Weed Technology

www.cambridge.org/wet

Herbicide selection to terminate grass, legume, and brassica cover crop species

Kara B. Pittman[1], Charles W. Cahoon[2], Kevin W. Bamber[3], Lucas S. Rector[4] and Michael L. Flessner[5]

[1]Research Associate, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA; [2]Assistant Professor, School of Plant and Environmental Sciences, Virginia Tech, Painter, VA, USA (current affiliation: Crop and Soil Sciences, North Carolina State University, Raleigh, NC, USA); [3]Senior Research Specialist, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA; [4]Graduate Research Assistant, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA and [5]Assistant Professor, School of Plant and Environmental Sciences, Virginia Tech, Blacksburg, VA, USA

Research Article

Cite this article: Pittman KB, Cahoon CW, Bamber KW, Rector LS, Flessner ML (2020) Herbicide selection to terminate grass, legume, and brassica cover crop species. Weed Technol. **34**: 48–54. doi: 10.1017/wet.2019.107

Received: 3 July 2019
Revised: 3 October 2019
Accepted: 8 October 2019
First published online: 18 November 2019

Associate Editor:
Aaron Hager, University of Illinois

Nomenclature:
Glyphosate; paraquat; crimson clover, *Trifolium incarnatum* L.; hairy vetch, *Vicia villosa* Roth; Austrian winter pea, *Pisum sativum* L. ssp. *sativum* var. *arvense*; rapeseed, *Brassica napus* L.

Keywords:
Mixes; cereal rye; cereal grains; annual ryegrass

Author for correspondence:
Michael L. Flessner, School of Plant and Environmental Sciences, Virginia Tech, 675 Old Glade Rd., Blacksburg, VA 24061.
Email: flessner@vt.edu

Abstract

Cover crops provide a number of agronomic benefits, including weed suppression, which is important as cases of herbicide resistance continue to rise. To effectively suppress weeds, high cover crop biomass is needed, which necessitates later termination timing. Cover crop termination is important to mitigate potential planting issues and prevent surviving cover crop competition with cash crops. Field studies were conducted in Virginia to determine the most effective herbicide options alone or combined with glyphosate or paraquat to terminate a range of cover crop species. Results revealed that grass cover crop species were controlled (94% to 98%) by glyphosate alone 4 wk after application (WAA). Overall, legume species varied in response to the single active-ingredient treatments, and control increased with the addition of glyphosate or paraquat. Mixes with glyphosate provided better control of crimson clover and hairy vetch by 7% to 8% compared with mixes containing paraquat 4 WAA. Mix partner did not influence control of Austrian winter pea. No treatment adequately controlled rapeseed in this study, with a maximum of 58% control observed with single active-ingredient treatments and 62% control with mixes. Height reduction for all cover crop species supports visible rating data. Rapeseed should be terminated when smaller, which could negate weed suppressive benefits from this cover crop species. Growers should consider herbicide selection and termination timing in their cover crop plan to ensure effective termination.

Introduction

The number of cases of herbicide-resistant weeds continues to increase. Relying solely on herbicides to combat this problem is not sustainable because of limited herbicide options and the development of multiple resistance (Crespo et al. 2017; Heap 2019). Instances of herbicide resistance have increased to 1,063 cases globally and are considered a major threat to production agriculture (Heap 2019; Holt and LeBaron 1990; Yu and Powles 2014). Increasing trends in herbicide-resistance cases and the desire to adopt more sustainable practices have led growers to develop integrated weed management (IWM) programs. One IWM strategy is to use cover crops. Cover crops are currently used for erosion control, recovering soil nitrogen, and increasing soil organic matter, but they also can be used for weed suppression (Burket et al. 1997; Clarke 2007; Dabney et al. 2001; Teasdale 1996). The number of cover crop hectares planted increased almost twofold from 2012 to 2017, according to a 2017 survey (CTIC 2017), with greatest adoption in the mid-Atlantic and southeastern regions of the United States (USDA ERS 2012). According to a 2017 survey, 69% of respondents stated a cereal rye cover crop sometimes or always improved herbicide-resistant weed control (CTIC 2017).

Fall-planted cover crops suppress weeds in subsequent cash crops after termination by creating a mulch layer on the soil surface to block germination cues, providing a physical barrier to weed growth, and some species exude allelochemicals that will hinder weed germination and growth (Mirsky et al. 2013). Many species can be used as a fall-planted cover crop (Clarke 2007). Popular grass species used include cereal rye (*Secale cereal* L.), oats (*Avena sativa* L.), winter wheat (*Triticum aestivum* L.), annual ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], triticale [*Triticosecale rimpaui* C. Yen & J.L. Yang (*Secale cereale* × *Triticum aestivum*)], and winter barley (*Hordeum vulgare* L.) (CTIC 2017). Among brassicaceous species, radish (*Raphanus sativus* L.) is most popular, followed by rapeseed. Among legumes, crimson clover is most popular, followed by winter pea and hairy vetch (CTIC 2017).

