Rapeseed (*Brassica napus* L.) Termination and Integration of Halauxifen-methyl into Virginia Cotton (*Gossypium hirsutum* L.) Production

Matthew Carter Askew

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science in Life Sciences

In

Plant Pathology, Physiology, and Weed Science

Charles W. Cahoon, Jr. Co-Chair
Michael L. Flessner Co-Chair
David B. Langston, Jr.

December 10, 2018
Suffolk, VA

Keywords: cover crop, burndown, horseweed, herbicide tolerance

Rapeseed (*Brassica napus* L.) Termination and Integration of Halauxifen-methyl into Virginia Cotton (*Gossypium hirsutum* L.) Production

M. Carter Askew

ABSTRACT

Cover crops have become an important part of cropping systems in the United States, especially in the Mid-Atlantic region. Rapeseed is a popular choice due to its deep growing taproot which creates soil macropores and increases water infiltration. If not properly terminated rapeseed can become problematic due to its pod-shattering tendency and its difficulty to terminate with herbicides once it enters reproductive growth. Results indicate termination of rapeseed is most effective when the cover crop is small. Combinations that successfully terminated rapeseed include glyphosate plus 2,4-D and paraquat plus 2,4-D. Halauxifen-methyl is a new Group 4 herbicide marketed for preplant burndown horseweed (*Conyza canadensis* L.) control. Previous research indicates that halauxifen effectively controls glyphosate-resistant horseweed. However, little is known about control of other common winter annual weeds by halauxifen. Results indicate halauxifen has a narrow spectrum of control providing adequate control (>80%) of horseweed, henbit (*Lamium amplexicaule* L.), and purple deadnettle (*Lamium purpureum* L.), while failing to control cutleaf evening-primrose (*Oenothera laciniata* Hill), curly dock (*Rumex crispus* L.), purple cudweed (*Gamochaeta purpurea* L. Cabrera), common chickweed (*Stellaria media* L.), and mousear chickweed (*Cerastium* L.). Little is known of cotton (*Gossypium hirsutum* L.) tolerance to halauxifen applied preplant burndown. Results indicate cotton is more tolerant to halauxifen than 2,4-D or dicamba when the interval between preplant application and cotton planting is less than 30 days.

Rapeseed (*Brassica napus* L.) Termination and Integration of Halauxifen-methyl into Virginia Cotton (*Gossypium hirsutum* L.) Production

M. Carter Askew

GENERAL AUDIENCE ABSTRACT

Cover crops are an important part of cropping systems in the United States, especially in the Mid-Atlantic region. Producers utilize cover crops to aid in weed suppression, reduce soil erosion, as well as to increase soil health. Cereals, legumes, and *Brassicaceae* species are popular cover crops planted either as monocultures or mixtures. Rapeseed can become problematic due to its difficulty to terminate once it enters reproductive stage, as well as its pod-shattering characteristic. Experiments were conducted to evaluate various herbicides and herbicide combinations for rapeseed termination two application timings. At three locations where rapeseed averaged 12 cm in height at early termination, and 52 cm in height at late termination, glyphosate + 2,4-D was most effective, controlling rapeseed (96%) 28 days after early termination (DAET). Paraquat + atrazine + atrazine (92%), glyphosate + saflufenacil (91%), glyphosate + dicamba (91%), and glyphosate (86%) all provided at least 80% control 28 DAET. Paraquat + 2,4-D (85%), glyphosate + 2,4-D (82%), and paraquat + atrazine + mesotrione (81%) were the only treatments to provide at least 80% control 28 days after late termination (DALT). At one location where rapeseed was much taller (41 cm early termination; 107 cm late termination), herbicides were much less effective, as no herbicide treatments

provided greater than 80% control. Results indicated that rapeseed size at time of termination was more critical to successful termination than herbicide choice.

Prior to the development of glyphosate-resistant horseweed, producers were able to control horseweed and other weeds with glyphosate applied preplant burndown. Producers now rely on auxin herbicides tank mixed with glyphosate and a residual herbicide to control horseweed and other winter weeds prior to cash crop planting. Experiments were conducted to evaluate halauxifen-methyl, a new Group 4 herbicide, for control of horseweed and other commonly encountered winter annual weeds. Halauxifen (89%) controlled small horseweed (<5 cm in height at time of application) similar to dicamba (91%), while providing better control of large horseweed (79%) (>15 cm in height at time of application) than either dicamba (77%) or 2,4-D evaluated (64%). Halauxifen provided adequate control (>80%) of henbit (*Lamium amplexicaule* L). and purple deadnettle (*Lamium purpureum* L.), while failing to effectively control of cutleaf evening-primrose (*Oenothera laciniata* Hill), curly dock (*Rumex crispus* L.), purple cudweed (*Gamochaeta purpurea* L. Cabrera), common chickweed (*Stellaria media* L. Vill.), and mousear chickweed (*Cerastium* L.). Results indicate that halauxifen has a narrow spectrum of control and should be tank mixed with 2,4-D or glyphosate in order to control weeds other than horseweed and henbit.

Glyphosate plus dicamba or 2,4-D plus a residual herbicide is typically applied prior to cotton planting. Previous research has shown that as long as rainfall requirements and rotation intervals are met, no adverse effects on cotton is observed from 2,4-D or dicamba herbicides. Little is known of cotton tolerance to halauxifen applied preplant burndown. Experiments were conducted to determine if halauxifen applied sooner than the labeled 30-day rotation interval would injure cotton. Very little injury was observed from halauxifen (9%) applied at-planting, however dicamba (26%) and 2,4-D (21%) applied at the same timing did injure cotton. Auxin herbicides applied earlier in the season resulted in little injury (<2%). Early season injury was transient as cotton recovered later in the season and seedcotton yield was unaffected.

Acknowledgements

I have been blessed to be surrounded by some great people throughout this process, and without their help, I would not have been able to make it to the finish line.

First and foremost, I would like to thank God for providing me with the strength and will power that has gotten me to this point.

I would like to thank Dr. Charlie Cahoon. I will always be thankful for the opportunity that you gave me as well as the example that you have set of hard work, dedication, and passion for agriculture.

I would also like to thank Drs. Michael Flessner and David Langston for their support and guidance.

To our technician, Tommy Hines and my labmates, Harrison Ferebee and Hunter Blake, thank you for the countless hours that you have helped me in the field and in class. Without your hard work, I would not have been able to accomplish this, and I will always be grateful for that.

To my parents, thank you for pushing me to always better myself and encouraging me to always do my best, because “your best, is the best that you can do.” It’s hard to believe that the “just checking in, keep pushing, the end is in sight” phones calls are finally over!

To my brothers, grandparents, and the rest of my family, thank you for your love and support. It takes a village to raise someone, and I was blessed to have you all as a part of my village.

To my Uncle Reggie, thank you for instilling your love of agriculture in me. I can truly say that without your presence in my life, I would not be completing this degree, and I would probably be in a totally unrelated field (probably hating my job).

To Dr. Alan York, thank you for allowing me the chance to work and learn under you as an undergraduate student. Without your guidance, I would never have met Charlie, and would not have had the opportunity to obtain this degree.

Most importantly, I thank my wife Brittany, for her constant love and support. You have been there for me and made many sacrifices of your own throughout this process. Being married to you makes me a better man every day.

Table of Contents

List of Tables

Termination of Cover Crop Rapeseed (*Brassica napus* L.)

Abstract

Cover crops have become a popular and important part of cropping systems as producers look to suppress weeds while improving soil quality. Cereals, legumes, and *Brassicaceae* species are commonly used cover crops either in monocultures or mixtures. Rapeseed is a popular cover crop choice due to its powerful taproot which creates soil macropores and increases water infiltration. Large *Brassicaceae* species can be troublesome to control, and Virginia producers have reported that cover crop rapeseed is difficult to terminate prior to planting. Four field experiments were conducted during 2016-2017 and 2017-2018 near Painter, VA and Georgetown, DE to evaluate various herbicides applied at two timings to simulate early and late burndown scenarios. "Dwarf Essex" rapeseed was planted at all four locations. Treatments included a factorial arrangement of two burndown application timings by fourteen herbicide treatments. Visible estimates of rapeseed control were collected 7, 14, and 28 days after each application. Rapeseed biomass was harvested 28 days after each application. At three locations where rapeseed averaged 12 cm in height at early termination and 52 cm in height at late termination, glyphosate + 2,4-D was most effective, controlling rapeseed 96% 28 days after early termination (DAET). Paraquat + atrazine + mesotrione (92%), glyphosate plus saflufenacil (91%), glyphosate plus dicamba (91%), and glyphosate (86%) all provided at least 80% control 28 DAET. Rapeseed biomass followed a similar trend. Paraquat plus 2,4-D (85%), glyphosate plus 2,4-D (82%), and paraquat plus atrazine plus mesotrione (81%) were the only treatments to provide at least 80% control 28 days after late termination (DALT). Herbicide efficacy was less at Painter in 2017 where rapeseed was 41 cm in height at early termination, and 107 cm in height

at late termination. No herbicide treatments controlled rapeseed greater than 80% 28 DAET or 28 DALT at this location. These experiments confirm rapeseed size is more critical for successful termination than herbicide choice. Herbicide termination of rapeseed is best when small; termination of large rapeseed may require mechanical of other methods beyond herbicides.

Cover crops have become an integral part of many cropping systems and are planted on over 10 million acres in the United States (USDA 2012). Benefits of cover crops include weed suppression, enhanced soil quality, reduced soil erosion, and increased cash crop yield (Power and Doran 1983; Smith et al. 1987; Teasdale 1996; Williams et al. 1998; Reddy et al. 2003; and Chen and Weil 2011). 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. 2000). 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 they do not provide season-long control of weeds nor eliminate the need for herbicides in cash crop management (Teasdale 1996; Reddy et al. 2003). However, combinations of cover crops and preemergence 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 (Mannering et al 1985; Brennan and Smith 2005). Monoculture cover crops are more popular with producers due to ease of planting and termination. Selecting a termination method is easier when facing one species.

