loamy, mixed, semiactive, thermic Typic Hapludults with a sandy loam surface structure. The three cultivars used in the experiment were AU Homer (a high-alkaloid, indeterminate cover crop type), AU Alpha (a low-alkaloid, indeterminate forage type), and ABL 1082 (a low-alkaloid, determinate grain type experimental cultivar).

Treatment	Class	Rate	Unit
None			
S-metolachlor + Linuron	PRE	1.12 + 1.12	kg ai ha^{-1}
Metribuzin	PRE	0.42	kg ai ha^{-1}
Linuron	PRE	1.12	kg ai ha^{-1}
S-metolachlor	PRE	1.12	kg ai ha^{-1}
Pendimethalin (0.5 X)	PRE	0.84	kg ai ha^{-1}
Pendimethalin (1 X)	PRE	1.68	kg ai ha^{-1}
Pendimethalin (2 X)	PRE	3.36	kg ai ha^{-1}
Diclosulam	PRE	0.026	kg ai ha^{-1}
Flumioxazin	PRE	0.071	kg ai ha^{-1}
Imazethapyr	PRE	0.071	kg ai ha^{-1}
Thifensulfuron (2007)	POST	0.071	kg ai ha^{-1}
Carfentrazone (2008)	PDS	46.8	g product ha^{-1}
Fluazifop	POST	0.84	kg ai ha-1
Fomesafen	POST	0.28	kg ai ha-1
2,4-DB	POST	0.28	kg ai ha-1
Chlorimuron (2007)	POST	0.052	kg ai ha-1
Clove/Cinnamon Oil (2008)	PDS	6.9	L product ha^{-1}
Glyphosate	PDS	1.12	kg ai ha-1
Sethoxydim	POST	0.28	kg ai ha-1
Flumioxazin	PDS	0.071	kg ai ha-1
Imazethapyr	POST	0.071	kg ai ha-1

Table 1. Herbicide treatments, timing, and rates for 2007 and 2008 at the Field Crops Unit and Plant Breeding Unit at E.V. Smith Research Center.

Crop management. Inoculated lupin was seeded in four-row plots with a John Deer 1700 four-row vacuum planter[1] with a row spacing of 90 cm at a depth of 1.25 cm in October 2007 and October 2008. Seeding density was 17 seeds m^{-1}. Smooth seedbeds were prepared one to two weeks prior to planting in 2007. In 2008, the cultivars were planted in raised beds prepared by a KMC four-row ripper/bedder[2] due to concerns about potential saturated soil conditions at both locations. The plot length was 7.5 m at PBU and 7.5 m and 6 m at FCU in 2007 and 2008, respectively. The PRE herbicide treatments were applied one day after planting in both years. Application of POST herbicides followed 13 (2007) to 16 (2008 due to rainfall) weeks after planting.

Ratings. Weed control ratings were recorded at both locations on a scale from 0% (no weed control) to 100% (complete weed control). The nontreated control was used to estimate the level of control in the treated plots. Two weed control ratings per treatment/plot were taken in each study year. The first rating was taken six weeks after planting and PRE application in both years. The second rating was taken 22 and 26 weeks after planting in 2007/2008 and 2008/2009, respectively.

Crop injury ratings were taken on a scale from 0 (no injury/alive) to 10 (complete injury/dead). The nontreated control was considered to have 0 crop injury. In 2007/2008, crop injury ratings were taken three weeks after planting and PRE application and 15 weeks after planting. In 2008/2009, injury ratings were taken four weeks after planting and PRE application and 18 weeks after planting. In study year 2007/2008, plots at PBU and FCU were harvested on June 17, 2008. In study year 2008/2009, plots at FCU were harvested on June 16, 2009 and at PBU on June 29, 2009 due to differences in attaining maturity. The two center rows of each plot were harvested with a 2-row/10 ft Massey Ferguson plot combine[3] to determine grain yield (kg ha^{-1}).

Statistical analysis. We used generalized linear mixed models procedures as implemented in SAS[4] PROC GLIMMIX to analyze weed control data. This tool is flexible in the analysis of data with nonnormal distribution and unbalanced designs. Violations of normality and homogeneity of variance issues are often encountered when including a nontreated control treatment or percent control data with a large range. Weed control data were modelled using a binary distribution function or arcsine transformed data. Crop injury data were modelled using arcsine transformed data and then analyzed with a normal distribution function. All treatment factors and their interactions were considered fixed effects except the block factor and its interaction with the various treatment factors. Statistical significance was declared at Dunnett's $P < 0.1$.

