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Evaluation of Chemical Termination Options for Cover Crops

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Nomenclature:
2,4-D; dicamba; glufosinate; glyphosate; metribuzin; paraquat; Austrian winterpea, *Lathryrus hirsutus* L.; cereal rye, *Secale cereale* L.; crimson clover, *Trifolium incarnatum* L.; hairy vetch, *Vicia villosa* Roth; rapeseed, *Brassica napus* L.; wheat, *Triticum aestivum* L.

Key words:
Cover crops; burndown herbicides; termination

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Abstract

Cover crop acreage has substantially increased over the last few years due to the intent of growers to capitalize on federal conservation payments and incorporate sustainable practices into agricultural systems. Despite all the known benefits, widespread adoption of cover crops still remains limited due to potential cost and management requirements. Cover crop termination is crucial, because a poorly controlled cover crop can become a weed and lessen the yield potential of the current cash crop. A field study was conducted in fall 2015 and 2016 at the Arkansas Agricultural Research and Extension Center in Fayetteville to evaluate preplant herbicide options for terminating cover crops. Glyphosate-containing treatments controlled 97% to 100% of cereal rye and wheat, but glyphosate alone controlled less than 57% of legume cover crops. The most effective way to control hairy vetch, Austrian winterpea, and crimson clover with glyphosate resulted from mixtures of glyphosate with glufosinate, 2,4-D, and dicamba. Higher rates of auxin herbicides improved control in these mixtures. Glufosinate alone or in mixture controlled legume cover crops 81% or more. Paraquat plus metribuzin was effective in terminating both cereal and legume cover crops, with control of cereal cover crops ranging from 87% to 97% and control of legumes ranging from 90% to 96%. None of these herbicides or mixtures adequately controlled rapeseed.

Introduction

In the United States, cover crop acreage has substantially increased over the last few years due to the intent of growers to capitalize on federal conservation payments and incorporate sustainable practices into agricultural systems (SARE 2015). Various reports have been published about benefits of cover crops in diverse areas of agriculture (Hartwig and Ammon 2002). The weed suppression provided by cover crops has been widely researched as a means to decrease selection pressure placed on herbicides for weed control (Creamer et al. 1996; Teasdale 1996). The evolution and spread of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) and the recent confirmation of protoporphyrinogen oxidase–resistant Palmer amaranth in the Midsouth threatens the ability of growers to manage weeds by using currently available herbicide technologies (Culpepper et al. 2008; Salas et al. 2016). Hence, successful weed management strategies must rely heavily on integrated management approaches using cultural, mechanical, and chemical methods of control (Jha and Norsworthy 2009; Price et al. 2011). Despite all the known benefits, widespread adoption of cover crops still remains limited due to potential cost and management requirements.

Termination of the cover crop is a critical component of management, because a poorly controlled cover crop can become a weed and lessen the yield potential of the current cash crop (Nascente et al. 2013). In no-till production systems, cover crop termination is commonly achieved by herbicides, but mechanical methods can also be used. Mowing can be used to control cover crops without soil disturbance, but problems such as cover crop regrowth and uneven residue distribution often arise with this method (Creamer and Dabney 2002). A roller-crimper is another option for cover crop termination in a no-till system. This implement crushes the cover crop to form a flat, uniform layer of residue over the soil surface (Ashford and Reeves 2003; Kornecki et al. 2006); however, termination of cover crops with a roller is not effective unless the cover crop has entered reproductive development (Creamer and Dabney 2002). Furthermore, this technique may be difficult in the Midsouth, because most agronomic crops are grown in raised beds.

Chemical termination of cover crop has been achieved by application of herbicides several weeks before planting. The efficacy of preplant herbicides on cover crops is likely to differ depending on the cover crop species planted (Cornelius and Bradley 2017). White and Worsham (1990) reported that application of glyphosate alone at 1.7 kg ae ha^{-1} controlled hairy vetch and crimson clover 65% and 70%, respectively, but the addition of 2,4-D increased hairy vetch control to 99% and crimson clover to 82%.

Table 1. Monthly rainfall data for 2014–2015 and 2015–2016.

Year[a]	September	October	November	December	January	February	March	April
				mm				
2014–2015[b]	114	184	78	75	14	1	82	81
2015–2016[c]	47	58	106	322	7	15	84	99

[a]Experiments were conducted under dryland conditions.
[b]Cover crop planting date: September 9, 2014.
[c]Cover crop planting date: September 19, 2015.

