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Chemical termination of cover crop rapeseed

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Abstract

Rapeseed is a popular cover crop choice due to its deep-growing taproot, which creates soil macropores and increases water infiltration. Brassicaceae spp. that are mature or at later growth stages can be troublesome to control. Experiments were conducted in Delaware and Virginia to evaluate herbicides for terminating rapeseed cover crops. Two separate experiments, adjacent to each other, were established to evaluate rapeseed termination by 14 herbicide treatments at two timings. Termination timings included an early and late termination to simulate rapeseed termination prior to planting corn and soybean, respectively, for the region. At three locations where rapeseed height averaged 12 cm at early termination and 52 cm at late termination, glyphosate + 2,4-D was most effective, controlling rapeseed 96% 28 d after early termination (DAET). Paraquat + atrazine + mesotrione (92%), glyphosate + saflufenacil (91%), glyphosate + dicamba (91%), and glyphosate (86%) all provided at least 80% control 28 DAET. Rapeseed biomass followed a similar trend. Paraquat + 2,4-D (85%), glyphosate + 2,4-D (82%), and paraquat + atrazine + mesotrione (81%) were the only treatments that provided at least 80% control 28 d after late termination (DALT). Herbicide efficacy was less at Painter in 2017, where rapeseed height was 41 cm at early termination, and 107 cm at late termination. No herbicide treatments controlled rapeseed >80% 28 DAET or 28 DALT at this location. Herbicide termination of rapeseed is best when the plant is small; termination of large rapeseed plants may require mechanical of other methods beyond herbicides.

Introduction

Cover crops have become an integral part of many cropping systems and are planted on more than 404,686 ha in the United States (USDA 2012). Benefits of cover crops include weed suppression, enhanced soil quality, reduced soil erosion, and increased cash crop yield (Chen and Weil 2011; Power and Doran 1988; Reddy et al. 2003; Smith et al. 1987; Teasdale 1996; Williams et al. 1998). A critical benefit of cover crops is erosion control during the winter months (Van Rijn 2011). Rapid establishment and biomass accumulation enables brassicas to reduce soil erosion from late fall to spring (Bowman et al. 2007). Winter-planted rapeseed can provide up to 80% ground cover, which is essential for reducing soil erosion (Eberlein et al. 1998). Cover crops help diversify weed management programs but do not provide season-long weed control or eliminate the need for herbicides in cash crop management (Reddy et al. 2003; Teasdale 1996). However, combinations of cover crops and PRE herbicides have been proven to effectively control weeds (Norsworthy et al. 2011).

Commonly used cover crops include legumes, cereals, and Brassicaceae species in both monocultures and mixtures (Brennan and Smith 2005; Mannering et al. 2007). Monoculture cover crops are more popular with producers because of their ease of planting and termination. Selecting a termination method is easier when facing only one species. Brassica species are multifunctional cover crops and a popular choice for producers because of their rapid growth, large taproot, and frost tolerance (Chen et al. 2007). However, some brassica species are susceptible to freezing temperatures. For example, tillage radish (*Raphanus sativus* L.), if planted early, can grow large, increasing its susceptibility to freezing temperatures. Tillage radish susceptibility to freezing temperatures is also dependent upon tuber depth; tubers 7 to 10 cm above the soil surface are more susceptible to freezing temperatures. However, tubers that are closer to the soil surface and more insulated by the soil may survive the winter, mature, and reach reproductive stage. At this stage, tillage radish is difficult to control with herbicides (Roberts 2015).

Table 1. Locations, soil descriptions, and herbicide application dates.

Location	Year	Soil series	Soil texture	pH	Organic matter[d]	Planting date	Early termination date	Late termination date
Painter, VA	2017	Bojac[a]	Sandy loam	6.4	1.0%	September 26, 2016	March 20	April 10
Georgetown, DE	2017	Hammonton[b]	Loamy sand	5.9	1.3%	October 7, 2016	April 5	April 17
Painter, VA	2018	Bojac	Sandy loam	6.4	1.0%	September 28, 2017	March 17	April 6
Georgetown, DE	2018	Rosedale[c]	Loamy sand	5.5	1.1%	October 10, 2017	April 11	April 26

[a]Coarse-loamy, mixed, semiactive, thermic Typic Hapludults.
[b]Coarse-loamy, siliceous, semiactive, mesic Aquic Hapludults.
[c]Loamy, siliceous, semiactive, mesic Arenic Hapludults.
[d]Percent organic matter determined according to Dean (1974).