3. Results and discussion

Weed control. Over the course of the two-year study, 14 weed species were observed. Not all species were present in all environments; therefore, weed control is presented for only those species that appear at both sites in each year of the study. At the first rating after planting, in both years, the following PRE herbicides provided greater than 90% control of all rated weed species when compared to the nontreated included: *S*-metolachlor[5]/linuron[6] mixture, metri-

http://dx.doi.org/10.5772/61708

buzin[7], diclosulam[8], flumioxazin[9], and imazethapyr[10] (Table 2). Linuron and *S*-metolachlor alone provided greater than 90% control in most instances except for henbit (*Lamium amplexicaule* L.), which was controlled by linuron at 86%, as well as lesser swinecress [*Coronopus didymus* (L.) Sm.] and heartwing sorrel (*Rumex hastatulus* Baldw.), which were controlled by *S*-metolachlor at 86% and 88%, respectively (Table 2). The mixture of *S*-metolachlor/linuron has been used previously in lupin study, even though linuron is not labeled for use in white lupin production in the southeastern US [17, 18]. In this study, at both early weed and late weed ratings, this mixture provided greater than 70% control of all rated weed species. Pendimethalin[11] provided good early season control of all weed species at the 0.5X, 1X, and 2X rate with the exception of lesser swinecress and heartwing sorrel, which were controlled less than 50% by the 0.5X and 1X rates.

Treatment		**Annual bluegrass**	**Corn spurry**		**Heartwing sorrel**	**Henbit**		**Lesser swinecress**
Name	Class	2008	2007	2008	2007	2007	2008	2008
None	Control	5	35	4	4	22	1	3
S-metolachlor/Linuron	PRE	94	99	99	94	99	92	93
Metribuzin	PRE	96	99	96	98	97	97	96
Linuron	PRE	98	99	99	92	95	86	94
S-metolachlor	PRE	95	98	76	88	90	98	86
Pendimethalin (0.5X)	PRE	86	98	97	48	97	88	45
Pendimethalin (1X)	PRE	89	94	94	46	99	97	41
Pendimethalin (2X)	PRE	93	98	98	79	99	98	78
Diclosulam	PRE	97	99	95	98	99	98	98
Flumioxazin	PRE	97	99	99	99	98	99	99
Imazethapyr	PRE	90	98	90	97	93	99	95

[a] All means were significantly different from the control plot using the Dunnett's test with P <0.1.

Table 2. Mean weed control ratings for 2007 and 2008 six weeks after lupin planting (prior to postemergence herbicide applications) at the Plant Breeding Unit at E.V. Smith Research Center, Tallassee, AL.[a]

In 2007, the second weed rating (22 weeks after planting) conducted after POST herbicide applications revealed PRE applied herbicide weed control to be greater than nontreated controls at both FCU and PBU for each rated weed species except for cutleaf evening-primrose (*Oenothera laciniata* Hill). At PBU, pendimethalin (0.5X rate) provided only 14% weed control and at FCU, cutleaf evening-primrose control was only 23% with the 1X rate of pendimethalin (Table 3). Less than 50% control was achieved for this weed species with the 2X rate of pendimethalin as well as *S*-metolachlor. The following POST applied herbicides provided greater than 50% control of all rated weed species included: fluazifop[12], chlorimuron[13], and imazethapyr. With the exception of black medic (*Medicago lupulina* L.) and crimson clover (*Trifolium incarnatum* L.), which were controlled by less than 70% (data not shown), imazethapyr controlled all broadleaf weed species by more than 80%. Ivany and McCully [13] evaluated various herbicides for use in sweet white lupin, they also showed that imazethapyr applied PRE and POST provided good broadleaf weed control (80% to 91%). Sethoxydim[14] provided good control for all weed species except for cutleaf evening-primrose, which was less than 50% at both sites. The grass weed species, annual bluegrass (*Poa annua* L.), was successfully controlled by the POST-applied grass active herbicides sethoxydim and fluazifop which is in agreement with previous research evaluating grass control in lupin [14, 19]. Thifensulfuron[15] did not provide greater weed control than the nontreated for cutleaf evening-primrose at FCU (15%) and provided less than 50% control of this species at PBU (31%) as well as corn spurry (*Spergula arvensis* L.) at FCU (43%) (Table 3). Corn spurry control was also less than 50% for fomesafen[16] at both FCU (22%) and PBU (37%) and 2,4-DB at FCU (39%). Glyphosate[17] and flumioxazin, which were both POST-directed spray applications, provided good weed control of all rated weeds at both locations (Table 3).