In soybean [*Glycine max* (L.) Merr.], Reddy (2001) observed that inadequate desiccation of Italian ryegrass [*Lolium perene* L. ssp. *multiflorum* (Lam.) Husnot] resulted in a yield reduction of 29% compared with plots without any cover crop. Price et al. (2009) also showed that inadequate termination of wheat, cereal rye, and black oats (*Avena strigosa* Schreb.) can significantly decrease seed cotton (*Gossypium hirsutum* L.) yield. White and Worsham (1990) reported that 65% control of crimson clover reduced corn (*Zea mays* L.) yield by 38% compared with conventional tillage. Seed germination and early seedling development can also be affected by a poorly controlled cover crop because of continued uptake of water from the soil, which depletes moisture available to crops at time of germination and seedling development (Price et al. 2009).

Another problem, commonly known as "hair pinning," has been linked to poorly controlled cover crops. In this case, cover crop residue is pushed into the soil by the disk openers or coulter, creating a condition in which the seed does not have appropriate soil coverage. As a result, stand loss can occur and may have a negative impact on yield (Kornecki et al. 2006). To avoid such problems, it is recommended that herbicides be applied 2 to 3 wk before row-crop planting to allow sufficient time for cover crop desiccation (Clark 2008). In case of inadequate cover crop control, paraquat can be applied immediately before planting to improve control (Bruce and Kells 1990). With a recent increase in cover crop use in the United States, information about herbicide efficacy for controlling cover crops is needed. Hence, a field study was conducted to determinate appropriate herbicide options for satisfactory cover crop control.

Materials and Methods

A field study was conducted in 2014 through 2016 at the University of Arkansas Agricultural Research and Extension Center in Fayetteville on a Captina silt loam soil (Fine-silty, siliceous, active, mesic Typic Fragiudults) with 33% sand, 49% silt, 18% clay, pH of 6.0, and 1.0% organic matter. Treatments were arranged in a randomized complete block design with a strip plot. The cover crop served as the strip plot, with herbicide treatments as the main plot. Four replications were used with plot sizes of 1.9 by 11.4 m. Cover crops were planted on September 9, 2014, and September 19, 2015. Cover crops were sown after harvest of a corn crop. Before cover crop was sown, the field was lightly tilled with a disk. Cover crops were broadcast in strips of 1.9 by 90 m followed by one more tillage operation to provide adequate soil coverage of the cover crop seeds. Monthly rainfall data for the period of this experiment are presented in Table 1.

Treatments were composed of herbicides used alone or in mixtures, typical preplant options in Arkansas (Table 2). Herbicides were applied at 143 L ha^{-1} using a three-nozzle CO_2-pressurized backpack sprayer on April 12, 2015, and April 14, 2016. Cover crop species, seeding rates, and the average height of each cover crop for both years at time of herbicide application are shown in Table 3. Effectiveness of the herbicide treatments was evaluated at 2 and 4 wk after treatment (WAT). Fresh aboveground biomass was harvested from a 1-m^2 quadrat and measured at 4 WAT. Samples were placed in a drier (65º C) for 5 d and weighed to assess dry biomass.

Table 2. Herbicide information for all products used in experiment.

Common name	Trade name	Manufacturer	Location
2,4-D	Weedar®	Nufarm, Inc.	Burr Ridge, IL
Dicamba	Clarity®	BASF Corporation	Research Triangle Park, NC
Dicamba	Clarity®	BASF Corporation	Research Triangle Park, NC
Flumioxazin + thifensulfuron + tribenuron	Afforia®	DuPont Crop Protection	Wilmington, DE
Glufosinate	Liberty®	Bayer CropScience LP	Research Triangle Park, NC
Glyphosate	Roundup PowerMax®	Monsanto Company	St. Louis, MO
Metribuzin	Metribuzin 75	Loveland Products, Inc.	Greeley, CO
Paraquat	Gramoxone®	Syngenta Crop Protection, LLC	Greensboro, NC
Rimsulfuron + thifensulfuron	LeadOff®	DuPont Crop Protection	Wilmington, DE
Saflufenacil	Sharpen®	BASF Corporation	Research Triangle Park, NC
Thifensulfuron + tribenuron	FirstShot®	DuPont Crop Protection	Wilmington, DE

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Table 3. List of cover crops with their respective seeding rate and cover crop height at termination with herbicide treatments.