Biomass accumulation is one of the best predictors of weed suppression; as biomass of a cover crop increases, weed suppression also increases (Mirsky et al. 2013). To allow cover crops to gain the most biomass possible, cover crop selection, planting date, and termination timing are

https://doi.org/10.1017/wet.2019.107 Published online by Cambridge University Press

important factors (Lawson et al. 2015; Mirsky et al. 2011). Cover crop selection also plays a role in biomass accumulation; some cover crop species can produce more biomass than others, with small grains cover crops usually producing more compared with legumes (Lawson et al. 2015). These species that produce more biomass provide a thicker residue layer to suppress weeds. Delaying termination increases biomass, which increases weed suppression. Lawson et al. (2015) reported a twofold increase of biomass in cereal rye–hairy vetch mixtures if termination was delayed for 4 wk.

Cover crop termination is important because if not done correctly, it can interfere with planting or allow surviving cover crops to compete with the following cash crop (Curran et al. 2015; Wayman et al. 2014). Mechanical methods available to terminate cover crops include tillage, mowing, rolling, or undercutting. Success of mechanical methods often relies on the cover crop species reaching a certain maturity or growth stage. For example, mechanical methods most effectively terminate cereal rye at anthesis and hairy vetch at late flowering through pod set (Mirsky et al. 2009; Mischler et al. 2010). However, cover crops do not always reach the ideal stage for mechanical termination before planting time for the following cash crop (Mirsky et al. 2009; Mischler et al. 2010; Miville and Leroux 2018). Also, it is unlikely that growth stages ideal for mechanical termination will coincide if multiple cover crop species are planted together. Some mechanical termination methods, such as tilling and mowing, render cover crop residue less suitable for weed suppression. Herbicides are successful for use at multiple growth stages, making them a preferred method of terminating cover crops (Cornelius and Bradley 2017; Westgate et al. 2005).

Research efforts into cover crop termination with herbicides are increasing because growers need reliable options to control cover crop species before planting cash crops. Studies have been conducted in Arkansas and Missouri to determine the best herbicide treatment to control various cover crop species (Cornelius and Bradley 2017; Palhano et al. 2018). However, more research needs to be conducted comparing the effectiveness of single active-ingredient treatments with mixes on a variety of commonly grown cover crop species. Similar studies did not include halauxifen-methyl, mixes with halauxifen-methyl, or saflufenacil. Halauxifen-methyl and saflufenacil are registered for preplant weed control in many common crops, such as corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium hirsutum* L.), with particular utility for horseweed [*Conyza canadensis* (L.) Cronq.] control (Owen et al. 2011; Waggoner et al. 2011; Zimmer et al. 2018a,b). In addition, cover crop species such as winter oats and winter barley were not evaluated in these previous studies. The objectives of this research were to determine the most effective herbicide options to terminate a wide range of cover crop species and determine if combining glyphosate or paraquat with other herbicides will improve termination.

Materials and Methods

Field studies were conducted from 2016 through 2018 at Kentland Farm in Blacksburg, VA (37.19°N, 80.57°W), and at the Tidewater Agricultural Research and Extension Center in Holland, VA (36.66°N, 76.73°W). The site in Blacksburg, VA, was located on a Ross loam (fine-loamy, mixed, superactive, mesic Cumulic Hapludolls) with a pH of 6.7 and 4.3% organic matter. The site in Suffolk was on a Kenansville loamy sand (loamy, siliceous, subactive, thermic Arenic Hapludults) soil with a pH of 6.3 and 0.5% organic matter. Both locations were prepared for planting with a preplant application of glyphosate at 1,260 g ae ha^{-1} (Roundup Powermax; Monsanto Co., St. Louis, MO). Studies were repeated in 2 years at each location for a total of 4 site-years.

Table 1. Cover crop species, cultivar, seeding rate, and average height at herbicide application for the termination studies in Blacksburg and Holland, VA, in 2017 and 2018.

Cover crop species	Cultivar[a]	Seeding rate	Height at termination[b]	Stage at termination[b]
		kg ha^{-1}	cm	
Winter wheat	Gore Soft Red	134	43[c]	Jointing
Winter barley	P919	134	53	Jointing to boot
Cereal rye	Elbon	134	99	Boot to heading
Winter oats	Bob	134	33[c]	Tillering to jointing
Austrian winter pea	VNS	56	33[c]	Vegetative
Crimson clover	Dixie	22	35	Vegetative to early flowering
Hairy vetch	TNT	28	38	Vegetative to early flowering
Annual ryegrass	Winterhawk	22	41	Tillering
Rapeseed	Trophy	7	100	Flowering to immature pod

[a]Abbreviation: VNS, variety not stated.
[b]Averaged across 4 site-years, except where noted.
[c]Averaged across 3 site-years, due to missing data, winterkill, or poor stand establishment.

The studies were arranged as a randomized complete split block design with four replications. Each block was split by cover crop species, which were planted in twin rows with 16.5-cm spacing. Cover crop species included winter wheat, winter barley, cereal rye, winter oats, Austrian winter pea, crimson clover, hairy vetch, annual ryegrass, and rapeseed (Green Cover Seeds, Bladen, NE). Cover crops were planted using a drill to a depth of approximately 1.5 cm, except rapeseed and crimson clover, which were drilled approximately 0.5 cm deep. Seeding rates are presented in Table 1 and were based on the Virginia National Resources Conservation Service Cover Crop Guide (USDA 2015). In Holland, cover crop species were planted on September 1, 2016, and September 6, 2017. In Blacksburg, planting occurred on September 19, 2016, and September 11, 2017. There were no additional inputs to the cover crops.