Brassica species are multifunctional cover crops and a popular choice for producers due to their rapid growth, large taproot, and frost tolerance, although some brassica species will winter kill (Chen et al. 2007). For example, tillage radish (*Raphanus sativus* L.), if planted early enough, will grow large enough to winter kill. Tillage radish winter kill is also dependent upon tuber depth. If tubers are 7 to 10 cm above the soil surface, tillage radish will effectively winter kill. However, if tubers are closer to the soil surface and more insulated by the soil they may survive the winter, mature, and reach reproductive stage. At this stage tillage radish is difficult to control with herbicides (Roberts 2015).

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 (Wolfe 2000; Alcantara et al. 2009). 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 (Williams and Weil 2004; Chen and Weil 2010). 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 Midwest U.S. utilize Brassica to scavenge residual N left after cash crop harvest (Gieske et al. 2016). Gieske et al. (2016) found brown mustard (*Brassica juncea* L.), rapeseed (*Brassica napus* L.), radish (*Raphanus sativus* L.), and white mustard (*Sinapis alba* L.) all accumulate comparable amounts 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, Natural Resource Conservation Service suggest seeding tillage radish during August or September while corn and soybean remain in the field (Virginia NRCS 2015). However, rapeseed can be planted 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 via the production of glucosinolates (Haramoto and Gallant 2005). Glucosinolates are sulfurcontaining molecules that when hydrolyzed form toxic compounds (e.g. isothiocyanates) that are capable of controlling some soil-borne organisms such as nematodes, fungi, and weeds (Brown and Morra 1997; Haramoto and Gallandt 2005; Blau et al. 1978; Muehlchen et al. 1990; Mojtahedi et al. 1993; Bell and Muller 1973; 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 rapeseed has a similar ability to inhibit weed seed germination (Brown and Morra 1996; Bangarwa et al. 2009). 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 soil (Virginia NRCS 2015).

Due to 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. ssp. arvensis) can reduce wheat yields up to 62% (Behdarvand et al. 2013). Specifically, previous research determined 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 preplant burndown. However, research is limited on efficacy of herbicides for rapeseed termination (Australian Oilseeds Federation 2014). However, control of other brassica species such as wild mustard and wild radish (*Raphanus raphanistrum*) is more understood (DiTomaso et al. 2013; Ferrell et al. 2015). Timing is critical when controlling these species (Culpepper 2009; DiTomaso et al. 2013; Cahoon 2016). Most herbicides are recommended to be applied 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, 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 used as a cover crop.

Materials and Methods

Experiments were conducted at the Eastern Shore Agriculture Research and Extension Center near Painter, VA (37.59°N, 75.78°W) and at the Carvel Research and Education Center near Georgetown, DE (38.69°N, 75.39°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, Dow 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 roto-tiller 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 and paraquat (Gramoxone® SL, Syngenta, Greensboro, NC) was applied at 840 g ai ha^{-1} prior to planting.

A factorial treatment structure was used consisting of two application timings and 14 herbicide treatments. 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. Fourteen herbicide treatments were applied at each termination timing. Herbicide treatments and rates can be found in Table 2 and source information in Table 3. Additionally, a nontreated check 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 and 107 cm at early and late termination, respectively whereas rapeseed height averaged 10 cm at early termination and 38 cm at late termination at Virginia during 2018. In Delaware, early and late termination treatments were applied when rapeseed height averaged 13 and 76 cm during 2017, respectively, and when rapeseed height averaged 13 and 41 cm during 2018, respectively.

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 days after late termination (DALT) using a 0 to 100% scale, where 0% = no weed control and 100% = complete necrosis (Frans et al. 1986). Rapeseed above-ground biomass was harvested from 0.25 m^{-2} 28 d after each termination timing, dried for 28 d in a drier, and then weighed to determine rapeseed dry biomass. Data for rapeseed biomass was extrapolated to present biomass as g m^{-2}.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS software (version 9.4, SAS Institute Inc., Cary, NC). Termination timing and herbicide treatment were treated as fixed factors, whereas location and replications were treated as random. Rapeseed was much larger at both termination timings at Virginia during 2017. Therefore, data are presented pooled across Delaware 2017 and 2018 and Virginia 2018 with data for Virginia 2017 presented separately. The main effects of termination timing and herbicide treatment were significant as well as the two-way interaction of termination timing by herbicide treatment; hence, data are presented by termination timing. Means were separated using Fisher's protected LSD at $P = 0.05$ when appropriate. Data for nontreated checks 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 checks to all other treatments.

Results and Discussion

Rapeseed was much smaller at Delaware and Virginia 2018. At these location, rapeseed height averaged 12 cm early termination compared to 41 cm at Virginia 2017. At late termination, rapeseed averaged 52 cm at Delaware and Virginia 2018 whereas rapeseed at Virginia 2017 was 107 cm tall. At-planting nitrogen applied in 2017, coupled with a warm February, are likely responsible for large rapeseed at Virginia 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 2018 and three-fold at Virginia 2017.

Delaware and Virginia 2018

Early Termination. As expected, herbicides terminated rapeseed more effectively when rapeseed was smaller in height. 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% or less (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 67 to 96% 28 DAET at Delaware and Virginia 2018. Of herbicides applied alone, glyphosate (86%) was most effective 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 plus glufosinate was 14% less effective than glyphosate alone. Cahoon and others (2015) reported 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 plus 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 plus 2,4-D LR (96%) and paraquat plus mesotrione plus atrazine (92%) were most effective.

In general, rapeseed biomass 28 DAET mirrored visible rapeseed control at the same time. Rapeseed biomass in nontreated checks averaged 200 g m^{-2}. All treatments, except dicamba (172 to 208 g m^{-2}) reduced rapeseed biomass relative to the nontreated check. All other herbicide treatments reduced rapeseed biomass 56 to 86% compared to the nontreated.

Late Termination. Rapeseed was larger at late termination dates, and control was less with the late termination applications. No herbicide treatment controlled the cover crop greater than 57% 7 DALT (Table 5). Similar to early termination, herbicide treatments containing paraquat (39 to 57%) terminated rapeseed best 7 DALT. Surprisingly, at this timing, saflufenacil (42%) and glyphosate plus saflufenacil (39%) controlled rapeseed similar to paraquat plus mesotrione plus 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 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%, respectively. Dicamba terminated rapeseed only 18 to 24% at this time. Unlike early termination, 2,4-D rate influenced termination of larger rapeseed. The higher rate of 2,4-D (1064 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 2,4-D at 1.1 kg ha^{-1} controlled 10- to 15-cm horseweed 16 to 30% greater than the herbicide applied at 0.6 kg ha^{-1}. Despite less rapeseed control when herbicide application was delayed, paraquat plus 2,4-D, glyphosate plus 2,4-D, paraquat plus mesotrione plus atrazine, and glyphosate plus saflufenacil controlled rapeseed 79 to 85% 28 DALT.

All herbicide treatments, except dicamba LR (256 g m^{-2}), reduced rapeseed biomass 28 DALT relative to the nontreated (Table 5). Compared to the nontreated, rapeseed biomass resulting from all other treatments ranged 64 to 184 g m^{-2}. Akin to visible rapeseed control 28 DALT, paraquat plus 2,4-D, glyphosate plus 2,4-D, paraquat plus mesotrione plus atrazine, and glyphosate plus saflufenacil reduced rapeseed biomass 56 to 74%.

Virginia 2017

Early Termination. Rapeseed termination was generally poor at Virginia during 2017 and was likely 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 wild radish 15 cm or less in height was controlled 90% or greater 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 in height at early termination.

Like Delaware and Virginia 2018, paraquat (58%), paraquat plus mesotrione plus atrazine (62%), and paraquat plus 2,4-D (67%) were more effective than other herbicide treatments 7 DAET at Virginia 2017 (Table 6). Although rapeseed control improved later in the season, no herbicide treatment terminated the cover crop greater than 78% 28 DAET, whereas at Delaware and Virginia 2018, the following six herbicide treatments controlled rapeseed at least 83%, glyphosate alone, glyphosate plus 2,4-D, glyphosate plus dicamba, glyphosate plus saflufenacil, paraquat plus 2,4-D, and paraquat plus mesotrione plus 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% 28 DAET; glyphosate plus 2,4-D (78%) was the most effective herbicide treatment at Virginia 2017. However, paraquat plus 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.

Further evidence of larger rapeseed at Virginia 2017 compared to other locations, rapeseed biomass in nontreated plots (816 g m^{-2}) was approximately four-fold greater than at Delaware and Virginia 2018 (Tables 4 and 6). Most treatments did reduce rapeseed biomass relative to the nontreated; however, reductions were minimal, ranging 37 to 59%.

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

Akin to visible rapeseed control 28 DALT, rapeseed biomass reduction was variable. Rapeseed biomass in the nontreated plots totaled 1140 g m^{-2} (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 plus 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 in height at Delaware and Virginia 2018 was easily controlled with many herbicide treatments; glyphosate, glyphosate plus 2,4-D, glyphosate plus dicamba, glyphosate plus saflufenacil, paraquat plus 2,4-D, and paraquat plus mesotrione plus atrazine controlled rapeseed ≥86% 28 DAET. Comparatively, these same treatments were less effective when rapeseed was larger. The aforementioned herbicide treatments controlled 41 to 107 cm rapeseed 17 to 85% 28 days after application at either Delaware and Virginia 2018 or Virginia 2017. Other research from Virginia investigating rapeseed termination by various herbicides, confirms 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% greater than 2,4-D LR 28 d after application, respectively. Similarly, moderate to large (10 to 15 cm in height) 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 need to be grown in a monoculture system. However, in a monoculture system, rapeseed would likely be too large in the spring to successfully terminate. Producers may mitigate the risk of large rapeseed by growing the brassica in cover crop mixtures with other species like cereal rye (*Secale cereal* L.). Producers can further ensure 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.