Cover crops	Seeding rate	Year	
		2015	2016
	kg ha^{-1}	——— cm ———	
Cereal rye	90	154	135
Wheat	90	77	65
Australian winterpea	84	56	56
Hairy vetch	22	48	47
Crimson clover	15	57	62
Rapeseed	11	142	130

All data were subjected to ANOVA using JMP 12 PRO (SAS Institute, Cary, NC). The analysis of percent control and biomass were performed by cover crop, because the objective of the study was to identify the adequate herbicide option for each cover crop. Herbicide treatment was considered a fixed effect in the model, while replication was considered a random effect. No interaction was observed between herbicide treatment and year for percent control and biomass; hence, year was also considered a random effect. Means were separated using Fisher's protected LSD at $\alpha = 0.05$, and orthogonal contrasts were conducted for unique groups of herbicide programs ($\alpha = 0.05$).

Results and Discussion

Legume Cover Crops

Paraquat in combination with metribuzin often provided the highest control of the legume cover crops (Table 4). Austrian winterpea, crimson clover, and hairy vetch were controlled 96%, 90%, and 96%, respectively, at 4 WAT by paraquat plus the high rate of metribuzin. Putnam and Ries (1967) reported that application of paraquat with a photosystem II (PSII)-inhibiting herbicide such as simazine or diuron was more effective for controlling quackgrass [*Elymus repens* (L.) Gould] than either herbicide applied alone. Additionally, Norsworthy et al. (2011) showed that both translocation and efficacy increase when paraquat is mixed with PSII-inhibiting herbicides. Increasing the rate of metribuzin mixed with paraquat did not further improve control of the legume cover crops.

Glufosinate alone was an effective option for legume cover crop termination, as evidenced by >90% control of hairy vetch and crimson clover at 4 WAT (Table 4). Austrian winterpea was controlled 81% by glufosinate at 4 WAT, with this lower control being attributed to inadequate coverage of dense biomass with the contact herbicide. With the exception of Austrian winterpea, the addition of 2,4-D or dicamba to glufosinate did not offer improved control compared with glufosinate alone, regardless of the auxin herbicide rate in most cases. The mixture of glyphosate and glufosinate also did not differ from glufosinate alone, yet it was superior to glyphosate alone.

Both dicamba and 2,4-D alone, regardless of rate tested, provided less than 80% control of each legume cover crop through 4 WAT (Table 4). Doubling the rate of either dicamba or 2,4-D often improved control of Austrian winterpea; however, neither of these herbicides would be deemed as a stand-alone option for termination of legume cover crops at the rates tested. White and Worsham (1990) reported that application of 2,4-D and dicamba on crimson clover at a similar growth stage to that evaluated here (flowering and 51- to 61-cm height) provided only 70% and 72% control, respectively.

Glyphosate alone also did not control legume cover crops effectively. The control provided by glyphosate on all three legume cover crops ranged from 47% to 56% at 4 WAT (Table 4). The addition of dicamba or 2,4-D increased control (from 63% to 85%), but the same effect was not observed when compared with the auxin herbicides alone. The three-way mixture of glyphosate, dicamba, and 2,4-D provided similar control compared with the two-way mixture of glyphosate plus dicamba or glyphosate plus 2,4-D, regardless of the rate of the auxin herbicide. The only exception was the superior control provided by the three-way tank mix compared with glyphosate plus the lower rate of dicamba on hairy vetch.

Fresh biomass varied in response to herbicides for each legume cover crop (Table 5). All herbicide treatments reduced the fresh biomass weight of legume cover crops compared with the nontreated check. Fresh Austrian winterpea biomass treated with paraquat or paraquat plus metribuzin was the lowest among herbicide treatments. Similar results were observed for crimson clover and hairy vetch; however, glufosinate and glufosinate-containing treatments did not differ from paraquat and paraquat-containing treatments for fresh biomass weight. The addition of an auxin herbicide to glyphosate decreased the fresh weight of Austrian winterpea and crimson clover compared with glyphosate alone, regardless of the rate of 2,4-D and dicamba. Comparable results were not observed with hairy vetch. Glyphosate plus dicamba at both rates did not differ from glyphosate alone for fresh weights.