The herbicide treatments are presented in Table 2, and a nontreated check was also included. Herbicides were applied perpendicular to the cover crop rows on April 19, 2017, and March 27, 2018, in Holland; and on April 13, 2017, and April 11, 2018, in Blacksburg, which is a typical time to burndown prior to cash crop planting in Virginia. Plot sizes were 3 by 7.6 m. Applications were made using a CO_2-pressurized backpack sprayer with a four-nozzle boom with 46-cm spacing. The boom was fitted with TeeJet Flat Fan XR 11002 nozzles (Spraying Systems Co., Wheaton, IL) calibrated to deliver 147 L ha^{-1} of spray solution.

Data collected after herbicide application included visible control ratings 2 and 4 wk after application (WAA) and heights 4 WAA. Visible control was rated on a scale of 0 to 100, with 0 being no control and 100 being complete necrosis (Frans et al. 1986). Visible control of grass cover crops was only collected in 3 site-years (Blacksburg in 2017 and 2018, and Holland in 2018). Four WAA, average heights were measured for individual species in each plot across 1 m of row. Previous studies have

https://doi.org/10.1017/wet.2019.107 Published online by Cambridge University Press

Table 2. Herbicide treatments used in cover crop termination studies in Blacksburg and Holland, VA, in 2017 and 2018.

Herbicide	Trade name	Rate	Manufacturer[a]	Location[a]
		g ai or ae ha^{-1}		
2,4-D	Shredder™ 2,4-D LV4	533	WinField United	Arden Mills, MN
Dicamba[b]	Banvel®	280	Arysta LifeScience, LLC	Research Triangle Park, NC
Halauxifen-methyl[c]	Elevore™	5	Dow AgroSciences, LLC	Indianapolis, IN
Glyphosate[d]	Roundup Powermax®	1,260	Monsanto Company	St. Louis, MO
Saflufenacil[c,e]	Sharpen®	37	BASF Corporation	Research Triangle Park, NC
Paraquat[f]	Gramoxone®	840	Syngenta Crop Protection, LLC	Greensboro, NC
Glufosinate[d]	Interline®	880	United Phosphorus, Inc.	King of Prussia, PA
2,4-d + glyphosate[d]	Shredder™ 2,4-D LV4 + Roundup Powermax®	533 + 1,260		
Dicamba + glyphosate[d]	Banvel® + Roundup Powermax®	280 + 1,260		
Halauxifen-methyl + glyphosate[d]	Elevore™ + Roundup Powermax®	5 + 1,260		
Saflufenacil + glyphosate[d]	Sharpen® + Roundup Powermax®	37 + 1,260		
Glufosinate + glyphosate[d]	Interline® + Roundup Powermax®	880 + 1,260		
2,4-d + paraquat[f]	Shredder™ 2,4-D LV4 + Gramoxone®	533 + 840		
Dicamba + paraquat[f]	Banvel® + Gramoxone®	280 + 840		
Halauxifen-methyl + paraquat[f]	Elevore™ + Gramoxone®	5 + 840		
Saflufenacil + paraquat[f]	Sharpen® + Gramoxone®	37 + 840		

[a]Manufacturer and location are only listed at first mention.
[b]Includes nonionic surfactant at 0.25% vol/vol.
[c]Includes methylated seed oil at 1% vol/vol.
[d]Includes ammonium sulfate at 10.2 g L^{-1}.
[e]Includes UAN at 4.67 L ha^{-1}.
[f]Includes crop oil concentrate at 2.34 L ha^{-1}.

demonstrated high correlation between plant height and biomass in various cereal and broadleaf cover crops (Bendig et al. 2014; Ehlert et al. 2008; Roth and Streit, 2018). In Blacksburg in 2018, data were not collected for oats and Austrian winter pea because of winterkill and poor stand establishment, respectively.

Data were analyzed by species. The model included herbicide as a fixed effect, with block and site-year serving as random effects, because this allows inferences about herbicide efficacy over a broad range of environments (Blouin et al. 2011; Carmer et al. 1989; Stephenson and Bond 2012). After an overall ANOVA indicated significant treatment differences, visible rating data were analyzed first with a means separation using Fisher protected LSD ($\alpha = 0.05$) of the treatments that included a single active ingredient and then using contrasts to compare the efficacy of using a single active ingredient compared with combinations including glyphosate or paraquat. The height data were analyzed by species, using the same model used for the visible rating data. Oat height data were square-root transformed to meet the model assumption of normality. Means comparison using the Dunnett method ($\alpha = 0.05$) was used to compare the height 4 WAA for each treatment to the nontreated check. Nontransformed data are presented, with means separation based on analysis of transformed data, where necessary. Visible control and height reduction of grasses resulting from the synthetic auxin herbicides and saflufenacil alone were excluded because of known lack of activity. Contrasts were not conducted for the grass cover crop species because of the amount of treatments that included an herbicide with known lack of acceptable activity. Data were analyzed in JMP (JMP Pro 13; SAS Institute, Cary, NC).