Mid-Atlantic producers are interested in rapeseed as a cover crop for its taproot, which creates soil macropores that reduce soil compaction and in turn increase water infiltration (Alcantara et al. 2009; Wolfe 2007). Soil compaction has become problematic in response to increased use of heavy machinery and adoption of conservation tillage (Hamza and Anderson 2005; Servadio et al. 2005). Brassica cover crops are capable of alleviating soil compaction. Taproots grow deeply and rapidly during the fall while the soil is relatively moist, allowing them to penetrate compacted layers, unlike fibrous roots of other commonly grown cover crops (Chen and Weil 2010; Williams and Weil 2004). The rapeseed taproot is cylindrical and fast-growing, allowing it to act as a "biodrill" that can reach one or more meters into the soil (Virginia NRCS 2015). Producers in the midwestern United States utilize brassica species to scavenge residual nitrogen left after cash crop harvest (Gieske et al. 2016). Gieske et al. (2016) found that brown mustard (*Brassica juncea* L.), rapeseed, radish (*Raphanus sativus* L.), and white mustard (*Sinapis alba* L.) all accumulate comparable amounts of nitrogen and biomass.

Compared to tillage radish, which is often used as a cover crop to reduce soil compaction, the planting date for rapeseed is more flexible. In Virginia, the Natural Resource Conservation Service suggests seeding tillage radish during August or September while corn and soybean remain in the field (Virginia NRCS 2015). However, rapeseed can be planted from September through November, giving producers flexibility to plant a brassica cover crop after cash crop harvest (Virginia NRCS 2015).

Producers are also interested in brassica cover crops for their potential as biofumigants (Haramoto and Gallandt 2005). Glucosinolates, produced in great quantity by some brassica species, are sulfur-containing molecules that when hydrolyzed form toxic compounds (e.g., isothiocyanates) that are capable of controlling some soilborne organisms such as nematodes, fungi, and weeds (Bell and Muller 1973; Blau et al. 1978; Brown and Morra 1997; Haramoto and Gallandt 2005; Mojtahedi et al. 1993; Muehlchen et al. 1990; Petersen et al. 2001; Teasdale and Taylorson 1986; Wolf et al. 1984). 'Caliente' mustard, a mixture of white and brown mustard, is the main species of interest for production of isothiocyanates; however, research has determined that rapeseed has a similar ability to inhibit weed seed germination (Bangarwa et al. 2009; Brown and Morra 1996). To maximize biofumigant activity of rapeseed and other brassica species, special management is required. This includes careful timing of termination, thorough chopping of residue to release the biofumigant, and subsequent incorporation of the residue into the soil (Virginia NRCS 2015).

As a result of its high growth rate and pod-shattering characteristics (Krato and Petersen 2012), rapeseed can be a problem for the subsequent crop when termination is unsuccessful. Although rapeseed is a useful cover crop, plants that survive termination can compete with cash crops. Uncontrolled weedy brassica species like wild mustard (*Sinapis arvensis* L. subsp. *arvensis*) can reduce wheat yields up to 62% (Behdarvand et al. 2013). Specifically, previous research determined that volunteer rapeseed can reduce wheat yield by as much as 49% (O'Donovan et al. 2008). Prior to cash crop establishment, producers have numerous chemical options available for use before plant burndown. However, research is limited on efficacy of herbicides for rapeseed termination (AOF 2014). However, control of other brassica species such as wild mustard and wild radish (*Raphanus raphanistrum* L.) is better understood (DiTomaso et al. 2013; Ferrell et al. 2015). Timing is critical when controlling these species (Cahoon 2016; Culpepper 2009; DiTomaso et al. 2013). Recommendations for most herbicides are to apply when wild mustard and wild radish are small and rapidly growing or while still in the rosette stage (DiTomaso et al. 2013). However, terminating a rapeseed cover crop at these stages would defeat its purpose as a cover crop. Small wild radish (<15 cm in height) control by 2,4-D is excellent (>90%); control declines to approximately 70% when applied to wild radish 30 cm or taller, and once wild radish begins to flower, control by 2,4-D is unacceptable (<40%) (Ferrell et al. 2015). Culpepper (2009) reported similar wild radish control with 2,4-D in Georgia. Wild mustard and wild radish control in the mid-Atlantic region can typically be accomplished by applying 2,4-D in March or early April; other options are available depending on rotation restrictions and cash crop choice (Cahoon 2016).