Treatment		**Annual bluegrass**		**Corn spurry**		**Cutleaf evening-primrose**				**Shepherd's purse**		**Winter vetch**	
		FCU	PBU	FCU	PBU	FCU		PBU		FCU	PBU	FCU	PBU
Name	Class	Mean*	Mean*	Mean*	Mean*	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean*	Mean*	Mean*	Mean*
None	Control	0	0	0	0	2		0		3	0	6	0
S-metolachlor/ Linuron	PRE	98	97	98	99	92	<0.0001	95	<0.0001	98	99	97	97
Metribuzin	PRE	98	78	96	86	94	<0.0001	91	<0.0001	99	99	89	81
Linuron	PRE	96	90	97	99	70	<0.0001	83	<0.0001	98	99	94	72
S-metolachlor	PRE	98	93	99	99	45	0.0015	36	0.0007	97	95	96	66
Pendimethalin (0.5X)	PRE	98	58	99	99	42	0.0031	14	0.5624	97	90	95	86
Pendimethalin (1X)	PRE	98	92	99	99	23	0.1595	28	0.0089	99	96	95	61
Pendimethalin (2X)	PRE	99	82	99	99	39	0.0065	48	0.0003	99	99	98	73
Diclosulam	PRE	95	68	88	97	96	<0.0001	94	<0.0001	99	99	99	97
Flumioxazin	PRE	98	80	99	99	97	<0.0001	95	<0.0001	99	99	83	74
Imazethapyr	PRE	97	87	88	97	85	<0.0001	92	<0.0001	89	97	79	60
Thifensulfuron	POST	98	64	43	98	15	0.5624	31	0.0005	98	99	98	89
Fluazifop	POST	97	99	80	65	57	0.0001	50	<0.0001	98	95	94	57

Treatment		Annual bluegrass		Corn spurry		Cutleaf evening-primrose				Shepherd's purse		Winter vetch	
Fomesafen	POST	94	67	22	37	59	<0.0001	70	<0.0001	97	98	93	63
2,4-DB	POST	93	76	39	60	98	<0.0001	99	<0.0001	99	90	96	76
Chlorimuron	POST	99	65	93	98	98	<0.0001	98	<0.0001	99	99	99	98
Glyphosate	PDS	98	89	88	92	69	<0.0001	83	<0.0001	97	99	92	71
Sethoxydim	POST	97	96	71	84	45	0.0014	45	0.0002	97	91	93	53
Flumioxazin	PDS	95	80	98	93	93	<0.0001	88	<0.0001	98	91	95	79
Imazethapyr	POST	97	77	86	88	81	<0.0001	85	<0.0001	98	96	91	65

* Denotes means within location that are all significantly different from control using Dunnett's test with P-value <0.1.

Table 3. Mean weed control ratings 22 weeks after lupin planting in 2007 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

The second weed control rating in 2008 was conducted 26 weeks after planting at both locations. Due to excessive crop injury in 2007, the POST herbicides thifensulfuron and chlorimuron were replaced with carfentrazone[18] and a clove/cinnamon oil[19] mixture. When compared to a nontreated, PRE herbicides at both locations provided good weed control for rated weed species with the exception of shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.] and cutleaf evening-primrose. At PBU, pendimethalin at the 0.5X rate and full rate did not provide better control of shepherd's purse than the nontreated (Table 4). Similar results were seen at both PBU and FCU for all rates of pendimethalin in cutleaf evening-primrose control with 10% to 12% control with the 0.5X rate, 6% to 23% control with the 1X rate, and 8% to 18% control with the 2X rate. Control of corn spurry at both locations was also lacking for several POST herbicides including: fluazifop (6% to 7%), fomesafen (14% to 19%), 2,4-DB (5% to 6%), and sethoxydim (7% to 45%) (Table 4). Fluazifop, 2,4-DB, and sethoxydim also did not increase control of shepherd's purse compared to the nontreated at PBU with 32%, 21%, and 36% control, respectively. The clove/cinnamon oil mixture achieved poor control of shepherd's purse (29%) and cutleaf evening-primrose (14%) at PBU.