Dry biomass, likewise, varied among herbicide treatments for each legume cover crop (Table 5). Austrian winterpea dry biomass when treated with dicamba (280 g ae ha^{-1}), glyphosate plus dicamba (280 g ae ha^{-1}), and glyphosate plus dicamba (210 g ae ha^{-1}) plus 2,4-D (330 g ae ha^{-1}) did not differ from the nontreated check. All remaining treatments had significantly less dry biomass than the nontreated check. However, treatments containing paraquat and glufosinate showed greater dry biomass weight reduction. The dry biomass weight of crimson clover did not differ from the nontreated check for 2,4-D (530 g ae ha^{-1}), dicamba (280 g ae ha^{-1}), glyphosate, and glyphosate plus flumioxazin plus thifensulfuron plus tribenuron (44 g ai ha^{-1}, 5 g ai ha^{-1}, and 5 g ai ha^{-1}) treatments. Paraquat plus metribuzin at both rates provided the lowest amounts of dry crimson clover biomass. Compared with the nontreated check, hairy vetch dry biomass was not negatively affected by dicamba (280 g ae ha^{-1}), glyphosate, and glyphosate plus flumioxazin plus thifensulfuron plus tribenuron (44 g ha^{-1}, 5 g ha^{-1}, and 5 g ha^{-1}). Conversely, glufosinate- and paraquat-containing treatments effectively reduced the dry weight of hairy vetch.

Orthogonal contrasts performed between contact and systemic herbicides showed that using a contact herbicide alone or in a tank mixture provided superior results for all parameters evaluated (Table 6). The efficacy of a systemic herbicide is linked to the ability of the active ingredient to move thorough the plant, whereas contact herbicides are relatively immobile and quick acting and rapidly desiccate foliage (Dodge and Harris 1970; Young 1994). When applied to foliage, systemic herbicides will be

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Table 4. Control of legume cover crops at 2 and 4 wk after treatment (WAT) averaged over 2015 and 2016.

Herbicide[a]	Rate	Austrian winterpea		Crimson clover		Hairy vetch	
		2 WAT	4 WAT	2 WAT	4 WAT	2 WAT	4 WAT
	g ai or ae ha^{-1}	———	———	——— %	———	———	———
2,4-D[b]	530	59	60	37	49	59	71
2,4-D[b]	1,060	67	71	44	54	68	78
Dicamba[c]	280	51	60	36	49	53	62
Dicamba[c]	560	58	74	38	59	65	69
Glufosinate	594	64	81	70	93	75	95
Glufosinate + 2,4-D[c]	594 + 530	68	88	72	90	77	97
Glufosinate + 2,4-D[c]	594 + 1060	71	93	73	93	78	99
Glufosinate + dicamba[b]	594 + 280	60	89	63	88	71	90
Glufosinate + dicamba[b]	594 + 560	64	89	73	93	72	97
Glyphosate	867	52	56	30	47	35	56
Glyphosate + 2,4-D	867 + 530	46	66	41	63	60	75
Glyphosate + 2,4-D	867 + 1,060	55	76	49	71	71	82
Glyphosate + dicamba	867 + 280	56	75	46	64	63	70
Glyphosate + dicamba	867 + 560	60	82	51	72	65	78
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	59	73	42	56	70	85
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	57	69	35	50	45	67
Glyphosate + glufosinate	867 + 594	78	87	79	92	72	94
Glyphosate + rimsu + thifen	867 + 8 + 8	50	59	44	56	45	64
Glyphosate + saflufenacil	867 + 50	67	71	58	72	64	74
Glyphosate + thifen + triben + 2,4-D	867 + 5 + 5 + 530	64	76	38	77	65	80
Glyphosate + thifen + Triben + dicamba	867 + 5 + 5 + 280	62	73	37	83	60	75
Paraquat[c]	840	65	79	66	68	68	86
Paraquat + metribuzin[c]	560 + 420	81	90	70	90	79	94
Paraquat + metribuzin[c]	560 + 560	83	96	72	90	80	96
Saflufenacil + thifen + triben[d]	50 + 5 + 5	73	79	53	70	65	77
LSD (0.05)		6	8	11	10	9	10

[a]Abbreviations: rimsu, rimsulfuron; thifen, thifensulfuron; triben, tribenuron.
[b]Nonionic surfactant: 0.25% v/v.
[c]Crop oil concentrate: 1.0% v/v.
[d]Methylated seed oil: 1.0% v/v.

translocated throughout the plant; however, such movement is dependent on the translocation capacity of the target plant at a specific growth stage (Foy 1961). The translocation of systemic herbicides is often greatest when plants are actively growing. In addition, the degradation of herbicides within older plants is often greater than in young plants (Singh and Singh 2004). Considerations of these two factors might explain why systemic herbicides have low activity on high biomass cover crops (Ahmadi et al. 1980; Culpepper and York 2001). It is likely that earlier application of these systemic herbicides would at least have improved control, but in turn, there would be less biomass production, which would limit weed suppression.