The objective of this research was to evaluate various herbicides and herbicide combinations for termination of rapeseed cover crop prior to simulated planting of corn and soybean.

Materials and Methods

Experiments were conducted at the Eastern Shore Agriculture Research and Extension Center near Painter, VA (37.5892°N, 75.8226°W) and at the Carvel Research and Education Center near Georgetown, DE (38.6419°N, 75.4603°W) during 2016–2017 and 2017–2018. Soil descriptions are listed in Table 1. The experimental design was a randomized complete block with treatments replicated four times. Plot size in both Virginia and Delaware was 3 m long by 2 m wide.

Rapeseed cultivar 'Dwarf Essex' was planted at each site on dates listed in Table 1. Rapeseed was drilled at 6.7 kg ha^{-1} into a conventional-tillage field in Virginia. Trifuralin (Treflan® 4L; Corteva AgroSciences, Indianapolis, IN) was applied at 560 g ai ha^{-1} along with 56 kg ha^{-1} of nitrogen, immediately followed by shallow incorporation with a rototiller just prior to planting in Virginia in 2017; no additional nitrogen was added during 2018. In Delaware, rapeseed was drilled into a no-tillage field,

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Table 2. Herbicide treatments and rates used in experiments.[a]

Herbicide treatment	Rate
	g ae or ai ha^{-1}
2,4-D (Low Rate, LR)	532
2,4-D (High Rate, HR)	1,064
Dicamba (LR)	280
Dicamba (HR)	560
Glyphosate[b]	1,266
Saflufenacil[c,d]	50
Paraquat[e]	840
Glufosinate[b]	885
Glyphosate + 2,4-D LR[b]	1,266 + 532
Glyphosate + dicamba LR[b]	1,266 + 280
Paraquat + 2,4-D LR[e]	840 + 532
Glyphosate + glufosinate[b]	1,266 + 885
Paraquat + mesotrione + atrazine[d,e]	840 + 105 + 560
Glyphosate + saflufenacil[c,d]	1,266 + 50

[a]Source information for herbicides can be found in Table 3.
[b]Ammonium sulfate applied 1% w/v.
[c]Methylated seed oil applied 1% v/v.
[d]30% Urea + ammonium nitrogen applied 0.25% v/v.
[e]Crop oil concentrate applied 1% v/v.

Table 3. Source information for herbicides used in experiments.[a]

Herbicides	Trade name	Manufacturer
Atrazine	Aatrex	Syngenta
Dicamba	Banvel	BASF
Glufosinate	Liberty	Bayer CropScience
Glyphosate	Roundup PowerMAX	Monsanto
Mesotrione	Callisto	Syngenta
Paraquat	Gramoxone	Syngenta
Saflufenacil	Sharpen	BASF
2,4-D	Weedone	Nufarm, Inc.
Ammonium sulfate	Spray Grade Ammonium Sulfate	Fertizona
Methylated seed oil	MSO Concentrate	Loveland Products, Inc.
Crop oil concentrate	Herbimax	Loveland Products, Inc.

[a]Specimen labels for each product and mailing addresses and website addresses of each manufacturer can be found at www.cdms.net.

and paraquat (Gramoxone® SL; Syngenta, Greensboro, NC) was applied at 840 g ai ha^{-1} prior to planting.

Two separate experiments, adjacent to each other, were established to evaluate rapeseed termination by 14 herbicide treatments at two timings. Termination timings included an early and late termination to simulate rapeseed termination prior to planting corn and soybean, respectively, for the region. Termination dates can be found in Table 1. Herbicide treatments and rates can be found in Table 2 and source information in Table 3. Additionally, a nontreated control was included for comparison. The lowest rate of 2,4-D and dicamba was used in combination with other herbicides. In Virginia during 2017, rapeseed height averaged 41 cm at early termination and 107 cm at late termination, whereas rapeseed height averaged 10 and 38 cm at early and late termination, respectively, in Virginia during 2018. In Delaware during 2017, early and late termination treatments were applied when rapeseed height averaged 13 and 76 cm, respectively, and when rapeseed height averaged 13 and 41 cm during 2018.

Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (AIXR 11002 TeeJet® Air Induction XR flat-spray nozzles; TeeJet Technologies, Wheaton, IL). In Virginia, applications were made at 140 L ha^{-1} of solution delivered at 165 kPa. In Delaware, applications were made at 186 L ha^{-1} of solution delivered at 214 kPa.

Visible control of rapeseed was recorded 7, 14, and 28 d after early termination (DAET) and 7, 14, and 28 d after late termination (DALT) using a 0 to 100% scale, where 0% = no control and 100% = complete control. Rapeseed aboveground biomass was harvested from a 0.25-m^2 section at 28 d after each termination timing, dried for 28 d in a dryer, and then weighed to determine rapeseed dry biomass. Data for rapeseed biomass were extrapolated to present biomass as kilograms per hectare.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS software (version 9.4; SAS Institute Inc., Cary, NC). Herbicide treatment was treated as a fixed factor, whereas location and replications were treated as random. Rapeseed was much larger at both termination timings at Virginia during 2017. Exclusion of Virginia 2017 data allowed for pooling across all other locations. Therefore, data are presented pooled across Delaware 2017 and 2018 and Virginia 2018, with data for Virginia 2017 presented separately. The main effect of herbicide treatment was significant for both termination timings at Virginia 2017 and pooled locations. Means were separated using Fisher's protected LSD at $P = 0.05$ when appropriate. Data for nontreated plots were excluded from analyses, except in a separate analysis for which Dunnett's procedure (Dunnett 1955) was used to compare rapeseed biomass in the nontreated plot to all other treatments.

Results and Discussion

Rapeseed was much smaller at Delaware and Virginia in 2018. At these locations, rapeseed height averaged 12 cm at early termination compared to 41 cm at Virginia in 2017. At late termination, rapeseed averaged 52 cm at Delaware and Virginia in 2018, whereas rapeseed at Virginia in 2017 was 107 cm tall. At-planting nitrogen applied in 2017, coupled with a warm February, are probably responsible for large rapeseed at Virginia in 2017. Early-termination and late-termination timings were separated by 12, 15, 21, and 20 d at Delaware 2017, Delaware 2018, Virginia 2017, and Virginia 2018, respectively. During that time, rapeseed increased approximately four-fold in size at Delaware and Virginia in 2018 and three-fold at Virginia in 2017.

Early-Termination Experiment

Delaware and Virginia 2018

As expected, herbicides terminated rapeseed more effectively when rapeseed was shorter. At Delaware and Virginia 2018, rapeseed control by most herbicide treatments was poor 7 DAET; paraquat alone or paraquat combinations controlled rapeseed 60% or better, whereas rapeseed termination by all other herbicide treatments was ≤46% (Table 4). Rapeseed control generally improved at later rating dates. Systemic herbicide activity can be slow, especially when air temperatures are cool during late winter and early spring (Caseley 1983). Given sufficient time to work, with the exception of dicamba alone, rapeseed termination ranged from 67% to 96% at 28 DAET at Delaware and Virginia 2018. Of herbicides applied alone, glyphosate (86%) was most effective in terminating rapeseed 28 DAET. Although less than glyphosate, rapeseed control by 2,4-D, saflufenacil, paraquat, and glufosinate were moderately effective, controlling the cover crop 67% to 72%, whereas rapeseed termination by dicamba was poor (24% to 40%). Adding 2,4-D low rate (LR), dicamba LR, and saflufenacil to glyphosate improved efficacy 5% to 10% compared to glyphosate alone. However, glyphosate + glufosinate was 14% less effective than glyphosate

Table 4. Rapeseed control 7, 14, and 28 d after early termination (DAET) and rapeseed biomass 28 DAET in Georgetown, DE, 2017 and 2018, and Painter, VA, 2018.[a,b]

Herbicide treatment[c,d]	Rapeseed control						Rapeseed biomass[e]	
	7 DAET		14 DAET		28 DAET			
	%						kg ha^{-1}	
2,4-D LR	27	G	43	E	67	E	800	BC
2,4-D HR	37	F	46	E	70	DE	880	B
Dicamba LR	19	H	22	G	24	G	2,080	A*
Dicamba HR	26	G	29	F	40	F	1,720	A*
Glyphosate	37	F	57	CD	86	C	600	BC
Saflufenacil	41	E	70	B	72	D	640	BC
Paraquat	67	AB	69	B	68	E	600	BC
Glufosinate	35	F	61	C	67	E	440	BC
Glyphosate + 2,4-D LR	38	EF	70	B	96	A	600	BC
Glyphosate + dicamba LR	36	F	66	B	91	B	480	BC
Paraquat + 2,4-D LR	70	A	76	A	83	C	440	BC
Glyphosate + glufosinate	37	F	56	D	72	D	480	BC
Paraquat + mesotrione + atrazine	60	C	76	A	92	AB	280	C
Glyphosate + saflufenacil	46	D	78	A	91	B	280	C
Nontreated	–		–		–		2,000	