Crop injury. Two-way interactions (herbicide–cultivar and location–herbicide) were significant; therefore, injury ratings are presented by location and cultivar. Injury ratings presented here as the mean crop injury was taken after the POST herbicide applications. PRE-applied herbicides in 2007 resulted in no significant increases in crop injury in comparison to nontreated, with a few exceptions. Metribuzin caused increased white lupin injury (4.45) at FCU in cultivar AU Alpha; pendimethalin at the 2X rate resulted in increased injury (3.95) at FCU for the same cultivar (Table 5). Although metribuzin injury was not repeated in 2008 for any cultivar, past research in lupin, as well as soybean has shown variable cultivar tolerance to this herbicide [8, 20]. Diclosulam caused significant injury (6.05 to 9.94) at both locations regardless of cultivar. In 2007, POST herbicide applications, in general, caused greater crop injury than PRE herbicide applications. Thifensulfuron and chlorimuron caused significant lupin damage

Treatment	Corn spurry				Cutleaf evening-primrose		Shepherd's purse					Wild radish		Winter vetch
		FCU			PBU	FCU		PBU		PBU		FCU	PBU	FCU
Name	Class	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean*	Mean*	Mean*
None	Control	0		0		0		0		0		2	0	0
S-metolachlor/ Linuron	PRE	94	<0.0001	97	<0.0001	77	<0.0001	72	<0.0001	92	<0.0001	98	99	96
Metribuzin	PRE	74	<0.0001	85	<0.0001	73	<0.0001	81	<0.0001	93	<0.0001	91	98	67
Linuron	PRE	83	<0.0001	93	<0.0001	85	<0.0001	75	<0.0001	98	<0.0001	93	99	76
S-metolachlor	PRE	57	<0.0001	63	<0.0001	30	0.0182	12	0.1984	42	0.0651	80	94	85
Pendimethalin (0.5X)	PRE	78	<0.0001	96	<0.0001	10	0.5673	12	0.1746	3	0.9999	63	97	46
Pendimethalin (1X)	PRE	98	<0.0001	92	<0.0001	23	0.0681	6	0.6044	21	0.3890	93	96	92
Pendimethalin (2X)	PRE	91	<0.0001	96	<0.0001	18	0.1434	8	0.4548	64	0.0051	96	99	83
Diclosulam	PRE	79	<0.0001	91	<0.0001	85	<0.0001	91	<0.0001	99	<0.0001	98	99	98
Flumioxazin	PRE	94	<0.0001	98	<0.0001	94	<0.0001	95	<0.0001	98	<0.0001	96	98	90
Imazethapyr	PRE	42	0.0003	97	<0.0001	48	0.0003	96	<0.0001	85	0.0002	95	99	49
Carfentrazone	POST	23	0.0292	55	0.0001	62	<0.0001	35	0.0007	69	0.0028	74	96	70
Fluazifop	POST	7	0.6489	6	0.8047	66	<0.0001	28	0.0041	32	0.1578	43	90	82
Fomesafen	POST	14	0.1718	19	0.1242	41	0.0018	75	<0.0001	94	<0.0001	99	99	77
2,4-DB	POST	6	0.7628	5	0.9214	82	<0.0001	96	<0.0001	21	0.3932	63	98	73
Clove/ Cinnamon Oil	POST	26	0.0160	32	0.0124	58	<0.0001	14	0.1984	29	0.2074	99	99	51
Glyphosate	PDS	94	<0.0001	98	<0.0001	95	<0.0001	91	<0.0001	96	<0.0001	57	97	94
Sethoxydim	POST	7	0.6549	45	0.0010	39	0.0028	25	0.0091	36	0.1083	83	95	54
Flumioxazin	PDS	80	<0.0001	81	<0.0001	81	<0.0001	68	<0.0001	60	0.0082	72	97	80
Imazethapyr	POST	34	<0.0001	96	<0.0001	82	<0.0001	96	<0.0001	97	<0.0001	71	99	68

* Denotes means within location that are all significantly different from control using Dunnett's test with P-value <0.1.

Table 4. Mean weed control ratings 26 weeks after lupin planting in 2008 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

(9.43 to 10.00), regardless of cultivar or location; therefore, they were discontinued in 2008 (Table 5). Thifensulfuron and chlorimuron were initially included in this study since they are registered for use in soybean; however, research has shown variable phytotoxicity among soybean cultivars for both herbicides [21, 22]. Research conducted by Knott [8] suggests that sulfonylurea herbicides such as metsulfuron cause variable crop injury in white lupin, ranging from limited to severe when applied at the normal field rate. Flumioxazin, as a POST-directed spray, caused significant crop injury at each location for each cultivar (4.50 to 7.84). Significant injury resulted from the use of fomesafen at FCU regardless of cultivar; however, increased injury was not observed with this herbicide at PBU. Glyphosate also resulted in increased lupin injury at FCU for ABL 1082 (6.30) and AU Alpha (5.89) (Table 5). Glyphosate is registered for POST-directed application in lupin in the US [16]; however, herbicide drift can easily cause significant crop injury. This was the most likely cause of lupin injury in our study. Injury from POST flumioxazin applications may also be attributed to drift since PRE applications of this herbicide did not result in increased crop injury in most cases; although, in drier soil conditions, increased phytotoxicity of flumioxazin has been observed in other crops. This could pose a risk for increased lupin damage [23]. Fluazifop (0.50 to 3.81), 2,4-DB (0.06 to 0.75), sethoxydim (0.26 to 2.28), and imazethapyr (0.94 to 4.45) did not result in increased lupin injury over the nontreated (Table 5).