Unlike systemic herbicides, contact herbicides are nonmobile and require adequate coverage of all foliage to obtain a high level of control. Developing plants might eventually show regrowth, because the roots and shoot system are generally unaffected (Bruce and Kells 1990). However, in this experiment, the overall performance of contact herbicides on legume cover crops at 4 WAT was superior to systemic herbicides (Table 6). Based on orthogonal contrasts, the efficacy of auxin

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Table 5. Effect of herbicides on cover crop biomass 4 WAT, averaged over 2015 and 2016.

Herbicide[a]	Rate	Austrian winterpea		Crimson clover		Hairy vetch	
		Fresh	Dry	Fresh	Dry	Fresh	Dry
	g ai or ae ha^{-1}	g m^{-2}					
Nontreated		3,670	500	3,340	520	2,800	490
2,4-D[b]	530	2,200	410	1,760	470	1,540	420
2,4-D[b]	1060	1,980	390	1,750	430	1,370	360
Dicamba[b]	280	2,440	440	1,740	490	1,430	380
Dicamba[b]	560	1,800	420	1,740	450	1,570	360
Glufosinate	594	1,130	300	720	310	380	110
Glufosinate + 2,4-D[b]	594 + 530	1,020	280	830	260	570	100
Glufosinate + 2,4-D[b]	594 + 1,060	830	280	730	290	480	100
Glufosinate + dicamba[b]	594 + 280	1,010	300	780	240	570	100
Glufosinate + dicamba[b]	594 + 560	940	280	790	270	500	90
Glyphosate	867	2,670	410	2,240	470	1,750	420
Glyphosate + 2,4-D	867 + 530	1,280	380	1,580	380	1,400	340
Glyphosate + 2,4-D	867 + 1,060	1,070	360	1,450	350	1,430	300
Glyphosate + dicamba	867 + 280	1,260	430	1,600	400	1,290	390
Glyphosate + dicamba	867 + 560	1,050	380	1,380	350	1,400	360
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	2,120	440	1,540	410	1,570	370
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	2,400	380	2,100	470	1,890	460
Glyphosate + glufosinate	867 + 594	1,080	290	600	260	730	140
Glyphosate + rimsu + thifen	867 + 8 + 8	1,700	370	2,450	450	1,980	460
Glyphosate + saflufenacil	867 + 50	1,590	390	1,430	340	1,610	390
Glyphosate + thifen + triben + 2,4-D	867 + 5 + 5 + 530	1,230	360	1,670	410	1,730	370
Glyphosate + thifen + triben + dicamba	867 + 5 + 5 + 280	1,270	390	1,820	380	1,240	390
Paraquat[c]	840	830	320	990	350	650	150
Paraquat + metribuzin[c]	560 + 420	560	260	500	160	520	110
Paraquat + metribuzin[c]	560 + 560	520	250	550	180	500	90
Saflufenacil + thifen + triben[d]	50 + 5 + 5	1,670	350	1,520	380	1,560	370
LSD (0.05)		360	70	320	70	310	70

[a]Abbreviations: rimsu, rimsulfuron; thifen, thifensulfuron; triben, tribenuron.
[b]Nonionic surfactant: 0.25% v/v.
[c]Crop oil concentrate: 1.0% v/v.
[d]Methylated seed oil: 1.0% v/v.

herbicides, specifically 2,4-D and dicamba, differed among legume cover crops.

Cereal Cover Crops

Both cereal cover crops were easily controlled by any glyphosate-containing treatment. Glyphosate alone at 867 g ae ha^{-1} or in mixture with other herbicides delivered at least 99% control of cereal rye at 4 WAT (Table 7). Similar results were observed with winter wheat; however, the mixture of glyphosate and glufosinate appeared antagonistic based on only 92% control from the tank mixture compared with 99% control from glyphosate alone. Whitaker et al. (2011) also observed a reduction in glyphosate plus glufosinate efficacy on grasses compared with glyphosate alone. According to Everman et al. (2009), such a decrease in efficacy of glyphosate by glufosinate is due to reduced translocation of glyphosate within the plant.

Paraquat or glufosinate alone demonstrated limited efficacy and biomass reduction on the cereal cover crops (Tables 7 and 8).

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Table 6. Orthogonal contrasts of percent control and biomass weight.