[a]Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b]Rapeseed height averaged 12 cm at time of early termination at Georgetown, DE during 2017 and 2018 and at Painter, VA during 2018.
[c]Abbreviations: HR, high rate; LR, low rate.
[d]2,4-D LR, 2,4-D HR, dicamba LR, dicamba HR, glyphosate, saflufenacil, paraquat, glufosinate, glyphosate + 2,4-D LR, glyphosate + dicamba LR, paraquat + 2,4-D LR, glyphosate + glufosinate, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil were applied at 532, 1,064, 280, 560, 1,266, 50, 840, 885, 1,266 + 532, 1,266 + 280, 840 + 532, 1,266 + 885, 840 + 105 + 560, and 1,266 + 50 g ae or ai ha^{-1}, respectively.
[e]Means for rapeseed biomass followed by an asterisk (*) are not different from the nontreated according to Dunnett's procedure at P = 0.05.

alone. Cahoon and others (2015) reported that large crabgrass (*Digitaria sanguinalis* L.) and goosegrass (*Eleusine indica* L.) control was reduced when glyphosate was co-applied with glufosinate compared to glyphosate alone. Similar to how 2,4-D LR improved rapeseed control by glyphosate, 2,4-D + paraquat was 15% more effective than paraquat alone. Curran et al. (2018) reported that 2,4-D added to paraquat improves cutleaf evening-primrose (*Oenothera laciniata* Hill), horseweed (*Conyza canadensis* L.), and brassica species control relative to paraquat alone. Comparing all herbicide treatments 28 DAET, glyphosate + 2,4-D LR (96%) and paraquat + mesotrione + atrazine (92%) were most effective.

In general, rapeseed biomass 28 DAET mirrored visible rapeseed control at the same time. Rapeseed biomass in nontreated plots averaged 2,000 kg ha^{-1}. All treatments, except dicamba (1,702 to 2,080 kg ha^{-1}) reduced rapeseed biomass relative to the nontreated. All other herbicide treatments reduced rapeseed biomass 56% to 86% compared to the nontreated.

Virginia 2017

Rapeseed termination was generally poor at Virginia during 2017 and was probably due to rapeseed size. Previous research noted control of wild radish and wild mustard, weeds related to rapeseed, is more difficult as the weeds mature (Cahoon 2016; Culpepper 2009; DiTomaso et al. 2013; Ferrell et al. 2015). Ferrell et al. (2015) reported that wild radish ≤15 cm tall was controlled ≥90% by 2,4-D; control of the weed when 30 cm tall or flowering by 2,4-D was approximately 70% and 50% or less, respectively. In Virginia 2017, rapeseed was 41 cm tall at early termination.

Like Delaware and Virginia in 2018, paraquat (58%), paraquat + mesotrione + atrazine (62%), and paraquat + 2,4-D (67%) were more effective than other herbicide treatments 7 DAET at Virginia 2017 (Table 5). Although rapeseed control improved later in the season, no herbicide treatment terminated the cover crop greater than 78% at 28 DAET, whereas at Delaware and Virginia 2018, the following six herbicide treatments controlled rapeseed at least 83%: glyphosate alone, glyphosate + 2,4-D, glyphosate + dicamba, glyphosate + saflufenacil, paraquat + 2,4-D, and paraquat + mesotrione + atrazine. At Virginia 2017, the higher rate of 2,4-D was 17% more effective than 2,4-D LR. Like other locations, 2,4-D LR improved efficacy of glyphosate 39% at 28 DAET; glyphosate + 2,4-D (78%) was the most effective herbicide treatment at Virginia 2017. However, paraquat + 2,4-D was no more effective than paraquat alone at the same timing. Dicamba (10% to 12%) was less effective than 2,4-D and did not improve glyphosate efficacy.