Literature Cited

Alcantara C, Sanchez S, Pujadas A, Saavedra M (2009) Brassica Species as Winter Cover Crops in Sustainable Agricultural Systems in Southern Spain. Journal of Sustainable Agriculture 33:619-635

Australian Oilseeds Federation (2014) Canola volunteer control. http://www.australianoilseeds.com/__data/assets/pdf_file/0018/9261/Canola_volunteer_control_guide_-_2014.pdf. Accessed February 8, 2018

Bangarwa SK, Norsworthy JK, and Gbur EE (2009) Integration of Brassicaceae Cover Crop with Herbicides in Plasticulture Tomato. Weed Technology 23:280-286

Behdarvand P, Chinchanikar GS, Dhumal KN, Baghestani MA (2013) Effects of wild mustard (*Sinapis arvensis L.*) and wild oat (*Avena ludoviciana L.*) densities on grain yield and yield components of wheat in response to various levels of nitrogen. Advances in Environmental Biology p. 1082

Bell DT and Muller CH (1973) Dominance of California annual grasslands by *Brassica nigra*. The American Midland Naturalist 90:277-299

Blau PA, Feeny P, Contardo L, and Robson DS (1978) Allylglucosinolate and herbivorous caterpillars: a contrast in toxicity and tolerance. Science 200:1296-1298

Bowman G, Shirley C, Cramer G (2000) Benefits of cover crops. In: A. Clark, editor, *Managing cover crops profitably*, Sustainable Agriculture Network, Beltsville, MD, p. 9-11

Brennan EB and Smith RF (2005) Winter cover crop growth and weed suppression on the central coast of California. Weed Technology 19: 1017-1024

Brown PD and Morra MJ (1996) Hydrolysis products of glucosinolates in *Brassica napus* tissues as inhibitors of seed germination. Plant and Soil 181:307-316

Brown PD and Morra MJ (1997) Control of soil-borne plant pests using glucosinolate-containing plants. Advances in Agronomy 61:167-231

Bybee-Finley KA, Mirsky SB, and Ryan MR (2017) Crop biomass not species richness drives weed suppression in warm-season annual grass-legume intercrops in the Northeast. Weed Science 65:669-680.

Cahoon C (2016) Wild Mustard and Wild Radish. http://blogs.ext.vt.edu/ag-pest-advisory/files/2016/11/Problem-Weed-Mustard-and-Radish.pdf. Accessed February 8, 2018

Cahoon CW, York AC, Jordan DL, Seagroves RW, Everman WJ, and Jennings KM (2015) Sequential and Co-Application of Glyphosate and Glufosinate in Cotton. The Journal of Cotton Science 19: 337-350

Caseley J (1983) The Effect of Weather on Herbicide Performance. Bulletin OEPP EPPO Bulletin 13:171-176

Chen G, Clark A, Kremen A, Lawley Y, Price A, Stocking L, Weil R (2007) Brassicas and mustards. In: A. Clark, editor, Managing cover crops profitably. 3rd ed. Sustainable Agriculture Research and Education, College Park, MD. p. 81–90.

Chen GH and Weil RR (2010) Penetration of cover crop roots through compacted soils. Plant and Soil 331:31-43

Chen G and Weil RR (2011) Root growth and yield of maize affected by soil compaction and cover crops. Soil and Tillage Research 117:17-27

Culpepper S (2009) Managing Wild Radish in Wheat. https://athenaeum.libs.uga.edu/bitstream/handle/10724/12202/C839.pdf?sequence=1. Accessed February 8, 2018

Curran W, Lingenfelter D, Johnson Q, VanGessel M, Vollmer K, Schulz B, Besancon T, Cahoon C, Flessner M, Hines T, and Chandran R (2018) Mid-Atlantic Field Crop Weed Management Guide. https://cdn.extension.udel.edu/wp-content/uploads/2012/08/13065349/AGRS-136-Low-Res-2018-Weed-Mgmt-Guide-1.pdf. Accessed November 18, 2018

Dean WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Petrology 44:242-248

DiTomaso JM and Kyser GB (2013) Weed Control in Natural Areas in the Western United States. Weed Research and Information Center, University of California. p. 544

Dunnett CW (1955) A multicomparisons procedure for comparing several treatments with a control. Journal of American Statistics Association 50:1096–1121

Eberlein CV, Morra MJ, Guttieri MJ, Brown PD, Brown J (1998) Glucosinolate production by five field-grown *Brassica napus* cultivars used as green manures. Weed Technology 12:712-718

Ferrell JA, Sellers B, MacDonald GE and Leon R (2015) Wild Radish-Biology and Control. http://edis.ifas.ufl.edu/pdffiles/WG/WG21500.pdf. Accessed February 8, 2018

Finny DM, White CM, and Kaye JP (2016) Biomass production and carbon/nitrogen ratio ecosystem services from cover crop mixtures. Agronomy Journal 108:39-52

Frans R E, 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. Champaign, IL: Southern Weed Science Society

Gieske MF, Ackroyd VJ, Baas DG, Mutch DR, Wyse DL, Durgan BR (2016) Brassica Cover Crop Effects on Nitrogen Availability and Oat and Corn Yield. Agronomy Journal 108:151-161

Hamza MA and Anderson WK (2005) Soil compaction in cropping systems- a review of the nature, causes and possible solutions. Soil Tillage Research. 82:121-145

Haramoto ER and Gallandt ER (2005) Brassica cover cropping: I. Effects on weed and crop establishment. Weed Science 53:695-701

Keeling JW, Henniger CG, and Abernathy JR (1989) Horseweed (*Conyza canadensis*) control in conservation tillage cotton (*Gossypium hirsutum*). Weed Technology 3:399-401

Krato C and Petersen J (2012) Competitiveness and yield impact of volunteer oilseed rape (*Brassica napus*) in winter and spring wheat (*Triticum aestivum*). Journal of Plant Diseases and Protection 119:74-82

Mannering JV, Griffith DR, Johnson KD (1985) Winter Cover Crops- Their Value and Management. http://www.agry.purdue.edu/est/forages/publications/ay247.htm. Accessed January 31, 2018

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

Mojtahedi H, Santo G, Wilson J, and Hang AN (1993) Managing *Meloidogyne chitwoodi* on potato with rapeseed as green manure. Plant Disease 77:42-46

Muehlchen A, Rand R, and Parke J (1990) Evaluation of crucifer green manures for controlling aphanomyces root rot of peas. Pant Disease 74: 651-654

Norsworthy JK, McClelland M, Griffith G, Bangarwa SK and Still J (2011) Evaluation of Cereal and Brassicaceae Cover Crops in Conservation-Tillage, Enhanced, Glyphosate-Resistant Cotton. Weed Technology 25:6-13

O'Donovan JR, Harker KN, Dew DA (2008) Effect of density and time of removal of volunteer canola (*Brassica rapa* L.) on yield loss of wheat (*Triticum aestivum* L.). Canada Journal of Plant Science 88:839-842

Petersen J, Belz R, Walker F, and Hurle K (2001) Weed suppression by release of isothiocyanates from turnip-raoe mulch. Agronomy Journal 93:37-43

Power JF and Doran JW (1988) Role of crop residue management in nitrogen cycling and use. In: W.L. Hargrove editor, Cropping strategies for efficient use of water and nitrogen. ASA Special Publication 51. ASA, CSSA, and SSSA, Madison, WI.

Reddy KN, Zablotowicz RM, Locke MA, Koger CH (2003) Cover Crop, Tillage, and Herbicide Effects on Weeds Soil Properties, Microbial Populations, and Soybean Yield. Weed Science 51:987-994

van Rijn LC (2011) Coastal erosion and control. Ocean & Coastal Management 54:867-887

Roberts T (2015) Tillage Radish- Not just for Tillage! Part 2 in a Series. http://www.arkansas-crops.com/2015/09/09/tillage-radish-series/. Accessed on March 2, 2018.

Servadio P, Marsili A, Vignozzi N, Pellegrini S, Pagliai M (2005) Effects on some soil qualities in central Italy following the passage of four-wheel drive tractor fitted with single and dual tires. Soil Tillage Research 84:87-100

Smith MS, Frye WW, Varco JJ (1987) Legume winter cover crops. Advances in Soil Science 7:95-139

Teasdale JR (1996) Contributions of cover crops to weed management in sustainable agriculture systems. Journal of Production Agriculture. 9:475-479

Teasdale JR and Taylorson RB (1986) Weed seed response to methyl isothiocyanate and metham. Weed Science 34:520-524

United States Department of Agriculture (2012) 2012 Census of Agriculture. https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf. Accessed January 31, 2018

Virginia Natural Resources Conservation Service (2015) Virginia NRCS Cover Crop Planning Manual 1.0. https://efotg.sc.egov.usda.gov/references/public/VA/VA_TN10_Agronomy.pdf. Accessed February 2, 2018

Williams MM, Mortensen DA, Doran JW (1998) Assessment of weed and crop fitness in cover crop residues for integrated weed management. Weed Science 46:595-603

Williams SM and Weil RR (2004) Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Science Society of America Journal 68:1403-1409

Wolf RB, Spencer GF, and Kwolek WE (1984) Inhibition of velvetleaf (*Abutilon theophrasti*) germination and growth by benzyl isothiocyanate, a natural toxicant. Weed Science 32:612-615

Wolfe D (2000) Summer covers relieve compaction. In: A. Clark, editor, *Managing cover crops profitably*, Sustainable Agriculture Network, Beltsville, MD, p. 84

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, 2017	April 10, 2017
Georgetown, DE	2017	Hammonton[b]	Loamy sand	5.9	1.3	October 7, 2016	April 5, 2017	April 17, 2017
Painter, VA	2018	Bojac	Sandy loam	6.4	1.0	September 28, 2017	March 17, 2018	April 6, 2018
Georgetown, DE	2018	Rosedale[c]	Loamy sand	5.5	1.1	October 10, 2017	April 11, 2018	April 26, 2018

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

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)	1064
Dicamba (LR)	280
Dicamba (HR)	560
Glyphosate[b]	1266
Saflufenacil[cd]	50
Paraquat[e]	840
Glufosinate[b]	885
Glyphosate + 2,4-D LR[b]	1266 + 532
Glyphosate + dicamba LR[b]	1266 + 280
Paraquat + 2,4-D LR[e]	840 + 532
Glyphosate + glufosinate[b]	1266 + 885
Paraquat + mesotrione + atrazine[de]	840 + 105 + 560
Glyphosate + saflufenacil[cd]	1266 + 50

[a] Source information for herbicides can be found in Table 3.
[b] Ammonium sulfate applied 1% wv^{-1}.
[c] Methylated seed oil applied 1% vv^{-1}.
[d] 30% UAN applied 0.25% vv^{-1}.
[e] Crop oil concentrate applied 1% vv^{-1}.