Crop injury in 2008 resulted in less overall lupin injury than in 2007. PRE applied herbicides did not cause significant injury in comparison to a nontreated at either location for any of the cultivars except for diclosulam (5.26 to 9.00), which caused unacceptable injury, regardless of location or cultivar (Table 6). Diclosulam, which is applied either preplant incorporated (PPI) or PRE, is registered in soybean [*Glycine max* (L.) Merr.] and peanut (*Arachis hypogaea* L.) with little injury to either crop [24, 25]. Lupin injury from PRE applications of diclosulam was significant for each cultivar included in the experiment. POST-applied herbicides did not increase crop injury over nontreated except for glyphosate (4.49 to 7.76) and fomesafen in AU Alpha at both locations (3.22 to 3.48) and in AU Homer at PBU (4.00) (Table 6). Crop injury from fomesafen was noted in both years of the study with inconsistent injury for each cultivar. In other crops, such as soybean and dry beans, previous research has reported negligible fomesafen injury regardless of cultivar [26, 27]. In this study, however, it is evident that fomesafen can produce significant injury to lupin.

Grain yield. Mean grain yields (kg ha-1) were much higher for all three cultivars in 2008 as compared to 2007 (Table 7). The grain type cultivar ABL 1082 yielded highest of the three cultivars in both years. The interaction of treatment and cultivar was statistically significant.

ABL 1082. The nontreated had a mean grain yield of 1337 kg ha^{-1} in 2007 and of 2074 kg ha^{-1} in 2008. In both years, none of the PRE herbicides, with the exception of diclosulam, reduced yield. Diclosulam caused yield losses of nearly 950 kg ha^{-1} in 2007 and 1430 kg ha^{-1} in 2008 (Table 7). Two POST-applied herbicides, thifensulfuron and chlorimuron, had no measurable yields in 2007. In 2008, glyphosate was the only POST-applied herbicide that caused significant yield losses of 1700 kg ha^{-1}.

Treatment		ABL 1082				AU Alpha		AU Homer					
		FCU	PBU	FCU	PBU	FCU	PBU						
Name	Class	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value
None	Control	1.49		0.91		0.21		1.68		0.57		1.06	
S-metolachlor/ Linuron	PRE	0.38	0.8758	2.16	0.9490	1.68	0.4758	1.22	1.0000	0.26	1.0000	0.57	1.0000
Metribuzin	PRE	1.85	1.0000	1.95	0.9891	4.45*	0.0011	1.68	1.0000	0.06	0.9795	1.22	1.0000
Linuron	PRE	0.88	1.0000	2.40	0.8482	0.75	0.9980	0.91	0.9997	0.26	1.0000	1.00	1.0000
S-metolachlor	PRE	2.05	1.0000	1.22	1.0000	1.04	0.9355	1.95	1.0000	1.68	0.9422	1.46	1.0000
Pendimethalin (0.5X)	PRE	2.32	0.9999	1.22	1.0000	0.38	1.0000	1.72	1.0000	0.26	1.0000	0.75	1.0000
Pendimethalin (1X)	PRE	1.99	1.0000	0.53	1.0000	0.57	1.0000	1.46	1.0000	1.22	0.9997	0.38	0.9970
Pendimethalin (2X)	PRE	2.88	0.9652	1.46	1.0000	3.95*	0.0042	1.22	1.0000	1.46	0.9891	2.00	0.9980
Diclosulam	PRE	9.06*	<0.0001	6.05*	0.0011	9.94*	<0.0001	4.74	0.2180	8.54*	<0.0001	6.79*	0.0002
Flumioxazin	PRE	1.56	1.0000	0.26	0.9934	2.86*	0.0555	1.00	1.0000	0.13	0.9989	0.75	1.0000
Imazethapyr	PRE	1.65	1.0000	1.46	1.0000	2.08	0.2500	1.35	1.0000	0.38	1.0000	1.68	1.0000
Thifensulfuron	POST	10.00*	<0.0001	10.00*	<0.0001	9.52*	<0.0001	9.87*	<0.0001	10.00*	<0.0001	9.43*	<0.0001
Fluazifop	POST	3.81	0.5138	1.68	0.9997	0.50	1.0000	2.62	0.9997	2.71	0.3323	1.68	1.0000
Fomesafen	POST	8.00*	<0.0001	2.40	0.8482	6.78*	<0.0001	3.36	0.8909	7.37*	<0.0001	2.71	0.8047
2,4-DB	POST	0.50	0.9631	0.75	1.0000	0.57	1.0000	0.75	0.9934	0.75	1.0000	0.06	0.6103
Chlorimuron	POST	9.94*	<0.0001	9.94*	<0.0001	9.99*	<0.0001	9.62*	<0.0001	10.00*	<0.0001	9.74*	<0.0001
Glyphosate	PDS	6.30*	0.0060	2.71	0.6636	5.89*	<0.0001	1.42	1.0000	2.91	0.2497	2.18	0.9868
Sethoxydim	POST	2.28	1.0000	3.81	0.1551	0.26	1.0000	1.22	1.0000	1.22	0.9997	0.75	1.0000
Flumioxazin	PDS	7.29*	0.0003	4.50*	0.0452	7.84*	<0.0001	3.70	0.7209	6.01*	0.0002	6.02*	0.0024
Imazethapyr	POST	4.45	0.2304	0.94	1.0000	1.06	0.9242	1.46	1.0000	1.12	1.0000	1.00	1.0000