As further evidence of taller rapeseed at Virginia 2017 compared to other locations, rapeseed biomass in nontreated plots (8,160 kg ha^{-1}) was approximately four-fold greater than at Delaware and Virginia 2018 (Tables 4 and 5). Most treatments did reduce rapeseed biomass relative to the nontreated; however, reductions were minimal, ranging 37% to 59%.

Late-Termination Experiment

Delaware and Virginia 2018

Rapeseed was larger at late-termination dates, and control was less with the late-termination applications. No herbicide treatment controlled the cover crop better than 57% at 7 DALT (Table 6). Similar to early termination, herbicide treatments containing paraquat (39% to 57%) terminated rapeseed best at 7 DALT. Surprisingly, at this timing, saflufenacil (42%) and glyphosate + saflufenacil (39%) controlled rapeseed similar to paraquat + mesotrione + atrazine (39%). Again, rapeseed termination improved with time. Rapeseed control by all herbicide treatments, except dicamba, ranged 30% to 71% 14 DALT compared to 26% to 57% control at 7 DALT.

Rapeseed termination was even greater 28 DALT. At this time, saflufenacil, glufosinate, 2,4-D LR, 2,4-D HR, paraquat, and glyphosate controlled rapeseed 42%, 43%, 45%, 55%, 63%, and 68%,

Table 5. Rapeseed control 7, 14, and 28 d after early termination (DAET) and rapeseed biomass 28 DAET in Painter, VA, 2017.[a,b]

Herbicide treatment[c,d]	Rapeseed control 7 DAET		14 DAET		28 DAET		Rapeseed biomass[e]	
	%						kg ha^{-1}	
2,4-D LR	29	BCD	34	EF	40	E	4,280	AB
2,4-D HR	39	B	45	D	57	CD	5,080	AB
Dicamba LR	12	FG	10	G	10	F	6,040	A*
Dicamba HR	14	EFG	13	G	12	F	5,080	AB
Glyphosate	10	G	27	F	39	E	5,240	AB
Saflufenacil	23	CDE	33	EF	20	F	3,640	B
Paraquat	58	A	65	C	62	BC	3,320	B
Glufosinate	20	CDEF	68	BC	46	DE	3,680	B
Glyphosate + 2,4-D LR	30	B	45	D	78	A	3,760	B
Glyphosate + dicamba LR	12	FG	26	F	35	E	5,240	AB
Paraquat + 2,4-D LR	67	A	75	AB	63	BC	5,440	AB
Glyphosate + glufosinate	21	CDEF	63	C	60	BC	3,560	B
Paraquat + mesotrione + atrazine	62	A	80	A	70	AB	3,880	AB
Glyphosate + saflufenacil	19	DEFG	40	DE	59	BC	5,440	AB
Nontreated	–		–		–		8,160	

[a]Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b]Rapeseed height averaged 41 cm at time of early termination at Painter, VA, during 2017.
[c]Abbreviations: LR, low rate; HR, high rate.
[d]2,4-D LR, 2,4-D HR, dicamba LR, dicamba HR, glyphosate, saflufenacil, paraquat, glufosinate, glyphosate + 2,4-D LR, glyphosate + dicamba LR, paraquat + 2,4-D LR, glyphosate + glufosinate, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil were applied at 532, 1,064, 280, 560, 1,266, 50, 840, 885, 1,266 + 532, 1,266 + 280, 840 + 532, 1,266 + 885, 840 + 105 + 560, and 1,266 + 50 g ae or ai ha^{-1}, respectively.
[e]Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated according to Dunnett's procedure at P = 0.05.

Table 6. Rapeseed control 7, 14, and 28 d after late termination (DALT) and rapeseed biomass 28 DALT in Georgetown, DE, 2017 and 2018, and Painter, VA, 2018.[a,b]