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 web site addresses of each manufacture can be found at www.cdms.net

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

Herbicide[c]	Rapeseed control 7 DAET	Rapeseed control 14 DAET	Rapeseed control 28 DAET	Rapeseed biomass[d]
	%	%	%	$g\ m^{-2}$
2,4-D LR	27 G	43 E	67 E	80 BC
2,4-D HR	37 F	46 E	70 DE	88 B
Dicamba LR	19 H	22 G	24 G	208 A*
Dicamba HR	26 G	29 F	40 F	172 A*
Glyphosate	37 F	57 CD	86 C	60 BC
Saflufenacil	41 E	70 B	72 D	64 BC
Paraquat	67 AB	69 B	68 E	60 BC
Glufosinate	35 F	61 C	67 E	44 BC
Glyphosate + 2,4-D LR	38 EF	70 B	96 A	60 BC
Glyphosate + dicamba LR	36 F	66 B	91 B	48 BC
Paraquat + 2,4-D LR	70 A	76 A	83 C	44 BC
Glyphosate + glufosinate	37 F	56 D	72 D	48 BC
Paraquat + mesotrione + atrazine	60 C	76 A	92 AB	28 C
Glyphosate + saflufenacil	46 D	78 A	91 B	28 C
Nontreated Check	---	---	---	200

[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] Application rates are listed in Table 2.
[d] Means for rapeseed biomass followed by an asterisk (*) are not different from the nontreated check according to Dunnett's procedure at $P = 0.05$.
[x] Abbreviations: LR, low rate; HR, high rate.

Table 5. Rapeseed control 7, 14, and 28 days after late termination (DALT) and rapeseed biomass 28 DALT in Georgetown, Delaware 2017 and 2018 and Painter, Virginia 2018.[a,b]

	Rapeseed control			
Herbicide[c]	7 DALT	14 DALT	28 DALT	Rapeseed biomass[d]
	%			$g\ m^{-2}$
2,4-D LR	27 E	32 G	45 G	184 B
2,4-D HR	32 D	30 G	55 F	160 B
Dicamba LR	12 G	13 I	18 H	256 A*
Dicamba HR	19 F	24 H	24 H	152 B
Glyphosate	26 E	46 F	68 DE	112 C
Saflufenacil	42 C	61 BC	42 G	104 C
Paraquat	47 B	57 CD	63 E	80 CD
Glufosinate	32 D	51 EF	43 G	92 CD
Glyphosate + 2,4-D LR	33 D	63 B	82 A	108 C
Glyphosate + dicamba LR	24 E	54 DE	75 BC	104 C
Paraquat + 2,4-D LR	57 A	66 B	85 A	64 D
Glyphosate + glufosinate	33 D	52 E	70 CD	92 CD
Paraquat + mesotrione + atrazine	39 C	63 B	81 A	64 D
Glyphosate + saflufenacil	39 C	71 A	79 AB	64 D
Nontreated Check	---	---	---	248

[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] Application rates are listed in Table 2.
[d] Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated check according to Dunnett's procedure at P = 0.05.
[x] Abbreviations: LR, low rate; HR, high rate.

Table 6. Rapeseed control 7, 14, and 28 days after early termination (DAET) and rapeseed biomass 28 DAET in Painter, Virginia 2017.[a,b]

Herbicide[c]	Rapeseed control 7 DAET	Rapeseed control 14 DAET	Rapeseed control 28 DAET	Rapeseed biomass[d]
	%	%	%	g m^{-2}
2,4-D LR	29 BCD	34 EF	40 E	428 AB
2,4-D HR	39 B	45 D	57 CD	508 AB
Dicamba LR	12 FG	10 G	10 F	604 A*
Dicamba HR	14 EFG	13 G	12 F	508 AB
Glyphosate	10 G	27 F	39 E	524 AB
Saflufenacil	23 CDE	33 EF	20 F	364 B
Paraquat	58 A	65 C	62 BC	332 B
Glufosinate	20 CDEF	68 BC	46 DE	368 B
Glyphosate + 2,4-D LR	30 B	45 D	78 A	376 B
Glyphosate + dicamba LR	12 FG	26 F	35 E	524 AB
Paraquat + 2,4-D LR	67 A	75 AB	63 BC	544 AB
Glyphosate + glufosinate	21 CDEF	63 C	60 BC	356 B
Paraquat + mesotrione + atrazine	62 A	80 A	70 AB	388 AB
Glyphosate + saflufenacil	19 DEFG	40 DE	59 BC	544 AB
Nontreated Check	---	---	---	816

[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] Application rates are listed in Table 2.
[d] Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated check according to Dunnett's procedure at P = 0.05.
[x] Abbreviations: LR, low rate; HR, high rate.

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

Herbicide[c]	Rapeseed control 7 DALT	Rapeseed control 14 DALT	Rapeseed control 28 DALT	Rapeseed biomass[d]
	%	%	%	g m^{-2}
2,4-D LR	10 CDE	17 CD	17 DE	656 ABC
2,4-D HR	17 AB	20 CD	28 CD	832 A*
Dicamba LR	5 E	5 F	5 E	728 ABC
Dicamba HR	7 DE	6 F	6 E	990 A*
Glyphosate	10 CDE	14 DE	27 D	600 ABC
Saflufenacil	12 BCD	14 DE	7 E	628 ABC
Paraquat	20 A	22 BC	38 BC	468 BC
Glufosinate	18 AB	18 CD	17 DE	504 ABC
Glyphosate + 2,4-D LR	10 CDE	18 CD	42 BC	472 BC
Glyphosate + dicamba LR	7 DE	8 EF	17 DE	848 A*
Paraquat + 2,4-D LR	22 A	38 A	68 A	412 C
Glyphosate + glufosinate	13 BCD	15 CDE	29 CD	652 ABC
Paraquat + mesotrione + atrazine	17 AB	28 B	52 B	440 BC
Glyphosate + saflufenacil	12 BCD	17 CD	33 C	640 ABC
Nontreated Check	---	---	---	1140

[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] Application rates are listed in Table 2.
[d] Means for rapeseed biomass followed by an asterisk (*) are not different from nontreated check according to Dunnett's procedure at P = 0.05.
[x] Abbreviations: LR, low rate; HR, high rate.

Evaluation of Horseweed and Other Weed Control by Halauxifen-methyl

Abstract

Horseweed (*Conyza canadensis* L.) is a problematic broadleaf weed commonly found in reduced- and no-tillage systems. Horseweed either overwinters in a rosette stage and begins to grow erect in early spring reaching up to 2 m in height, or germinates in spring. Prior to selection for glyphosate-resistant biotype, horseweed was easily controlled by glyphosate applied preplant burndown. Along with the glyphosate-resistance development, horseweed biotypes have also evolved resistance to paraquat and ALS-inhibiting herbicides. An experiment was conducted to evaluate control of horseweed and other winter annual weeds encountered preplant burndown with halauxifen alone and in combination with glyphosate and other commonly used preplant herbicides. Experiments were conducted near Painter, VA, Rocky Mount, NC, Jackson, NC, and Gates, NC during the 2017 and 2018 growing seasons. Control of small horseweed (5 cm in height at application), large horseweed (15 cm in height at application), henbit (*Lamium amplexicaule* L), purple deadnettle (*Lamium purpureum* L.), daisy fleabane (*Erigeron annuus* L. Pers.), cutleaf evening-primrose (*Oenothera laciniata* Hill), curly dock (*Rumex crispus* L.), purple cudweed (*Gamochaeta purpurea* L. Cabrera), common chickweed (*Stellaria media* L. Vill.),and mousear chickweed (*Cerastium* L.) were evaluated at two locations or more. Halauxifen and dicamba controlled small horseweed similarly 4 weeks after treatment (WAT). Halauxifen (79%) controlled large horseweed greater than dicamba (77%) or 2,4-D (50 to 64%). Halauxifen was the only auxin herbicide to effectively control henbit (90%) and purple deadnettle (99%). No auxin herbicide controlled daisy fleabane effectively; however, halauxifen (66%) controlled the weed greater than 2,4-D and dicamba (24 to 55%). Halauxifen provided little control of cutleaf evening-primrose, curly dock, purple cudweed, and common chickweed

(4 to 7%) and was less effective than 2,4-D for control of cutleaf evening-primrose and curly dock. No auxin herbicide provided adequate control of purple cudweed or common chickweed whereas glyphosate controlled these weeds well. These experiments demonstrate halauxifen needs a tank-mix partner outside of glyphosate for weeds including cutleaf evening-primrose and curly dock which are not adequately controlled by glyphosate.