Results and Discussion

Grass Cover Crops

Visible control data were pooled across cereal grain cover crop species (i.e., winter wheat, winter barley, cereal rye, and winter oats) for response to herbicidally active treatments, including glyphosate, glufosinate, paraquat, and glufosinate plus glyphosate (Table 3). Saflufenacil was not included because control was less than 16% at 2 WAA and less than 5% at 4 WAA for cereal grains and annual ryegrass, which is well below an acceptable standard for control. Glyphosate provided the best control of the cereal grains at 2 WAA and 4 WAA (Table 3). Paraquat and glufosinate alone provided similar control of the cereal grains 2 WAA, but control declined for both 4 WAA. Annual ryegrass was best controlled with glyphosate 4 WAA, when 94% control was observed, despite glyphosate, paraquat, and glufosinate resulting in similar control (75% to 82%) 2 WAA (Table 3). The mix of glufosinate and glyphosate provided similar control to glyphosate alone at 4 WAA for both cereal grains and annual ryegrass.

Table 3. Visible estimates of control of grass cover crop species, including winter wheat, winter barley, cereal rye, winter oats, and annual ryegrass, from herbicidally active treatments across 3 site-years in Blacksburg and Holland, VA, in 2017 and 2018.

		2 WAA[a,b]		4 WAA	
Treatment	Rate	Cereal grains[c]	Annual ryegrass	Cereal grains	Annual ryegrass
	g ai or ae ha^{-1}	———————%———————			
Glyphosate	1,260	88 a	79	98 a	94 a
Paraquat	840	74 c	82	71 b	73 b
Glufosinate	880	77 c	75	62 c	56 c
Glufosinate + glyphosate	880 + 1,260	81 b	83	96 a	81 ab

[a]Numbers in each column that are not followed by the same letter are significantly different from according to Fisher protected LSD ($\alpha = 0.05$).
[b]Abbreviation: WAA, weeks after application.
[c]Data were pooled across species for analysis because herbicide by cover crop species interaction was not detected. Oats were excluded in Blacksburg in 2018 because of winterkill.

Similar studies also have indicated that glyphosate and combinations with glyphosate generally provided better control than other herbicide options for winter wheat, cereal rye, and annual ryegrass control (Cornelius and Bradley 2017; Palhano et al. 2018). Other research indicates that glyphosate provides better control of annual grasses compared with glufosinate (Culpepper et al. 2000; Whitaker et al. 2011).

Cover crop heights measured 4 WAA mostly corroborate visible control findings (Table 4). For the cereal cover crop species,

https://doi.org/10.1017/wet.2019.107 Published online by Cambridge University Press

Table 4. Percent reduction in grass cover crop heights compared to the nontreated check 4 weeks after application, averaged across 4 site-years in Blacksburg and Holland, VA, in 2017 and 2018.

	Winter wheat		Winter barley		Cereal rye		Winter oats[a]		Annual ryegrass	
Treatment	%	P value[b]	%	P value	%	P value	%	P value	%	P value
Glyphosate	60	<0.001	71	<0.001	75	<0.001	62	<0.001	63	<0.001
Paraquat	48	<0.001	39	<0.001	62	<0.001	54	<0.001	33	0.172
Glufosinate	44	<0.001	46	<0.001	55	<0.001	52	<0.001	33	0.174
2,4-D + glyphosate	73	<0.001	68	<0.001	78	<0.001	62	<0.001	84	<0.001
Dicamba + glyphosate	76	<0.001	65	<0.001	79	<0.001	63	<0.001	60	<0.001
Halauxifen-methyl + glyphosate	85	<0.001	70	<0.001	75	<0.001	63	<0.001	51	0.006
Saflufenacil + glyphosate	77	<0.001	65	<0.001	78	<0.001	60	<0.001	65	<0.001
Glufosinate + glyphosate	60	<0.001	64	<0.001	66	<0.001	52	<0.001	44	0.026
2,4-D + paraquat	58	<0.001	48	<0.001	65	<0.001	52	<0.001	47	0.015
Dicamba + paraquat	52	<0.001	48	<0.001	63	<0.001	52	<0.001	35	0.125
Halauxifen-methyl + paraquat	56	<0.001	49	<0.001	63	<0.001	54	<0.001	35	0.131
Saflufenacil + paraquat	52	<0.001	48	<0.001	65	<0.001	54	<0.001	42	0.034

[a]Oats were excluded in Blacksburg in 2018 because of winterkill. Oat height data were square-root transformed to meet the model assumption of normality. Nontransformed data are presented, with means separation based on analysis of transformed data.
[b]Significance of heights shown for each treatment when compared to the nontreated check using the Dunnett method ($\alpha = 0.05$).

Table 5. Visible estimates of control of legume cover crops (Austrian winter pea, crimson clover, and hairy vetch) and rapeseed to herbicide treatments, averaged across 4 site-years in Blacksburg and Holland, VA, in 2017 and 2018.