Herbicide treatment[c,d]	Rapeseed control 7 DALT		14 DALT		28 DALT		Rapeseed biomass[e]	
	%						kg ha^{-1}	
2,4-D LR	27	E	32	G	45	G	1,840	B
2,4-D HR	32	D	30	G	55	F	1,600	B
Dicamba LR	12	G	13	I	18	H	2,560	A*
Dicamba HR	19	F	24	H	24	H	1,520	B
Glyphosate	26	E	46	F	68	DE	1,120	C
Saflufenacil	42	C	61	BC	42	G	1,040	C
Paraquat	47	B	57	CD	63	E	800	CD
Glufosinate	32	D	51	EF	43	G	920	CD
Glyphosate + 2,4-D LR	33	D	63	B	82	A	1,080	C
Glyphosate + dicamba LR	24	E	54	DE	75	BC	1,040	C
Paraquat + 2,4-D LR	57	A	66	B	85	A	640	D
Glyphosate + glufosinate	33	D	52	E	70	CD	920	CD
Paraquat + mesotrione + atrazine	39	C	63	B	81	A	640	D
Glyphosate + saflufenacil	39	C	71	A	79	AB	640	D
Nontreated	–		–		–		2,480	

[a]Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b]Rapeseed height averaged 52 cm at time of late termination at Georgetown, DE during 2017 and 2018 and at Painter, VA during 2018.
[c]Abbreviations: LR, low rate; HR, high rate.
[d]2,4-D LR, 2,4-D HR, dicamba LR, dicamba HR, glyphosate, saflufenacil, paraquat, glufosinate, glyphosate + 2,4-D LR, glyphosate + dicamba LR, paraquat + 2,4-D LR, glyphosate + glufosinate, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil were applied at 532, 1,064, 280, 560, 1,266, 50, 840, 885, 1,266 + 532, 1,266 + 280, 840 + 532, 1,266 + 885, 840 + 105 + 560, and 1,266 + 50 g ae or ai ha^{-1}, respectively.
[e]Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated according to Dunnett's procedure at P = 0.05.

respectively. Dicamba terminated rapeseed only 18% to 24% at this time. Unlike early termination, the rate of 2,4-D applied influenced termination of larger rapeseed. The higher rate of 2,4-D (1,064 g ai ha^{-1}) was 10% more effective than 532 g ha^{-1}. Higher rates of 2,4-D have been reported to provide more consistent control of some weeds. Keeling et al. (1989) noted that 2,4-D at 1.1 kg ha^{-1} controlled 10- to 15-cm horseweed 16% to 30% better than the herbicide applied at 0.6 kg ha^{-1}. Despite poorer rapeseed control when herbicide application was delayed, paraquat + 2,4-D, glyphosate + 2,4-D, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil controlled rapeseed 79% to 85% at 28 DALT.

All herbicide treatments, except dicamba LR (256 kg ha^{-1}), reduced rapeseed biomass at 28 DALT relative to the nontreated (Table 6). Compared to the nontreated, rapeseed biomass resulting from all other treatments ranged 640 to 1,840 kg ha^{-1}. Akin to visible rapeseed control 28 DALT, paraquat + 2,4-D, glyphosate + 2,4-D, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil reduced rapeseed biomass 56% to 74%.

Table 7. Rapeseed control 7, 14, and 28 d after late termination (DALT) and rapeseed biomass 28 DALT in Painter, VA, 2017.[a,b]

Herbicide treatment[c,d]	Rapeseed control 7 DALT		Rapeseed control 14 DALT		Rapeseed control 28 DALT		Rapeseed biomass[e]	
	%						kg ha^{-1}	
2,4-D LR	10	CDE	17	CD	17	DE	6,560	ABC
2,4-D HR	17	AB	20	CD	28	CD	8,320	A*
Dicamba LR	5	E	5	F	5	E	7,280	ABC
Dicamba HR	7	DE	6	F	6	E	9,900	A*
Glyphosate	10	CDE	14	DE	27	D	6,000	ABC
Saflufenacil	12	BCD	14	DE	7	E	6,280	ABC
Paraquat	20	A	22	BC	38	BC	4,680	BC
Glufosinate	18	AB	18	CD	17	DE	5,040	ABC
Glyphosate + 2,4-D LR	10	CDE	18	CD	42	BC	4,720	BC
Glyphosate + dicamba LR	7	DE	8	EF	17	DE	8,480	A*
Paraquat + 2,4-D LR	22	A	38	A	68	A	4,120	C
Glyphosate + glufosinate	13	BCD	15	CDE	29	CD	6,520	ABC
Paraquat + mesotrione + atrazine	17	AB	28	B	52	B	4,400	BC
Glyphosate + saflufenacil	12	BCD	17	CD	33	C	6,400	ABC
Nontreated	–		–		–		11,400	