Horseweed (*Conyza canadensis* L.) is an annual broadleaf weed which either overwinters in a rosette stage and begins to grow erect in early spring reaching up to 2 m in height, or germinates in the spring (Weaver 2001). Horseweed can produce up to 200,000 seeds per plant (Bhowmik and Bekech 1993) with a majority of the seed immediately germinable (Loux et al. 2006). The weed is problematic in reduced- or no-tillage systems (Uva et al. 1997). An Indiana survey showed horseweed occurrence decreased 53% where conventional-tillage was employed compared to no-till (Loux et al. 2006). Further complicating management, producers have to combat horseweed every year as the seed are easily dispersed by wind (Shields et al. 2006). The lightweight seed have a pappus of bristles capable of carrying the seed 500 km in a single wind event (Shields et al. 2006). Additionally, horseweed seeds have been detected 140 m above the earth's surface, further facilitating widespread dispersal (Shields et al. 2006). This study also provides evidence that resistance genes easily spread from field-to-field, increasing the need to employ multiple tactics for horseweed control. Left uncontrolled, horseweed competes with crops for light, water, nutrients, and space. Horseweed has been reported to reduce soybean (*Glycine max* L.) yield up to 83% and cotton (*Gossypium hirsutum* L.) lint yield by as much as 46% (Bruce and Kells 1990; Steckel and Gwathmey 2009).

Traditionally, horseweed was controlled by glyphosate applied preplant burndown. However, glyphosate-resistant horseweed was first confirmed in Delaware during 2000 and has since spread to many other states (Bruce and Kells 1990; Heap 2018; VanGessel 2001). Along with glyphosate, horseweed biotypes have also evolved resistance to paraquat and ALS-inhibiting herbicides. Furthermore, biotypes of the weed have developed multiple resistance to glyphosate and ALS-inhibitors (Heap 2018). Multiple resistant horseweed has left producers with few options for chemical management (Eubank et al. 2008, 2012).

Current recommendations for managing horseweed include an auxin herbicide in combination with glyphosate applied preplant burndown. This mixture offers broad spectrum weed control as well as control of glyphosate- and ALS-resistant horseweed (Bruce and Kells 1990; Eubank et al. 2008; Loux et al. 2006). These herbicides are particularly effective if applied while horseweed is small (Byker 2013). Researchers reported 2,4-D controlled horseweed 97 to 100% at 0.56 kg ae ha^{-1} and at 100% at 1.12 kg ae ha^{-1} (Bruce and Kells 1990). Dicamba, another auxin herbicide, effectively controls glyphosate- and ALS-resistant horseweed (Byker et al. 2013; Eubank et al. 2008; Loux et al. 2006). Byker et al. (2013) observed similar glyphosate-resistant horseweed control by dicamba plus glyphosate as 2,4-D plus glyphosate. In another study, dicamba alone controlled horseweed 30 cm or less in height 97 to 99% and was similar to control by 2,4-D alone; dicamba alone was more effective than 2,4-D controlling horseweed larger than 30 cm (Kruger et al. 2010). Despite effectiveness, researches have observed horseweed biotypes with varying tolerances to 2,4-D, raising concern over selecting for auxin-resistant horseweed (Eubank et al. 2008; Kruger et al. 2007).

Halauxifen-methyl is a new Group 4 synthetic auxin herbicide and a member of the pyridine-2-carboxylate (or arylpicolinate) herbicide chemical family (Epp et al. 2016; WSSA 2018). Other members of the pyridine-2-carboxylate family include picloram, clopyralid, and aminopyralid (Epp et al. 2016). Halauxifen was recently commercialized under the trade name Elevore™ (Anonymous 2018a) from Corteva Agriscience and is being marketed for preplant burndown control of glyphosate- and ALS-resistant horseweed. Halauxifen is also sold in a pre-mix with florasulam, an ALS-inhibiting herbicide, for postemergence control of broadleaf weeds in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and triticale (*Triticosecale rimpaui* C. Yen & J.L. Yang) under the trade name Quelex™ (Anonymous 2018b). Previous research has shown halauxifen to effectively control horseweed at varying sizes (McCauley and Young 2016; Zimmer et al 2018a, Zimmer et. al 2018b). Zimmer et al. (2018a, 2018b) reported that halauxifen applied alone at 5 g ae ha^{-1} controlled glyphosate-resistant horseweed 90%, and treatments where halauxifen was tank mixed controlled glyphosate-resistant horseweed 87 to 97%. In another study, dicamba and halauxifen provided 80% control of 30-cm horseweed, while 2,4-D applied at 560 g ae ha^{-1} controlled the weed less than 50% control (McCauley and Young 2016). Similar to control of horseweed, researchers observed 93% control of common ragweed (*Ambrosia artemisiifolia* L.) control by halauxifen (Zimmer et al. 2018b). Braz et al. (2017) observed that halauxifen plus diclosulam controlled Sumatran fleabane (*Conyza sumatrensis* (Retz.) E. Walker), a weed species closely related to horseweed, 80 to 100% 45 days after treatment depending on rate and weed height. Although previous research concludes halauxifen effectively controls horseweed, research is limited on its effectiveness for many other weeds. Of particular interest is cutleaf evening-primrose, a common weed in reduced- and no-till systems not adequately controlled by glyphosate (Steckel 2008). The objective of this study was to further investigate halauxifen for horseweed control and its efficacy against many prevailing weeds frequently encountered preplant burndown.

Materials and Methods

Experiments were conducted at the Eastern Shore Agriculture Research and Extension Center near Painter, VA (37.58° N, 75.78° W), at the Upper Coastal Plain Research Station near Rocky Mount, NC (35.9382° N, 77.7905° W), and in a producer’s field near Jackson, NC (36.3896° N, 77.4214° W) during both the 2017 and 2018 seasons, as well as in two producers’ fields near Gates, NC (36.4202° N, 76.6875° W) during the 2018 season. Adjacent areas of the same fields were used for multiple locations at Painter, Rocky Mount, and Jackson. Soil descriptions and application dates are listed in Table 8. The experimental design was a randomized complete block with treatments replicated three or four times, depending on location. Plot sizes ranged from 2.8 to 3.7 m in width and 6 m to 12 m in length depending on locations.

Herbicide treatments consisted of halauxifen, dicamba, 2,4-D low rate (LR), 2,4-D high rate (HR), glyphosate, halauxifen plus glyphosate, dicamba plus glyphosate, 2,4-D LR plus glyphosate, and 2,4-D HR plus glyphosate. Halauxifen, dicamba, 2,4-D LR, 2,4-D HR, and glyphosate were applied at 5, 280, 533, 1066, and 1260 g ae ha^{-1}, respectively. Methylated seed oil at a rate of 1% v v^{-1} was added to halauxifen and halauxifen plus glyphosate whereas nonionic surfactant at 0.25% v v^{-1} was included with dicamba, 2,4-D LR, and 2,4-D HR. A nontreated check was included for comparison. Herbicide application dates are listed in Table 8, and herbicide sources are listed in Table 9. Herbicides were applied using a CO_2-pressurized backpack sprayer equipped with flat-fan nozzles (TTI 110015 Turbo TeeJet® Induction flat spray tip, TeeJet Technologies, Wheaton, IL) delivering 140 L ha^{-1} at 207 kPa.

Weed species and size varied across locations. Weeds included horseweed, henbit (*Lamium amplexicaule* L.), purple deadnettle (*Lamium purpureum* L.), purple cudweed (*Gnaphalium purpurea* L. Cabrera), common chickweed (*Stellaria media* L.), mouseear chickweed (*Cerastium fontanum* L.), cutleaf evening-primrose, curly dock (*Rumex crispus* L.), and daisy fleabane (*Erigeron annus* L.). Average diameter of cutleaf evening-primrose, curly dock, and cudweed at time of herbicide application was 16, 53, and 10 cm, respectively. Average height of mouseear chickweed, common chickweed, purple deadnettle, henbit, and daisy fleabane at time of herbicide application was 11, 13, 15, 13, and 18 cm, respectively.

Horseweed size varied among locations; therefore, locations were grouped according to horseweed size (small or large). Small horseweed averaged 5 cm tall and large horseweed averaged 15 cm tall at herbicide applications. Small horseweed, large horseweed, henbit, purple deadnettle, purple cudweed, common chickweed, mouseear chickweed, cutleaf evening-primrose, curly dock, and daisy fleabane were present at 6, 3, 4, 2, 7, 6, 2, 7, 3, and 3 locations respectively.

Visible weed control data were collected 2 and 4 wk after application using a 0 to 100% scale, where 0% = no weed control and 100% = complete necrosis (Frans et al. 1986). Weed density was collected 4 wk after application by counting the number of weeds per plot or the number of weeds from three 0.25 m^2 subsamples. Weed densities were extrapolated to report data as plants 100 m^{-2}.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS software (version 9.4, SAS Institute Inc., Cary, NC). Herbicide treatment was considered a fixed factor, whereas location and replications were treated as random; hence, data were pooled across all locations with the exception of horseweed. Data for small and large horseweed are reported separately pooled over 6 and 3 locations, respectively. Means were separated using Fisher's protected LSD at P = 0.05 when appropriate. Data for nontreated checks were excluded from analysis, except in a separate analysis for which Dunnett's procedure (Dunnett 1955) was used to compare weed density in the nontreated checks to all other treatments.

Results and Discussion

Plant response to auxin herbicides is relatively slow (Ross and Childs 1996); therefore, results focus on visible weed control and weed density 4 wk after treatment (WAT).