		Austrian winter pea[a]		Crimson clover		Hairy vetch		Rapeseed	
Treatment	Rate	2 WAA[b,c]	4 WAA	2 WAA	4 WAA	2 WAA	4 WAA	2 WAA	4 WAA
	g ai or ae ha^{-1}	%							
2,4-D	533	27 d	32 d	24 e	29 e	63 b	80 ab	20 c	34 b
Dicamba	280	54 bc	74 abc	37 de	46 cde	65 b	87 a	18 c	9 c
Halauxifen-methyl	5	47 c	70 bc	45 cd	49 cd	67 b	82 ab	6 d	3 c
Glyphosate	1,260	63 b	92 a	42 d	74 b	43 c	69 b	40 b	58 a
Saflufenacil	37	82 a	61 c	60 b	37 de	46 c	20 d	55 a	33 b
Paraquat	840	84 a	85 ab	59 bc	59 bc	65 b	44 c	57 a	51 a
Glufosinate	880	93 a	87 ab	89 a	92 a	89 a	81 ab	51 a	49 a

[a]Austrian winter pea was excluded in Blacksburg in 2018 because of poor stand establishment.
[b]Numbers in each column that are not followed by the same letter are significantly different according to Fisher's protected $LSD_{\alpha = 0.05}$.
[c]Abbreviation: WAA, weeks after application.

which include winter wheat, winter barley, cereal rye, and winter oats, all treatments reduced height in comparison to the nontreated check.

Annual ryegrass heights were affected differently than the other grass cover crops for the other treatments. Differences could not be detected in annual ryegrass height measured 4 WAA for paraquat, glufosinate, dicamba plus paraquat, and halauxifen-methyl plus paraquat compared to the nontreated check, but differences were detected among these treatments and the nontreated check for the other four grass cover crop species. Cornelius and Bradley (2017) reported that paraquat-based programs did not consistently control annual ryegrass.

Legume Cover Crops

Treatment was significant for the visible control ratings for all of the legume cover crop species, both 2 and 4 WAA. Each of the legume species in this study responded differently to individual herbicide treatments, but there was greater control from mixes with paraquat or glyphosate compared with the single active-ingredient treatments for each of the three species.

For Austrian winter pea, saflufenacil, paraquat, and glufosinate provided the best initial control: 82% to 93% control at 2 WAA (Table 5). Control from saflufenacil decreased to 61% at 4 WAA, showing recovery from initial injury. Glyphosate, paraquat, and glufosinate provided greater than 80% control at 4 WAA. Austrian winter pea control increased with both the addition of glyphosate and paraquat; however, control was similar with the addition of glyphosate or paraquat: 92% and 90% control, respectively (Table 6).

Cornelius and Bradley (2017) reported similar findings, showing that herbicide mixes containing paraquat controlled Austrian winter pea similarly or slightly better than mixes containing glyphosate. This is the only species in our study in which mixes with glyphosate did not increase control 4 WAA when compared to mixes with paraquat.

Glufosinate provided the best control for crimson clover at 2 and 4 WAA: 89% and 92% control, respectively (Table 5). Halauxifen-methyl, dicamba, 2,4-D, saflufenacil, and paraquat resulted in less than 60% crimson clover control at 4 WAA. No difference was detected in control between glyphosate and paraquat, but mixes with the addition of glyphosate provided more control 4 WAA than mixes with the addition of paraquat (Table 6).

The poor performance of auxin herbicides is in contrast to other research, which showed 91% and 100% control from 2,4-D and dicamba, respectively, and the 2019 Mid-Atlantic Weed Management Guide that suggests 2,4-D and dicamba should provide 75% to 85% control of crimson clover (McCurdy et al. 2013; Wallace

https://doi.org/10.1017/wet.2019.107 Published online by Cambridge University Press

Table 6. Contrast statements showing the visible control of legume cover crops, including Austrian winter pea, crimson clover, and hairy vetch, and rapeseed, averaged across 4 site-years in Blacksburg and Holland, VA, in 2017 and 2018.

Contrast			2 WAA[a]			4 WAA		
First term		Second term	First term, mean	Second term, mean	P value	First term, mean	Second term, mean	P value
Austrian winter pea[b]			———%———			———%———		
Single a.i.[a,c]	vs.	addition of glyphosate[d]	64	81	<0.001	71	92	<0.001
Single a.i.	vs.	addition of paraquat[e]	64	97	<0.001	71	90	<0.001
Addition of glyphosate	vs.	addition of paraquat	81	97	<0.001	92	90	0.6
Crimson clover								
Single a.i.	vs.	addition of glyphosate	51	61	<0.001	55	79	<0.001
Single a.i.	vs.	addition of paraquat	51	74	<0.001	55	72	<0.001
Addition of glyphosate	vs.	addition of paraquat	61	74	<0.001	79	72	0.035
Hairy vetch								
Single a.i.	vs.	addition of glyphosate	62	77	<0.001	66	87	<0.001
Single a.i.	vs.	addition of paraquat	62	83	<0.001	66	79	<0.001
Addition of glyphosate	vs.	addition of paraquat	77	83	0.014	87	79	0.022
Rapeseed								
Single a.i.	vs.	addition of glyphosate	35	44	<0.001	34	62	<0.001
Single a.i.	vs.	addition of paraquat	35	62	<0.001	34	56	<0.001
Addition of glyphosate	vs.	addition of paraquat	44	62	<0.001	62	56	0.03