Contrast	Austrian winterpea Control	Austrian winterpea Fresh	Austrian winterpea Dry	Crimson clover Control	Crimson clover Fresh	Crimson clover Dry	Hairy vetch Control	Hairy vetch Fresh	Hairy vetch Dry
Contact[a] vs. systemic[b]	***	***	***	***	***	***	***	***	***
2,4-D[c] vs. dicamba[d]	*	NS	*	NS	NS	NS	**	NS	NS
Low dicamba vs. high dicamba[e]	***	*	NS	**	NS	*	***	NS	NS
Low 2,4-D vs. high 2,4-D[f]	***	*	NS	*	NS	NS	**	NS	*

[a]Indicates chemical treatments containing contact herbicide alone or in mixture with systemic herbicide. Contact herbicides included paraquat, glufosinate, and saflufenacil.
[b]Indicates treatments containing only systemic herbicides such as glyphosate, dicamba, and 2,4-D.
[c]Indicates treatments containing 2,4-D.
[d]Indicates treatments containing dicamba.
[e]"Low dicamba" indicates treatments that contained dicamba at 280 g ae ha^{-1}; "high dicamba" indicates treatments that contained dicamba at 560 g ae ha^{-1}.
[f]"Low 2,4-D" indicates treatments that contained 2,4-D at 530 g ae ha^{-1}; "high 2,4-D" indicates treatments that contained 2,4-D at 1,060 g ae ha^{-1}.
*Significant at $P = 0.05$ to 0.01 levels.
**Significant at $P = 0.01$ to 0.001 levels.
***Significant at $P \leq 0.001$ levels.

However, similar to legume cover crops, the paraquat plus metribuzin mixture increased control of cereal rye and wheat over paraquat alone. Similar results were observed by Norsworthy et al. (2011) when evaluating herbicide options for control of failed stands of corn. Eubank et al. (2012) also observed this synergistic effect with the addition of metribuzin to paraquat on control of

Table 7. Control of cereal cover crops at 2 and 4 wk after treatment (WAT), averaged over 2015 and 2016.

Herbicide[a]	Rate	Cereal rye 2 WAT	Cereal rye 4 WAT	Wheat 2 WAT	Wheat 4 WAT
	g ai or ae ha^{-1}	%			
Glufosinate	594	70	79	58	78
Glufosinate + 2,4-D[b]	594 + 530	70	76	56	77
Glufosinate + 2,4-D[b]	594 + 1,060	69	77	60	77
Glufosinate + dicamba[b]	594 + 280	71	79	58	76
Glufosinate + dicamba[b]	594 + 560	71	78	57	78
Glyphosate	867	80	100	75	98
Glyphosate + 2,4-D	867 + 530	81	100	75	99
Glyphosate + 2,4-D	867 + 1,060	83	100	74	99
Glyphosate + dicamba	867 + 280	81	99	77	99
Glyphosate + dicamba	867 + 560	84	100	75	99
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	83	100	77	100
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	82	100	77	100
Glyphosate + glufosinate	867 + 594	81	99	73	92
Glyphosate + rimsu + thifen	867 + 18 + 18	84	100	75	100
Glyphosate + saflufenacil	867 + 50	83	100	76	99
Glyphosate + thifen + tribenuron + 2,4-D	867 + 5 + 5 + 530	82	99	79	100
Glyphosate + thifen + triben + dicamba	867 + 5 + 5 + 280	81	100	77	98
Paraquat[c]	840	78	84	57	75
Paraquat + metribuzin[c]	560 + 420	89	97	75	87
Paraquat + metribuzin[c]	560 + 560	90	98	78	86
LSD (0.05)		10	9	12	10

[a]Abbreviations: rimsu, rimsulfuron; thifen, thifensulfuron; triben, tribenuron.
[b]Nonionic surfactant: 0.25% v/v.
[c]Crop oil concentrate: 1.0% v/v.
[d]Methylated seed oil: 1.0% v/v.

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Table 8. Effect of herbicides on cover crop biomass 4 WAT, averaged over 2015 and 2016.