Horseweed control. Large horseweed (15 cm in height) was more difficult to control than small horseweed (5 cm in height) (Table 10) and agrees with previous research (Budd et al. 2017; McCauley and Young 2016; Zimmer et al. 2018a; 2018b). Halauxifen controlled small horseweed well (89%) and was similar to small horseweed control by dicamba (91%). Both rates of 2,4-D were less effective than halauxifen and dicamba, controlling small horseweed 72 to 80%. Indiana researchers observed similar results; halauxifen plus glyphosate and dicamba plus glyphosate controlled glyphosate-resistant horseweed 87 and 86%, respectively (Zimmer et al. 2018b). Despite a history of glyphosate-resistant horseweed in North Carolina and Virginia, glyphosate-resistant biotypes only made up a small portion of the horseweed populations used for this experiment as demonstrated by excellent horseweed control by glyphosate alone. Herbicide treatments that contained glyphosate controlled small horseweed 95 to 99%.

Horseweed control by halauxifen, dicamba, and both rates of 2,4-D decreased when horseweed averaged 15 cm in height compared to horseweed that averaged 5 cm in height (Table 10). Of the auxin herbicide treatments applied alone, halauxifen was most effective, controlling large horseweed 79% compared to 77% control by dicamba, 50% by 2,4-D LR, and 64% by 2,4-D HR. Similar to control of small horseweed, 2,4-D HR controlled large horseweed greater than 2,4-D LR. It has been well documented that 2,4-D applied at 1066 g ae ha^{-1} provides more consistent control of horseweed than 533 g ae ha^{-1}, especially after horseweed begins to bolt (Eubank et al. 2008; Keeling et al. 1989). Similar to results observed on small horseweed glyphosate alone and glyphosate plus halauxifen, dicamba, or 2,4-D controlled horseweed 95 to 99%. Glyphosate plus halauxifen, dicamba, or 2,4-D was 3 to 4% more effective than glyphosate alone

In general, horseweed density followed similar trends as visible control data. Small and large horseweed density in nontreated checks averaged 603 and 484 plants 100 m^{-2}, respectively. (Table 11). All herbicide treatments reduced small and large horseweed density compared to the nontreated check. Halauxifen (16 plants 100 m^{-2}), dicamba (19 plants 100 m^{-2}), glyphosate alone (21 plants 100 m^{-2}) and glyphosate combinations (1 to 11 plants 100 m^{-2}) reduced small horseweed density greater than both rates of 2,4-D (25 to 42 plants 100 m^{-2}). When horseweed were larger (15 cm in height), halauxifen and dicamba remained more effective than 2,4-D LR, but provided equivalent reductions in density to 2,4-D HR. Glyphosate alone, dicamba alone, and auxin combinations with glyphosate were most effective, reducing large horseweed density by 79 to 100%.

Henbit and Purple Deadnettle. Henbit and purple deadnettle are members of the *Lamiaceae* plant family and responded similarly to herbicide treatments (Tables 10 and 11). Halauxifen provided excellent control of henbit (90%) and purple deadnettle (99%). For both species, halauxifen was much more effective than 2,4-D and dicamba which controlled henbit 8% and purple deadnettle 3 to 7%. Research on halauxifen for control of henbit and purple deadnettle is limited. Steckel (2018) reported halauxifen plus florasulam adequately controlled henbit in winter wheat. Glyphosate has traditionally controlled henbit and purple deadnettle well (York and Cahoon 2018). Similar results were observed in these experiments. Henbit control was complete with glyphosate alone and glyphosate combinations and 10% greater than control by halauxifen. Purple deadnettle control by glyphosate alone, glyphosate combinations, and halauxifen alone was similar (99%) and much greater than control by dicamba or 2,4-D alone

Akin to visible henbit and purple deadnettle control data, density of the weeds was greatest in plots treated with dicamba and 2,4-D (Table 11). Henbit and purple deadnettle densities were similar in the nontreated check and in dicamba- or 2,4-D-treated plots. Compared to nontreated check plots, halauxifen, glyphosate alone, and glyphosate combinations reduced henbit and purple deadnettle densities 97 to 100% while no reduction was noted with dicamba or 2,4-D applied alone.

Daisy Fleabane. Daisy fleabane control was not adequately controlled by the auxin herbicides applied alone (Table 10). Halauxifen, dicamba, 2,4-D LR, and 2,4-D HR controlled the weed 66, 55, 24, and 39%, respectively. However, halauxifen was more effective than dicamba or either rate of 2,4-D. Daisy fleabane control by auxin herbicides is less understood than horseweed. Although daisy fleabane control by auxin herbicides was less than horseweed in this experiment, similar trends for control of both weeds were observed. Like horseweed, halauxifen and dicamba were more effective than 2,4-D. Furthermore, like horseweed, 1066 g ai ha^{-1} 2,4-D controlled daisy fleabane greater than 2,4-D at 33 g ai ha^{-1} 2,4-D. Herbicide treatments containing glyphosate controlled daisy fleabane well (98 to 100%). Daisy fleabane is not as prominent in the southern U.S. as horseweed (Webster 2013) and there are no confirmed cases of herbicide-resistant daisy fleabane (Heap 2018).

Daisy fleabane density was much less than other weeds; 5 plants 100 m^{-2} were observed in nontreated checks (Table 11). All herbicide treatments reduced daisy fleabane density compared to nontreated checks. Similar to visible estimates, daisy fleabane density was greatest in plots treated only with auxin herbicides. The low rate of 2,4-D was least effective reducing daisy fleabane density (60%) whereas halauxifen, dicamba, and 2,4-D HR reduced daisy fleabane density 80%. Glyphosate alone and glyphosate combinations completely removed daisy fleabane.

Cutleaf Evening-Primrose. Cutleaf evening-primrose is commonly encountered preplant burndown in conservation or no-till systems (Culpepper et al. 2005; Vidrine et al. 2007; York and Cahoon 2018). Complicating cutleaf evening-primrose management is inadequate control by glyphosate and paraquat (Culpepper et al. 2005). York and Cahoon (2018) rate glyphosate poor to fair (50% expected control) for cutleaf evening-primrose. Additionally, the researchers reported paraquat can provide fair cutleaf evening-primrose control (50 to 80% expected control) only if the weed is blooming when treated. Likewise, Culpepper et al. (2005) reported glyphosate and paraquat controlled cutleaf evening-primrose 60 and 56% 28 d after treatment, respectively. Because cutleaf evening-primrose control by glyphosate and paraquat is inadequate, 2,4-D is normally recommended with the aforementioned herbicides to improve control of cutleaf evening-primrose and other weeds (York and Cahoon 2018). North Carolina researchers report cutleaf evening-primrose control by 2,4-D and glyphosate plus 2,4-D as excellent ($\geq$ 90%) and similarly Culpepper et al. (2005) documented the addition of 2,4-D to glyphosate improved cutleaf evening-primrose 37% 28 days after treatment compared to glyphosate alone.

Comparable to previous research, cutleaf evening-primrose control by glyphosate was inadequate (35%) in this experiment whereas 2,4-D LR and 2,4-D HR controlled the weed 74 to 85% (Table 12). Halauxifen and dicamba were less effective than 2,4-D, controlling the weed 4 and 51%, respectively. Halauxifen efficacy against cutleaf evening-primrose has not been documented previously although control is claimed on the label (Anon. 2018a). Auxin combinations with glyphosate were more effective than auxin herbicides alone or glyphosate alone. However, cutleaf evening-primrose control by glyphosate plus halauxifen (46%) and glyphosate plus dicamba (65%) was unacceptable. On the other hand, glyphosate plus 2,4-D controlled cutleaf evening-primrose 83 to 93%.

Cutleaf evening-primrose density in nontreated check plots averaged 1846 plants 100 m^{-2} (Table 13). All herbicide treatments, except halauxifen alone, reduced cutleaf evening-primrose density compared to the nontreated (Table 13). Similar to visible control data, of the auxin herbicides applied alone, 2,4-D reduced cutleaf evening-primrose density the greatest compared to the nontreated and was more effective than halauxifen and dicamba. Glyphosate reduced cutleaf evening-primrose density only 20%. Compared to glyphosate alone, halauxifen added to glyphosate had no effect on cutleaf evening-primrose density. Glyphosate plus 2,4-D had the greatest impact on cutleaf evening-primrose density, reducing density of the weed 77 to 91% compared to the nontreated. This research confirms 2,4-D is the product of choice for cutleaf evening-primrose control.

Curly Dock. Curly dock is a prominent weed observed in no-till fields prior to planting cotton (York and Collins 2016). Like cutleaf evening-primrose, curly dock control by glyphosate can be difficult (Culpepper 2018; Scott et al. 1998; York and Cahoon 2018). Scott et al. (1998) reported glyphosate at 560 to 1680 g ai ha^{-1} controlled curly dock 50 to 69% 2 WAT. Likewise, glyphosate in this study, controlled curly dock only 37% (Table 12). However, glyphosate more effectively controlled curly dock than halauxifen (5%). Dicamba and 2,4-D were more effective than glyphosate and halauxifen, controlling the weed 59 to 70%. Culpepper (2018) and York and Cahoon (2018) both reported 2,4-D to control curly dock 50 to 80%. Likewise, the researchers noted glyphosate plus 2,4-D to controlled the weed well. In this study, glyphosate plus 2,4-D HR controlled curly dock 78% and was the most effective treatment.

All treatments, except halauxifen, reduced curly dock density relative to the nontreated check (Table 13). Compared to the nontreated, glyphosate, dicamba, 2,4-D LR, and 2,4-D HR reduced curly dock density 56, 68, 77, and 96%, respectively. Similar to visible control data, 2,4-D HR and glyphosate plus 2,4-D HR reduced curly dock density the greatest.