[a]Abbreviation: WAA, weeks after application.
[b]Austrian winter pea was excluded in Blacksburg in 2018 due to poor stand establishment.
[c]Single active-ingredient treatments included 2,4-D, dicamba, halauxifen-methyl, glyphosate, glufosinate, paraquat, and saflufenacil.
[d]Addition of glyphosate to 2,4-D, dicamba, halauxifen-methyl, saflufenacil, and glufosinate.
[e]Addition of paraquat to 2,4-D, dicamba, halauxifen-methyl, and saflufenacil.

et al. 2019). McCurdy et al. (2013) cut crimson clover plants to 8 cm in the days before herbicide application, which would have made them much smaller than plants in this study, which were 35-cm tall at application. Multiple studies show that as plant size increases, herbicide efficacy decreases (Kegode and Fronning 2005; Klingaman et al. 1992; Sellers et al. 2009). In a similar study, in which crimson clover was 57 to 62 cm, dicamba and 2,4-D did not provide adequate control (Palhano et al. 2018).

Hairy vetch control from the three synthetic auxin herbicides (i.e., 2,4-D, dicamba, and halauxifen-methyl) and glufosinate ranged from 80% to 87%, greater than control afforded by saflufenacil, and paraquat: 20% and 44% control, respectively (Table 5). Although glyphosate and paraquat alone did not provide the best control of the single active-ingredient treatments, addition of glyphosate or paraquat increased control by 21% and 13%, respectively, over the single a.i. treatments (Table 6). Similar studies also reported adequate hairy vetch control from applications of 2,4-D and dicamba, as well as increased control from mixes containing glyphosate as compared to paraquat (Cornelius and Bradley 2017; Curran et al. 2015).

All herbicide treatments led to a reduction in height as compared with the nontreated check for all legume cover crop species with the exception of 2,4-D on Austrian winter pea, which is consistent with the visible control data that all herbicides had some effect on the legume cover crop species. Of the legume cover crop species, Austrian winter pea had the greatest reduction in height, with most treatments reducing height by 82% to 100%. The reduction in height was not as severe in the other two cover crop species; generally, there was a greater reduction in height with herbicide mixes compared with the single active-ingredient treatments (Table 7).

Rapeseed

Treatment was significant for the visible control ratings for rapeseed 2 and 4 WAA. The greatest control observed 4 WAA ranged from 49% to 58%, from glufosinate, paraquat, and glyphosate applications, which is not a commercially acceptable level of control (Table 5). Poor control resulted from all the synthetic auxin herbicides, but there was a difference between control from 2,4-D (34% control) compared with dicamba and halauxifen-methyl (<10% control) 4 WAA. Saflufenacil had similar control to paraquat and glufosinate 2 WAA, and control decreased 4 WAA, indicating that rapeseed was beginning to recover from the herbicide application; this trend was noted across all broadleaf cover crop species. Adding glyphosate or paraquat increased control compared with the single active-ingredient treatments (Table 6). At 4 WAA, the addition of glyphosate had greater control than the addition of paraquat: 62% and 56%, respectively. However, this level of rapeseed control before cash-crop planting is not satisfactory. Rapeseed height was reduced by all herbicide treatments except halauxifen-methyl, which aligns with the visible control ratings 4 WAA (Table 7).

Rapeseed is a difficult cover crop species to control late in the spring. Palhano et al. (2018) reported a maximum control of 71% from treatments in their study and maximum control of 55% from treatments also used in this study. Askew et al. (2019) reported less than 38% control from herbicides on rapeseed that was the same size as that in this experiment. Control improved on rapeseed half that size, 52 cm, reaching 68% from glyphosate (Askew et al. 2019). To effectively terminate rapeseed, herbicide applications need to be made at an earlier growth stage when plants are smaller. Beckie et al. (2004) reported greater success when controlling volunteer rapeseed with 2,4-D at a two- to three-leaf stage compared with a five- to six-leaf stage. In our study, rapeseed had reached 100 cm in height and was flowering at the time of application. When using rapeseed as a cover crop, termination as early as in the Beckie et al. (2004) study is impractical because the plants would not get large enough to provide weed-suppression benefits.

Practical Implications

As implementation of cover crops is becoming more prevalent, proper termination of the cover crop is important to prevent

Table 7. Percent reduction in broadleaf cover crop heights compared to the nontreated check 4 weeks after application, averaged across 4 site-years in Blacksburg and Holland, VA, in 2017 and 2018.