[a]Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[b]Rapeseed height averaged 107 cm at time of late termination at Painter, VA, during 2017.
[c]Abbreviations: LR, low rate; HR, high rate.
[d]2,4-D LR, 2,4-D HR, dicamba LR, dicamba HR, glyphosate, saflufenacil, paraquat, glufosinate, glyphosate + 2,4-D LR, glyphosate + dicamba LR, paraquat + 2,4-D LR, glyphosate + glufosinate, paraquat + mesotrione + atrazine, and glyphosate + saflufenacil were applied at 532, 1,064, 280, 560, 1,266, 50, 840, 885, 1,266 + 532, 1,266 + 280, 840 + 532, 1,266 + 885, 840 + 105 + 560, and 1,266 + 50 g ae or ai ha^{-1}, respectively.
[e]Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated according to Dunnett's procedure at P = 0.05.

Virginia 2017

When rapeseed reached 107 cm in height at Virginia 2017, no herbicide treatment terminated rapeseed better than 22% and 38% at 7 and 14 DALT, respectively (Table 7). At this termination timing, rapeseed was flowering. Ferrell and others (2015) observed that efficacy of 2,4-D decreased 40% or more when the herbicide was applied to flowering wild radish compared to wild radish ≤15 cm tall. At 28 DALT, paraquat + 2,4-D terminated rapeseed 68%; all other treatments controlled the cover crop ≤52%.

Akin to visible rapeseed control 28 DALT, rapeseed biomass reduction was variable. Rapeseed biomass in the nontreated plots totaled 11,400 kg ha^{-1} (Table 7). Like rapeseed biomass reductions at early termination, all herbicide treatments, except 2,4-D HR and dicamba HR, reduced rapeseed biomass 36% to 64%. Similar to visible ratings collected at the same time, paraquat + 2,4-D caused the greatest rapeseed biomass reduction.

Rapeseed, as a cover crop, has many potential benefits (Chen et al. 2007; Chen and Weil 2010; Gieske et al. 2016; Virginia NRCS 2015; Williams and Weil 2004). However, termination can be difficult, as demonstrated in these experiments and reported by growers. Successful rapeseed termination is mostly predicated on size. Rapeseed 12 cm tall at Delaware and Virginia in 2018 was easily controlled with many herbicide treatments; glyphosate, glyphosate + 2,4-D, glyphosate + dicamba, glyphosate + saflufenacil, paraquat + 2,4-D, and paraquat + mesotrione + atrazine controlled rapeseed >86% at 28 DAET. Comparatively, these same treatments were less effective when rapeseed was taller. The aforementioned herbicide treatments controlled 41- to 107-cm rapeseed 17% to 85% at 28 d after application at either Delaware and Virginia 2018 or Virginia 2017. Other research from Virginia investigating rapeseed termination by various herbicides confirms that rapeseed size is critical to successful termination (Michael Flessner, personal communication). Likewise, control of many weedy brassica species is dependent upon weed size (Cahoon 2016; Culpepper 2009; DiTomaso et al. 2013; Ferrell et al. 2015). Rate of 2,4-D also seemed to influence rapeseed termination, especially when the cover crop was larger. The high rate of 2,4-D controlled 41- and 52-cm rapeseed 17% and 10% better than 2,4-D LR at 28 d after application, respectively. Similarly, moderate to large (10 to 15 cm tall) horseweed is more consistently controlled with 1.1 kg ha^{-1} 2,4-D than the 0.6 kg ha^{-1} rate of the herbicide (Keeling et al. 1989).

Weed suppression by cover crops is determined by biomass accumulation; greater cover crop biomass increases weed suppression (Bybee-Finley et al. 2017; Finney et al. 2016; Mirsky et al. 2013). To maximize rapeseed biomass, the cover crop would have to be grown in a monoculture system. However, in a monoculture system, rapeseed would probably be too large in the spring to successfully terminate. Producers may mitigate the risk of tall rapeseed by growing the brassica in cover crop mixtures with other species like cereal rye (*Secale cereale* L.). Producers can further ensure that rapeseed is not too large at termination by effectively managing other crop species grown in competition with rapeseed. If cereal rye grown in competition with rapeseed is healthy, rapeseed is unlikely to reach 41 to 107 cm in height by termination as we observed in these monoculture rapeseed experiments. In years favoring growth of rapeseed over other cover crop species, producers should plan to terminate early before rapeseed becomes unmanageable with herbicides.

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