Purple Cudweed. Purple cudweed control by halauxifen, dicamba, and 2,4-D was poor (Table 12). Purple cudweed control by these treatments ranged 7 to 21% and corroborates cudweed species (*Gnaphalium* ssp.) control ratings reported by other researchers (Culpepper 2018; York and Cahoon 2018). These researchers also note glyphosate results in excellent cudweed species control. Similarly, purple cudweed was controlled 100% by glyphosate alone and glyphosate combinations in these experiments.

Purple cudweed densities corresponded to visible control data. Nontreated plots had 249 purple cudweed plants 100 m^{-2} whereas plots treated with an auxin herbicide alone had similar densities (172 to 236 plants 100 m^{-2}). Only treatments containing glyphosate reduced purple cudweed density compared to the nontreated. Glyphosate and glyphosate combinations reduced purple cudweed density 95 and 100% compared to the nontreated, respectively.

Common Chickweed. The weed is also encountered burndown prior to planting cotton and other crops (York and Collins 2016). Common chickweed can be difficult to control with auxin herbicides (Culpepper 2018; York and Cahoon 2018). Monning and Bradley (2007) noted 2,4-D provided relatively poor control of common chickweed when applied during the fall or 30 and 60 days prior to planting no-till soybean. Results were similar for this experiment; 2,4-D controlled common chickweed 10 to 12% (Table 12). Akin to 2,4-D, common chickweed control by halauxifen (6%) and dicamba (10%) was also inadequate. On the other hand, glyphosate alone and glyphosate plus auxin herbicides controlled common chickweed 100%. These results were similar to previous reports of effective common chickweed control by glyphosate plus 2,4-D (Hasty et al. 2004; Monning and Bradley 2007)

Common chickweed density averaged 1111 plants 100 m^{-2} (Table 13). Relative to the nontreated, halauxifen, dicamba, and 2,4-D did not reduce common chickweed density. Glyphosate alone and glyphosate combinations reduced common chickweed density 95 to 100%.

Trends for mouseear chickweed control and density were similar to common chickweed (data not shown); halauxifen, dicamba, and 2,4-D provided poor control whereas treatments including glyphosate provided near complete control.

These data from North Carolina and Virginia and research from Indiana (Zimmer et al. 2018a, 2018b) indicate halauxifen effectively controls horseweed. In this experiment, halauxifen controlled horseweed averaging 5 cm in height similar to dicamba and was more effective than 2,4-D at 533 or 1066 g ai ha^{-1}. For horseweed 15 cm tall, halauxifen was slightly more effective than dicamba and controlled the weed 15 to 29% greater than 2,4-D. Outside of horseweed, information is limited on efficacy of halauxifen for many other weed species. Steckel (2018) observed halauxifen plus florasulam controlled henbit. However, it was not distinguished which active ingredient or if both were responsible for henbit control. In this experiment, henbit and purple deadnettle control by halauxifen was excellent compared to poor control by 2,4-D and dicamba. Likewise, halauxifen controlled daisy fleabane greater than dicamba and 2,4-D. Despite effectiveness against horseweed, daisy fleabane, henbit, and purple deadnettle, halauxifen was less effective against other weeds in this experiment. Like 2,4-D and dicamba, purple cudweed, common chickweed, and mouseear chickweed control by halauxifen was poor (Culpepper 2018; Monning and Bradley 2007; York and Cahoon 2018). More notable, halauxifen controlled cutleaf evening-primrose and curly dock less than dicamba and 2,4-D. This is of particular concern because cutleaf evening-primrose and curly dock are commonly encountered preplant burndown (York and Collins 2016) and glyphosate is weak on these species (Culpepper 2018; Culpepper et al. 2005; Scott et al. 1998; York and Cahoon 2018); 2,4-D is often relied upon in combination with glyphosate to control these weeds. Replacing 2,4-D with halauxifen in preplant burndown applications may result in inadequate control of cutleaf evening-primrose and curly dock. In conclusion, halauxifen is a useful tool for horseweed, henbit, and purple deadnettle management. However, future research should address combinations of halauxifen with glyphosate and various rates of 2,4-D for broader spectrum weed control, especially where cutleaf evening-primrose and curly dock are commonplace.

Literature Cited

Anonymous (2018a) Elevore™ herbicide product label. Dow AgroSciences. Indianapolis, IN: http://www.cdms.net/ldat/ldE1J001.pdf. Accessed March 2, 2018.

Anonymous (2018b) Quelex™ herbicide product label. Dow AgroSciences. Indianapolis, IN: http://www.cdms.net/ldat/ldDBL000.pdf. Accessed March 2, 2018.

Bhowmik PC and Bekech MM (1993) Horseweed (*Conyza canadensis*) seed production, emergence, and distribution in no-tillage and conventional-tillage corn (*Zea mays*). Agronomy Trends in Agriculture Science 1:67-71

Braz GBP, Oliveira RS, Zobiole LHS, Rubin RS, Voglewede C, Constantin J, Takano HK (2017) Sumatran fleabane (*Conyza sumatrensis*) control in notillage soybean with diclosulam plus halauxifen-methyl. Weed Technology 31:184–192

Bruce JA and Kells JT (1990) Horseweed (*Conyza canadensis*) Control in No-Tillage Soybeans (*Glycine max*) with Preplant and Preemergence Herbicides. Weed Technology 4:642-647

Budd CM, Soltani N, Robinson DE, Hooker DC, Mill RT, and Sikkema P (2017) Efficacy of Saflufenacil for Control of Glyphosate-Resistant Horseweed (*Conyza canadensis*) as Affected by Height, Density, and Time of Day. Weed Science 65:275-284

Byker HP, Soltani N, Robinson DE, Tardif FJ, Lawton MK, and Sikkema PH (2013) Control of Glyphosate-Resistant Horseweed (Conyza canadensis) with Dicamba Applied Preplant and Postemergence in Dicamba-Resistant Soybean. Weed Technology 27:492-496

Culpepper AS, Carlson DS, and York AC (2005) Pre-plant Control of Cutleaf Eveningprimrose (*Oenothera laciniata* Hill) and Wild Radish (*Raphanus* raphanistrum L.) in Conservation Tillage Cotton (*Gossypium hirsutum* L.). The Journal of Cotton Science 9:223-228

Culpepper S (2018) Weed Management in Cotton. Pages 16-71 in 2018 Georgia Cotton Production Guide. http://www.ugacotton.com/vault/file/2018-UGA-COTTON-PRODUCTION-GUIDE-1.pdf. Accessed November 18, 2018

Dunnett CW (1955) A multicomparisons procedure for comparing several treatments with a control. J Am Stat Assoc 50:1096–1121

Epp JB, Alexander AL, Balko TW, Buysse AM, Brewster WK, Bryan K, Daeuble JF, Fields SC, Gast RE, Green RA, Irvine NM, Lo WC, Lowe CR, Renga JM, Richburg JS, Ruiz JM, Satchivi NM, Schmitzer PR, Siddall TL, Webster JD, Wimer MR, Whiteker GT, and Yerkes CN (2016) The discovery of Arylex™ active and Rinskor™ active: Two novel auxin herbicides. Journal of Bioorganic and Medicinal Chemistry 24:362-371

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, and Reynolds DB (2008) Glyphosate-Resistant Horseweed (*Conyza canadensis*) Control using Glyphosate, Paraquat, and Glufosinate-based Herbicide Programs. Weed Technology 22:16-21

Eubank TW, Nandula VK, Poston DH, Shaw DR (2012) Multiple Resistance to Glyphosate and Paraquat and Its Control with Paraquat and Metribuzin Combinations. Agronomy 2:358-370

Frans R E, 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. Champaign, IL: Southern Weed Science Society

Hasty RF, Sprague CL, and Hager AG (2004) Weed Control with fall and early preplant herbicide application in no-till soybean. Weed Technology 18:887-892

Heap I (2018) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=61. Accessed on February 28, 2018

Keeling JW, Henniger CG, and Abernathy JR (1989) Horseweed (*Conyza canadensis*) control in conservation tillage cotton (*Gossypium hirsutum*). Weed Technology 3:399-401

Kruger GR, Davis VM, Weller SC, and Johnson WG (2007) Investigating Indiana horseweed (*Conyza canadensis*) populations for response to 2,4-D. Proceedings of the North Central Weed Science Society. 62:101

Kruger GR, Davis VM, Weller SC, and Johnson WG (2010) Control of Horseweed (*Conyza canadensis*) with Growth Regulator Herbicides. Weed Technology 24:425-429

Loux M, Stachler J, Johnson B, Nice G, Davis V, and Nordby D (2006) Biology and Management of Horseweed. Purdue Extension Publication GWC-9. Pp. 1-11

McCauley CL and Young B (2016) Control of Glyphsoate-Resistant Horseweed (*Conyza canadensis*) with Halauxifen-methyl Versus Dicamba and 2,4-D. Page 37 *In* Proceedings of the 71st Annual North Central Weed Science Society. Des Moines, IA.