	Austrian winter pea[a]		Crimson clover		Hairy vetch		Rapeseed	
Treatment	%	P value[b]	%	P value	%	P value	%	P value
2,4-D	26	0.283	36	<0.001	76	<0.001	32	<0.001
Dicamba	62	<0.001	53	<0.001	81	<0.001	19	0.011
Halauxifen-methyl	82	<0.001	58	<0.001	78	<0.001	13	0.23
Glyphosate	97	<0.001	51	<0.001	80	<0.001	51	<0.001
Saflufenacil	91	<0.001	42	<0.001	47	<0.001	47	<0.001
Paraquat	91	<0.001	44	<0.001	61	<0.001	49	<0.001
Glufosinate	82	<0.001	71	<0.001	85	<0.001	54	<0.001
2,4-D + glyphosate	100	<0.001	62	<0.001	80	<0.001	58	<0.001
Dicamba + glyphosate	97	<0.001	60	<0.001	95	<0.001	56	<0.001
Halauxifen-methyl + glyphosate	97	<0.001	60	<0.001	80	<0.001	52	<0.001
Saflufenacil + glyphosate	100	<0.001	49	<0.001	73	<0.001	63	<0.001
Glufosinate + glyphosate	94	<0.001	76	<0.001	92	<0.001	63	<0.001
2,4-D + paraquat	100	<0.001	58	<0.001	93	<0.001	58	<0.001
Dicamba + paraquat	94	<0.001	67	<0.001	92	<0.001	54	<0.001
Halauxifen-methyl + paraquat	100	<0.001	60	<0.001	86	<0.001	52	<0.001
Saflufenacil + paraquat	97	<0.001	53	<0.001	80	<0.001	54	<0.001

[a]Austrian winter pea was excluded in Blacksburg in 2018 because of poor stand establishment.
[b]Significance of heights shown for each treatment when compared to the nontreated check using the Dunnett method ($\alpha = 0.05$).

interference of the cover crop in the cash crop that follows it. The results of this study indicate herbicide selection to terminate cover crops depends heavily on the species grown, because these cover crop species responded differently to herbicides, especially the legumes. Overall, grass cover crop species, including winter wheat, winter barley, cereal rye, winter oats, and annual ryegrass, were best controlled by glyphosate and mixes containing glyphosate. However, for legume species, herbicides selection should include glyphosate or paraquat and be selected on the basis of which individual herbicide has better activity on the specific legume species. Cover crops that are difficult to control, like rapeseed, which was not adequately controlled in this study by any single active-ingredient treatment or mix, need to be terminated earlier when the plants are smaller or by alternative methods.

Acknowledgements. We thank Shawn Beam, Susannah Gonia, and Ranjeet Randhawa for aiding in data collection. We are grateful to the Virginia Corn Board, the Virginia Agricultural Experiment Station, and the Hatch Program of the National Institute of Food and Agriculture, U.S. Department of Agriculture, for providing funding for this research. No conflicts of interest have been declared.

References

Askew MC, Cahoon CW Jr, Flessner ML, VanGessel MJ, Langston DB Jr, Ferebee JH IV (2019) Chemical termination of cover crop rapeseed. Weed Technol 33:686–692

Beckie HJ, Nair GSH, Warwick SI, Johnson E (2004) Multiple herbicide-resistant canola can be controlled by alternative herbicides. Weed Sci 52:152–157

Bendig J, Bolten A, Bennertz S, Broscheit J, Eichfuss S, Bareth G (2014) Estimating biomass of barley using crop surface models (CSM) derived from UAV-based RGB imaging. Remote Sens 6:10395–10412

Blouin DC, Webster EP, Bond JA (2011) On the analysis of combined experiments. Weed Technol 25:165–169

Burket, JZ, Hemphill DD, Dick RP (1997) Winter cover crops and nitrogen management in sweet corn and broccoli rotations. HortScience 32:664–668

Carmer SG, Nyquist WE, Walker WM (1989) Least significant differences for combined analyses of experiments with two- or three-factor treatment designs. Agron J 81:665–672

Clarke A, ed (2007) Managing Cover Crops Profitably. 3rd edn. College Park, MD: Sustainable Agriculture Research and Education. Pp 9–33

Cornelius CD, Bradley KW (2017) Herbicide programs for the termination of various cover crop species. Weed Technol 31:514–522

Crespo RJ, Wingeyer AB, Kruger GR, Riggins CW, Tranel PJ, Bernards ML (2017) Multiple-herbicide resistance in a 2,4-D-resistant waterhemp (*Amaranthus tuberculatus*) population from Nebraska. Weed Sci 65:743–754

[CTIC] Conservation Technology Information Center (2017) Report of the 2016-17 National Cover Crop Survey. Joint publication of the Conservation Technology Information Center, the North Central Region Sustainable Agriculture Research and Education Program, and the American Seed Trade Association. https://www.sare.org/content/download/79876/1402074/2016-2017_Cover_Crop_Survey_Report.pdf?inlinedownload=1. Accessed: March 3, 2019

Culpepper AS, York AC, Batts RB, Jennings KM (2000) Weed management in glufosinate- and glyphosate-resistant soybean (*Glycine max*). Weed Technol 14:77–88

Curran WS, Wallace JM, Mirsky S, Crockett B (2015) Effectiveness of herbicides for control of hairy vetch (*Vicia villosa*) in winter wheat. Weed Technol 29:509–518