* Denotes mean crop injury significantly different from control within location using Dunnett's P-value <0.1.

Table 5. Mean crop injury ratings 15 weeks after planting in 2007 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

Treatment		**AU Alpha**						**AU Homer**					
		FCU	PBU	FCU	PBU	FCU	PBU						
Name	Class	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value	Mean crop injury	Dunnett's P-value
None	Control	0.75		1.72		0.57		1.00		1.90		1.46	
S-metolachlor/ Linuron	PRE	1.00	1.0000	3.09	0.8164	0.57	1.0000	0.57	0.9999	1.95	1.0000	1.22	1.0000
Metribuzin	PRE	2.40	0.3071	1.72	1.0000	0.26	0.9999	0.57	0.9999	0.53	0.4054	1.00	1.0000
Linuron	PRE	0.26	0.9871	1.22	1.0000	0.06	0.8164	0.57	0.9999	0.75	0.7267	1.46	1.0000
S-metolachlor	PRE	1.88	0.7463	1.22	1.0000	1.22	0.9871	0.06	0.2778	1.95	1.0000	0.57	0.8730
Pendimethalin (0.5X)	PRE	0.53	1.0000	0.94	0.9871	0.38	1.0000	0.57	0.9999	0.06*	0.0120	1.22	1.0000
Pendimethalin (1X)	PRE	0.53	1.0000	1.72	1.0000	1.06	0.9994	0.38	0.9716	0.26	0.1031	1.00	1.0000
Pendimethalin (2X)	PRE	0.91	1.0000	2.11	1.0000	0.57	1.0000	1.00	1.0000	0.38	0.2178	1.00	1.0000
Diclosulam	PRE	8.78*	<0.0001	5.26*	0.0080	9.00*	<0.0001	9.00*	<0.0001	7.60*	<0.0001	7.26*	<0.0001
Flumioxazin	PRE	0.75	1.0000	6.28*	0.0002	0.57	1.0000	2.51	0.5138	0.38	0.2178	1.68	1.0000
Imazethapyr	PRE	0.57	1.0000	2.51	0.9986	0.26	0.9999	1.22	1.0000	1.46	1.0000	1.00	1.0000
Carfentrazone	PDS	0.94	1.0000	1.22	1.0000	1.46	0.8730	0.57	0.9999	1.12	0.9932	1.72	1.0000
Fluazifop	POST	1.72	0.8730	1.46	1.0000	1.46	0.8730	1.22	1.0000	0.75	0.7267	1.22	1.0000
Fomesafen	POST	2.66	0.1776	3.22	0.7188	3.22*	0.0155	3.48*	0.0648	2.11	1.0000	4.00*	0.0981
2,4-DB	POST	1.00	1.0000	2.40	0.9998	0.38	1.0000	0.26	0.8164	0.06*	0.0120	1.00	1.0000
Clove/ Cinnamon Oil	PDS	0.57	1.0000	2.40	0.9998	0.06	0.8164	1.00	1.0000	0.75	0.7267	1.22	1.0000
Glyphosate	PDS	6.01*	<0.0001	6.26*	0.0002	4.49*	0.0001	5.25*	0.0002	3.09	0.9334	7.76*	<0.0001
Sethoxydim	POST	1.42	0.9932	0.75	0.8730	1.00	0.9999	1.00	1.0000	0.75	0.7267	1.00	1.0000
Flumioxazin	PDS	1.22	0.9999	1.22	1.0000	0.38	1.0000	1.22	1.0000	1.72	1.0000	1.72	1.0000
Imazethapyr	POST	1.22	0.9999	0.75	0.8730	0.06	0.8164	0.38	0.9716	0.94	0.9331	1.46	1.0000