Herbicide[a]	Rate	Cereal rye		Wheat	
		Fresh	Dry	Fresh	Dry
	g ai or ae ha^{-1}	——— % ———			
Glufosinate	594	2,850	490	2,120	390
Glufosinate + 2,4-D[b]	594 + 530	1,580	440	1,530	310
Glufosinate + 2,4-D[b]	594 + 1,060	1,610	430	1,450	340
Glufosinate + dicamba[b]	594 + 280	1,400	430	1,550	340
Glufosinate + dicamba[b]	594 + 560	1,560	460	1,510	340
Glyphosate	867	1,550	430	1,590	370
Glyphosate + 2,4-D	867 + 530	1,080	440	1,170	310
Glyphosate + 2,4-D	867 + 1,060	1,120	420	990	300
Glyphosate + dicamba	867 + 280	1,190	440	1,070	320
Glyphosate + dicamba	867 + 560	1,010	420	1,020	330
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	1,070	450	1,180	330
Glyphosate + flumioxazin + thifens + triben	867 + 44 + 5 + 5	1,090	440	1,180	310
Glyphosate + glufosinate	867 + 594	1,140	410	1,010	340
Glyphosate + rimsulfuron + thifensulfuron	867 + 18 + 18	940	410	1,080	340
Glyphosate + saflufenacil	867 + 50	1,080	440	1,100	320
Glyphosate + thifen + triben + 2,4-D	867 + 5 + 5 + 530	1,110	430	1,060	340
Glyphosate + thifen + triben + dicamba	867 + 5 + 5 + 280	1,140	430	1,070	330
Paraquat[c]	840	1,260	460	1,750	330
Paraquat + metribuzin[c]	560 + 420	1,060	420	1,060	300
Paraquat + metribuzin[c]	560 + 560	1,070	420	1,000	320
LSD (0.05)		390	60	240	50

[a]Abbreviations: rimsu, rimsulfuron; thifen, thifensulfuron; triben, tribenuron.
[b]Nonionic surfactant: 0.25% v/v.
[c]Crop oil concentrate: 1.0% v/v.

glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq.]. It is well established that contact herbicides are less effective than glyphosate in controlling grasses (Riar et al. 2011; Whitaker et al. 2011). Although significantly less fresh biomass weight was observed in the glufosinate-treated plots compared with the nontreated check, dry biomass weights did not show such differences among treatments on both cover crops (Table 8). The fact that cereal rye and wheat are erect plants and have a wide carbon:nitrogen ratio and a low rate of decomposition may explain the narrow differences in dry biomass weight between treated and nontreated plots.

Rapeseed

Overall, rapeseed was the most difficult to kill cover crop. None of the herbicide treatments controlled rapeseed adequately, as evident by control ratings of 71% or less at 4 WAT (Table 9). The fresh weight of rapeseed when treated with glyphosate or dicamba alone was not different from the nontreated check; hence, individuals planting a cover crop blend that contains rapeseed may have difficulty terminating this cover crop. Similar to legume cover crops, orthogonal contrasts conducted with rapeseed data showed that contact herbicide–containing treatments were superior to the systemic treatments in all parameters evaluated (Table 10). In addition, rapeseed was more sensitive to 2,4-D than dicamba. Beckie et al. (2004) reported that 2,4-D applied at 560 g ae ha^{-1} effectively controlled volunteer rapeseed at the 6-leaf stage. Hence, earlier application of the preplant herbicides might further enhance rapeseed control.

Practical Implications

Cover crop termination by herbicides can be challenging depending upon the cover crop species. The use of herbicides such as glyphosate, paraquat, 2,4-D, and dicamba alone to control cover crops might not provide sufficient control of legume cover crops. However, based on these data, effective control of legume cover crops can be obtained with mixtures of glufosinate plus dicamba or

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Table 9. Rapeseed control at 2 and 4 wk after treatment (WAT), averaged over 2015 and 2016.