Dabney SM, Delgado JA, Reeves DW (2001) Using winter cover crops to improve soil and water quality. Commun Soil Sci Plant Anal 32:1221–1250

Ehlert D, Horn HJ, Adamek R (2008) Measuring crop biomass density by laser triangulation. Comput Electron Agr 61:117–125

Frans R, Talbert R, Marx D, Crowley H (1986) Experimental design and techniques for measuring and analyzing plant responses to weed control practices. Pages 29–46 *in* Camper ND, ed. Research Methods in Weed Science, 3rd edn. Westminster, CO: Southern Weed Science Society

Heap I (2019) International survey of herbicide resistant weeds. http://www.weedscience.org Accessed: March 3, 2019

Holt JS, LeBaron HM (1990) Significance and distribution of herbicide resistance. Weed Technol 4:141–149

Kegode GO, Fronning BE (2005) *Artemisia biennis* (biennial wormwood) control is influenced by plant size and weed flora at time of herbicide application. Crop Prot 24:915–920

Klingaman TE, King CA, Oliver LR (1992) Effect of application rate, weed species, and weed stage of growth on imazethapyr activity. Weed Sci 40:227–232

Lawson A, Cogger C, Bary A, Fortuna A (2015) Influence of seeding ratio, planting date, and termination date on rye-hairy vetch cover crop mixture performance under organic management. PLoS ONE 10(6):e0129597

McCurdy JD, McElroy JS, Flessner ML (2013) Differential response of four *Trifolium* species to common broadleaf herbicides: implications for mixed grass-legume swards. Weed Technol 27:123–128

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2009) Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J 101:1589–1596

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller crimper. Weed Sci 59:380–389

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the Eastern United States. Weed Technol 27:193–203

Mischler R, Duiker SW, Curran WS, Wilson D (2010) Hairy vetch management for no-till organic corn production. Agron J 102:355–362

Miville D, Leroux GD (2018) Rolled winter rye-hairy vetch cover crops for weed control in no-till pumpkin. Weed Technol 32:251–259

Owen LN, Mueller TC, Main CL, Bond J, Steckel LE (2011) Evaluating rates and application timings of saflufenacil for control of glyphosate-resistant horseweed (*Conyza canadensis*) prior to planting no-till cotton. Weed Technol 25:1–5

Palhano MG, Norsworthy JK, Barber T (2018) Evaluation of chemical termination options for cover crops. Weed Technol 32:227–235

Roth L, Streit B (2018) Predicting cover crop biomass by lightweight UAS-based RGB and NIR photography: an applied photogrammetric approach. Precis Agric 19:93–114

Sellers BA, Ferrell JA, MacDonald GE, Kline WM (2009) Dogfennel (*Eupatorium capillifolium*) size at application affects herbicide efficacy. Weed Technol 23:247–250

Stephenson DO, Bond JA (2012) Evaluation of thiencarbazone-methyl- and isoxaflutole-based herbicide programs in corn. Weed Technol 26:37–42

Teasdale JR (1996) Contribution of cover crops to weed management in sustainable agricultural systems. J Prod Agric 9: 475–479

[USDA] U.S. Department of Agriculture (2015) Virginia NRCS Cover Crop Planning Manual 1.0. https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf. Accessed: September 13, 2018

[USDA ERS] U.S. Department of Agriculture, Economic Research Service (2012) Distribution of cover crop use in the contiguous U.S., 2012. https://www.ers.usda.gov/webdocs/charts/81674/percent_of_cropland_acres_with_cover_crops_by_county__2012_rred-01.png?v=8661.2. Accessed: March 3, 2019

Waggoner BS, Mueller TC, Bond JA, Steckel LE (2011) Control of glyphosate-resistant horseweed (*Conyza canadensis*) with saflufenacil tank mixtures in no-till cotton. Weed Technol 25:310–315

Wallace J, Lingenfelter D, VanGessel M, Johnson Q, Vollmer K, Besancon T, Flessner M, Chandran R (2019) 2019 Mid-Atlantic Field Crop Weed Management Guide. University Park, PA: Penn State Agricultural Communications and Marketing. 55 p

Wayman S, Cogger C, Benedict C, Burke I, Collins D, Bary A (2014) The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renew Agr Food Syst 30:450–460

Westgate LR, Singer JW, Kohler KA (2005) Method and timing of rye control affects soybean development and resource utilization. Agron J 97:806–816

Whitaker JR, York AC, Jordan DL, Culpepper AS (2011) Weed management with glyphosate- and glufosinate-based systems in PHY 485 WRF Cotton. Weed Technol 25:183–191

Yu Q, Powles S (2014) Metabolism-based herbicide resistance and cross-resistance in crop weeds: a threat to herbicide sustainability and global crop production. Plant Physiol 166:1106–1118

Zimmer M, Young B, Johnson W (2018a) Herbicide programs utilizing halauxifen-methyl for glyphosate-resistant horseweed (*Conyza canadensis*) control in soybean. Weed Technol 32:659–664

Zimmer M, Young B, Johnson W (2018b) Weed control with halauxifen-methyl applied alone and in mixtures with 2,4-D, dicamba, and glyphosate. Weed Technol 32:597–602