* Denotes mean crop injury significantly different from control within location using Dunnett's P-value <0.1.

Table 6. Mean crop injury ratings 18 weeks after planting in 2008 at the Plant Breeding Unit (PBU) and the Field Crops Unit (FCU) at E.V. Smith Research Center, Tallassee, AL.

Treatment			**ABL 1082**		**AU Alpha**	**AU Homer**	**ABL 1082**	**AU Alpha**		**AU Homer**	
Name	Class	Mean	Dunnett's P-value	Mean*	Mean*	Mean	Dunnett's P-value	Mean	Dunnett's P-value	Mean	Dunnett's P-value
None	Control	1337		702	555	2074		1957		1219	
S-metolachlor/ Linuron	PRE	1331	1.0000	734	877	1936	1.0000	1108	0.0011	1262	1.0000
Metribuzin	PRE	1174	0.9831	778	551	1612	0.2811	1410	0.1150	1368	0.9315
Linuron	PRE	1370	1.0000	700	729	2126	1.0000	1484	0.2526	1359	1.0000
S-metolachlor	PRE	1176	0.9855	825	671	1910	0.9998	1426	0.1384	1027	0.5331
Pendimethalin (0.5X)	PRE	1353	1.0000	664	740	1937	1.0000	1567	0.5104	1522	0.7994
Pendimethalin (1X)	PRE	1256	1.0000	767	617	2025	1.0000	1504	0.3048	1233	1.0000
Pendimethalin (2X)	PRE	1294	1.0000	719	585	1907	0.9997	1619	0.7094	1442	0.8990
Diclosulam	PRE	391	<0.0001	383	214	648	<0.0001	210	<0.0001	548	0.0667
Flumioxazin	PRE	1305	1.0000	594	674	1470	0.0565	1264	0.0159	1217	1.0000
Imazethapyr	PRE	1323	1.0000	632	630	1742	0.7320	1460	0.1984	1309	1.0000
Thifensulfuron (2007)	POST	0	<0.0001	218	177	----	----	----	----	----	----
Carfentrazone (2008)	POST	----	----	----	----	2081	1.0000	1877	1.0000	1203	1.0000
Fluazifop	POST	1094	0.6993	893	536	1889	0.9987	1827	1.0000	1573	0.7980
Fomesafen	POST	1167	0.9744	666	666	1738	0.7189	1511	0.3234	1372	0.9390
2,4-DB	POST	1216	0.9996	892	783	2180	1.0000	1321	0.0364	1580	0.7716
Chlorimuron (2007)	POST	0	<0.0001	0	143	----	----	----	----	----	----
Clove/cinnamon oil (2008)	POST	----	----	----	----	2195	1.0000	1618	0.7065	1347	1.0000
Glyphosate	PDS	971	0.1563	673	634	364	<0.0001	735	<0.0001	839	0.3234
Sethoxydim	POST	1261	1.0000	706	525	1941	1.0000	1309	0.0309	1313	1.0000
Flumioxazin	PDS	1229	0.9999	597	652	1938	1.0000	1350	0.0545	1153	1.0000
Imazethapyr	POST	1317	1.0000	557	695	2020	1.0000	1226	0.0087	1433	0.9770

* Denotes mean grain yield not significantly different from control within cultivar using Dunnett's P-value <0.1.

Table 7. Mean grain yield (kg ha^{-1}) for 2007 and 2008 at E.V. Smith Research Center, Tallassee, AL averaged across location.

AU Alpha. Mean grain yields of 702 kg ha^{-1} in 2007 and 1957 kg ha^{-1} were obtained in the nontreated (Table 7). In 2007, none of the PRE- and POST-applied herbicides reduced yield. However, the POST herbicides, thifensulfuron and chlorimuron, yielded 218 kg ha^{-1} and 0 kg ha^{-1}, respectively. In 2008, diclosulam, with a mean grain yield of 210 kg ha^{-1}, was the only PRE herbicide that reduced mean grain yield of this cultivar. Similarly, glyphosate, with a mean grain yield 735 kg ha^{-1}, was the only POST herbicide that caused significant yield reduction in 2008.