		Control		Biomass	
Herbicide[a]	Rate	2 WAT	4 WAT	Fresh	Dry
	g ai or ae ha^{-1}	—————— % ——————		—————— g m^{-2} ——————	
Nontreated		0	0	3,400	530
2,4-D[b]	530	33	55	1,630	410
2,4-D[b]	1,060	35	62	1,710	420
Dicamba[b]	280	9	16	3,090	460
Dicamba[b]	560	14	21	3,040	490
Glufosinate	594	27	48	2,470	390
Glufosinate + 2,4-D[b]	594 + 530	48	56	1,480	380
Glufosinate + 2,4-D[b]	594 + 1,060	59	64	1,480	390
Glufosinate + dicamba[b]	594 + 280	37	46	2,340	410
Glufosinate + dicamba[b]	594 + 560	42	51	2,160	440
Glyphosate	867	22	36	3,120	520
Glyphosate + 2,4-D	867 + 530	32	61	1,690	440
Glyphosate + 2,4-D	867 + 1,060	36	65	1,490	430
Glyphosate + dicamba	867 + 280	30	36	2,690	450
Glyphosate + dicamba	867 + 560	35	39	2,650	450
Glyphosate + dicamba + 2,4-D	867 + 210 + 330	47	48	2,180	430
Glyphosate + flumioxazin + thifen + triben	867 + 44 + 5 + 5	30	42	2,130	500
Glyphosate + glufosinate	867 + 594	35	55	1,710	420
Glyphosate + rimsu + thifen	867 + 18 + 18	30	47	1,990	490
Glyphosate + saflufenacil	867 + 25	37	58	1,720	490
Glyphosate + thifen + tribe + 2,4-D	867 + 5 + 5 + 530	46	65	1,460	440
Glyphosate + thifen + tribe + dicamba	867 + 5 + 5 + 330	33	53	2,230	450
Paraquat[c]	840	45	50	2,300	410
Paraquat + metribuzin[c]	560 + 420	47	67	1,320	380
Paraquat + metribuzin[c]	560 + 560	54	71	1,410	400
Saflufenacil + thifen + triben[d]	25 + 5 + 5	46	60	1,360	430
LSD (0.05)		12	9	600	80

[a]Abbreviations: rimsu, rimsulfuron; thifen, thifensulfuron; triben, tribenuron.
[b]Nonionic surfactant: 0.25% v/v.
[c]Crop oil concentrate: 1.0% v/v.
[d]Methylated seed oil: 1.0% v/v.

2,4-D and paraquat plus metribuzin. The use of a contact herbicide for controlling legume cover crops at the bloom stage proved to be superior to use of systemic herbicides.

In contrast, cereal cover crops can be easily controlled with glyphosate. The addition of auxin herbicides to glyphosate in an attempt to broaden the spectrum of winter weed control will negatively impact cereal rye and wheat control. Paraquat plus metribuzin is also effective in terminating both cereal cover crops and would be an option when planting soybean following cover crop termination. The use of other PSII-inhibiting herbicides like atrazine, diuron, or fluometuron also are known to cause a synergistic affect when tank mixed with paraquat; hence, these herbicides would be additional options depending on the subsequent crop to be planted (Norsworthy et al. 2011).

Growers should avoid planting rapeseed based on the difficulty in successfully terminating this cover crop. If rapeseed is included in a cover crop blend, alternative methods of cover crop termination may be needed. Based on the lack of response of rapeseed

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Table 10. Orthogonal contrasts of percent control and biomass weight.

	Rapeseed		
Contrast	Control	Fresh	Dry
Contact[a] vs. systemic[b]	***	***	***
2,4-D[c] vs. dicamba[d]	***	***	***
Low dicamba vs. high dicamba[e]	*	NS	NS
Low 2,4-D vs. high 2,4-D[f]	**	NS	NS

[a]Indicates chemical treatments containing contact herbicide alone or in mixture with systemic herbicide. Contact herbicides included paraquat, glufosinate, and saflufenacil.
[b]Indicates treatments containing only systemic herbicides such as glyphosate, dicamba, and 2,4-D.
[c]Indicates treatments containing 2,4-D.
[d]Indicates treatments containing dicamba.
[e]"Low dicamba" indicates treatments that contained dicamba at 280 g ae ha^{-1}; "high dicamba" indicates treatments that contained dicamba at 560 g ae ha^{-1}.
[f]"Low 2,4-D" indicates treatments that contained 2,4-D at 530 g ae ha^{-1}; "high 2,4-D" indicates treatments that contained 2,4-D at 1060 g ae ha^{-1}.
*Significant at the $P = 0.05$ to 0.01 levels.
**Significant at the $P = 0.01$ to 0.001 levels.
***Significant at the $P \leq 0.001$ levels.

to herbicides, further research is needed to evaluate termination options for other mustards (*Sinapis* spp.) and radishes (*Raphanus* spp.) that could serve as a cover crop replacements for rapeseed.

Another important factor to consider is the interval needed between cover termination and crop planting. Most of the treatments showed substantial differences in control between 2 and 4 WAT (Tables 4, 7, and 9). Allowing sufficient time between application and complete kill of the cover crop can help with avoiding problems with lack of available soil moisture during the crop germination period and negative effects on crop establishment (Clark et al. 1997). In this experiment, to ensure maximum biomass production, all cover crops were sprayed at the bloom stage. Perhaps an earlier application would improve control of these difficult to kill cover crops, although the amount of biomass produced by the cover crops would be lessened.

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