AU Homer. The nontreated control had a mean grain yield of 555 kg ha^{-1} in 2007 and 1219 kg ha^{-1} in 2008 (Table 7). None of the PRE and POST herbicide treatments significantly reduced or increased yield as compared to the control in 2007. In 2008, none of the PRE or POST herbicide applications, with the exception of PRE diclosulam (548 kg ha^{-1}), yielded lower than the nontreated control.

Experiments conducted by Payne et al. [4] in the Pacific Northwest showed a maximum white lupin yield of 2128 kg ha^{-1}, but this yield is not stable. In our study, yield within each cultivar varied greatly between years depending on the treatment. The grain-type cultivar ABL 1082 had the highest mean grain yield, followed by the forage-type cultivar AU Alpha and the cover-crop-type cultivar AU Homer. In this experiment, diclosulam, thifensulfuron, chlorimuron, and glyphosate caused major grain yield losses. AU Homer appears to be the least sensitive to herbicide-induced yield reductions, since neither thifensulfuron nor chlorimuron reduced grain yield. Ivany and McCully [13] stated that POST applications of imazethapyr caused severe crop injury and yield loss in sweet white lupin. The results of this study did not confirm their findings. Neither the PRE nor the POST imazethpyr applications caused significant crop injury or subsequent yield reduction. This could be due, in part, to the use of different cultivars than those used by Ivany and McCully [13].

In general, PRE herbicide applications included in this study, excluding diclosulam, could be used in lupin without posing a significant risk of crop injury. Previous observations by Dittman [28] agree with findings that PRE herbicides may cause less lupin injury than POST herbicide options. Certain POST herbicides, such as thifensulfuron, chlorimuron, and fomesafen, are not viable herbicide options for use in lupin. Other POST options, like fluazifop, 2,4-DB, sethoxydim, and imazethapyr, may offer additional options for weed control in lupin without increasing crop injury.

The results of this experiment show that good weed control can be achieved by using a broad spectrum of herbicides that are currently not registered for use in US lupin production such as imazethapyr, flumioxazin, and linuron. With glyphosate and *S*-metolachlor, which are registered for use in lupin in the US, good weed control in lupin is possible; however, the use of a limited number of active ingredients can potentially increase resistance development in weed species in these systems. Based on these results, it is necessary to expand the number of registered herbicides for use in US lupin production.

4. Sources of materials

[1] John Deere 1700 four-row vacuum planter, John Deere, Moline, IL.

[2] Four-row ripper/bedder, Kelley Manufacturing Co., Tifton, GA.

[3]Two-row Massey Ferguson plot combine, AGCO Corporation, Duluth, GA.

[4]Statistical Analysis Systems®, version 9.2, SAS Institute, Inc., Cary, NC.

[5] S-metolachlor, Dual Magnum®, Syngenta Crop Protection, Inc., Greensboro, NC.

[6] Linuron, Lorox® DF, Tessenderlo Kerley, Inc., Phoenix, AZ.

[7] Metribuzin, Sencor®, Bayer CropScience, Research Triangle Park, NC.

[8] Diclosulam, Strongarm®, Dow AgroSciences, LLC, Indianapolis, IN.

[9] Flumioxazin, Valor®, Valent USA Corporation, Walnut Creek, CA.

[10] Imazethapyr, Pursuit®, BASF Corporation, Research Triangle Park, NC.

[11] Pendimethalin, Prowl® H2O, BASF Corporation, Research Triangle Park, NC.

[12] Fluazifop, Fusilade® DX, Syngenta Crop Protection, Inc., Greensboro, NC.

[13] Chlorimuron, DupontTM Classic®, E.I. duPont de Nemours & Company, Wilmington, DE.

[14] Sethoxydim, Poast Plus®, BASF Corporation, Research Triangle Park, NC.

[15] Thifensulfuron, DupontTM Harmony® SG, E.I. duPont de Nemours & Company, Wilmington, DE.

[16] Fomesafen, Reflex®, Syngenta Crop Protection, Inc., Greensboro, NC.

[17] Glyphosate, Honcho® Plus, Monsanto Company, St. Louis, MO.

[18] Carfentrazone, Aim® EC, FMC Corporation, Philadelphia, PA.

[19] Clove/cinnamon oil, Weed ZapTM, JH Biotech, Inc., Ventura, CA.

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http://dx.doi.org/10.5772/61708

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