Mehlich A (1984) Photometric determination of humic matter in soils, a proposed method. Communications in Soil Science and Plant Analysis 15:1417–1422

Monning N and Bradley KW (2007) Influence of Fall and Early Spring Herbicide Applications on Winter and Summer Annual Weed Population in No-till Soybean. Weed Technology 21:724-731

Ross MA, and Childs DJ (1996) Herbicide Mode-Of-Action Summary. https://www.extension.purdue.edu/extmedia/ws/ws-23-w.html. Accessed November 18, 2018

Scott R, Shaw DR, and Barrentine WL (1998) Glyphosate Tank Mixtures with SAN 582 for Burndown or Postemergence Applications in Glyphosate-Tolerant Soybean (*Glycine max*). Weed Technology 12:23-26

Shields EJ, Dauer JT, VanGessel MJ, and Neumann G (2006) Horseweed (*Conyza canadensis*) seed collected in a planetary boundary layer. Weed Science 54:1063-1067

Steckel LE and Gwathmey CO (2009) Glyphosate-Resistant Horseweed (Conyza canadensis) Growth, Seed Production, and Interference in Cotton. Weed Science 57:346-350

Steckel L (2008) Cutleaf evening primrose (*Oenothera laciniata Hill*). https://extension.tennessee.edu/publications/Documents/W209.pdf. Accessed November 2, 2018

Steckel L (2018) New broadleaf herbicide options available in wheat. http://eds.a.ebscohost.com.ezproxy.lib.vt.edu/eds/pdfviewer/pdfviewer?vid=5&sid=84bf2840-ea10-4d19-9438-d029a2d93c1d%40sessionmgr4009. Accessed October 1, 2018

Uva RH, Neal JC, DiTomaso JM (1997) *Weeds of the Northeast*. Ithaca, NY: Cornell University Press. 397

VanGessel MM (2001) Glyphosate-resistant horseweed from Delaware. Weed Science 49:703-705

Vidrine PR, Miller DK, Sanders DE, Scroggs DM, and Stewart AM (2007) Controlling Weeds in Cotton. https://www.lsuagcenter.com/~/media/system/e/6/6/4/e664015324796f18eea141420974bc2c/pub2746weedsincotton2007final.pdf. Accessed November 3, 2018

Weaver SE (2001) The biology of Canadian weeds' 115: *Conyza canadensis*. Canada Journal of

Webster TM (2013) Weed Survey- Southern States Broadleaf Crops Subsection (Cotton, Peanut, Soybean, Tobacco, Forestry). Pages 275-287 *In* Proceedings of the 66th Annual Southern Weed Science Society. Houston, TX.

Weed Science Society of America (2018) Summary of Herbicide Mechanism of Action According to WSSA. http://wssa.net/wp-content/uploads/WSSA-Mechanism-of-Action.pdf. Accessed March 2, 2018

York AC and Collins G (2016) March is Burndown Time. https://cotton.ces.ncsu.edu/2016/03/march-is-burndown-time-york-collins/. Accessed November 18, 2018

York AC and Cahoon CW (2018) Weed Management in Cotton. Pages 83-132 *in* 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Zimmer M, Young BG, and Johnson WG (2018a) Herbicide Programs Utilizing Halauxifen-Methyl for Glyphosate-Resistant Horseweed (*Conyza canadensis*) Control in Soybean. Weed Technology doi: 10.1017/wet.2018.60

Zimmer M, Young BG, Johnson WG (2018b) Weed Control with Halauxifen-Methyl Applied Alone and in Mixtures with 2,4-D, Dicamba, and Glyphosate. Weed Technology 32:597–602

Table 8. Locations, soil descriptions, and herbicide application dates.

Location	Year	Soil series	Soil texture	pH	Humic matter[f]	Application date
Painter, VA Field 1	2017	Bojac[a]	Sandy-loam	6.4	0.5	March 20
Painter, VA Field 2	2017	Bojac	Sandy-loam	6.4	0.5	April 20
Painter, VA Field 3	2017	Bojac	Sandy-loam	6.4	0.5	March 3
Rocky Mount, NC	2017	Aycock[b]	Sandy-loam	5.9	0.36	March 23
Jackson, NC	2017	Craven[c]	Sandy-loam	5.7	0.13	March 23
Painter, VA Field 1	2018	Bojac	Sandy-loam	6.4	0.5	March 31
Painter, VA Field 2	2018	Bojac	Sandy-loam	6.4	0.5	April 6
Jackson, NC Field 1	2018	Craven	Sandy-loam	6.5	0.32	March 28
Jackson, NC Field 2	2018	Craven	Sandy-loam	6.5	0.32	April 3
Gates, NC Field 1	2018	Noboco[d]	Sandy-loam	7.1	0.46	March 28
Gates, NC Field 2	2018	Goldsboro[e]	Sandy-loam	6.0	0.56	March 28
Rocky Mount, NC	2018	Aycock	Sandy-loam	6.4	0.32	April 18

[a] Coarse-loamy, mixed, semiactive, thermic Typic Hapludults
[b] Fine-silty, siliceous, subactive, thermic Typic Paleudults
[c] Fine, mixed, subactive, thermic Aquic Hapludults
[d] Fine-loamy, siliceous, subactive, thermic Oxyaquic Paleudults
[e] Fine-loamy, siliceous, subactive, thermic Aquic Paleudults
[f] Humic matter determined according to Mehlich (1984)

Table 9. Herbicides and adjuvants used in experiments.[a]

Herbicides and adjuvants	Trade name	Formulation concentration	Application rate	Manufacturer
2,4-D	Weedar 64	456 g ae L^{-1}	533 (LR) or 1066 (HR) g ae ha^{-1}	Nufarm Inc.
Dicamba	Clarity	480 g ae L^{-1}	280 g ae ha^{-1}	BASF
Halauxifen-methyl	Elevore	69 g ae L^{-1}	5 g ae ha^{-1}	Corteva Agriscience
Glyphosate	Roundup PowerMAX	540 g ae L^{-1}	1260 g ae ha^{-1}	Monsanto Co.
Methylated seed oil	MSO Concentrate	100%	1% (v v^{-1})	Loveland Products, Inc.
Nonionic surfactant	Induce	90%	0.25% (v v^{-1})	Helena Chemical Co.

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

Table 10. Small horseweed, large horseweed, henbit, purple deadnettle, and daisy fleabane control 4 wks after treatment.[a]

Herbicide[b]	Small horseweed[c]	Large horseweed[c]	Henbit	Purple deadnettle	Daisy fleabane
			%		
Halauxifen	89 C	79 C	90 B	99 A	66 B
Dicamba	91 C	77 D	8 C	5 B	55 C
2,4-D LR	72 E	50 F	8 C	3 C	24 D
2,4-D HR	80 D	64 E	8 C	7 B	39 E
Glyphosate	95 B	95 B	100 A	99 A	99 A
Glyphosate + halauxifen	99 A	99 A	100 A	99 A	100 A
Glyphosate + dicamba	99 A	99 A	100 A	99 A	100 A
Glyphosate + 2,4-D LR	96 AB	98 A	100 A	99 A	98 A
Glyphosate + 2,4-D HR	98 AB	98 A	100 A	99 A	98 A

[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] Application rates are listed in Table 9.
[c] Small and large horseweed averaged 5 and 15 cm in height, respectively.

Table 11. Small horseweed, large horseweed, henbit, purple deadnettle, and daisy fleabane density 4 wks after treatment.[a,b]

Herbicide[c]	Small horseweed[d]	Large horseweed[d]	Henbit	Purple deadnettle	Daisy fleabane
	plants 100 m^{-2}				
Halauxifen	16 BCD	166 AB	0 B	0 B	1 B
Dicamba	19 BC	104 BC	994 A*	1550 A*	1 B
2,4-D LR	42 A	260 A	838 A*	1600 A*	2 A
2,4-D HR	25 B	195 AB	731 A*	1600 A*	1 B
Glyphosate	21 B	48 C	19 B	0 B	0 C
Glyphosate + halauxifen	6 CD	0 C	0 B	0 B	0 C
Glyphosate + dicamba	1 D	23 C	44 B	0 B	0 C
Glyphosate + 2,4-D LR	11 BCD	9 C	38 B	0 B	0 C
Glyphosate + 2,4-D HR	2 D	9 C	25 B	0 B	0 C
Nontreated	603	484	1363	1600	5

[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] Means within a column followed by an asterisk (*) are not different from nontreated check according to Dunnett's procedure at P = 0.05.

[c] Application rates are listed in Table 9.

[d] Small and large horseweed averaged 5 and 15 cm in height, respectively.

Table 12. Cutleaf evening-primrose, curly dock, purple cudweed, and common chickweed control 4 wks after treatment.[a]

Herbicide[b]	Cutleaf evening-primrose	Curly dock	Purple cudweed	Common chickweed
	%			
Halauxifen	4 H	5 F	7 D	6 D
Dicamba	51 E	59 D	21 B	10 C
2,4-D LR	74 C	62 D	13 C	10 C
2,4-D HR	85 B	70 C	21 B	12 B
Glyphosate	35 G	37 E	100 A	100 A
Glyphosate + halauxifen	46 F	38 E	100 A	100 A
Glyphosate + dicamba	65 D	72 B	100 A	100 A
Glyphosate + 2,4-D LR	83 B	74 B	100 A	100 A
Glyphosate + 2,4-D HR	93 A	78 A	100 A	100 A

[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] Application rates are listed in Table 9.

Table 13. Cutleaf evening primrose, curly dock, purple cudweed, and common chickweed density 4 wks after treatment.[a,b]

Herbicide[c]	Cutleaf evening-primrose	Curly dock	Purple cudweed	Common chickweed
	plants 100 m^{-2}			
Halauxifen	1979 A*	617 A*	236 A*	1552 A*
Dicamba	853 C	269 CD	224 A*	1322 A*
2,4-D LR	567 DE	190 D	172 A*	1322 A*
2,4-D HR	343 EF	36 E	217 A*	1387 A*
Glyphosate	1480 B	371 BC	13 B	58 B
Glyphosate + halauxifen	1275 B	454 AB	0 B	17 B
Glyphosate + dicamba	779 CD	135 DE	0 B	0 B
Glyphosate + 2,4-D LR	424 EF	102 DE	0 B	0 B
Glyphosate + 2,4-D HR	163 F	86 E	0 B	0 B
Nontreated	1846	836	249	1111

[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] Means within a column followed by an asterisk (*) are not different from nontreated check according to Dunnett’s procedure at P = 0.05.
[c] Application rates are listed in Table 9.

Cotton (*Gossypium hirsutum* L.) Tolerance to Halauxifen-methyl Applied Preplant

Abstract

Due to the conservation tillage being widely adopted, herbicides applied preplant are essential for controlling weeds. Auxin herbicides are widely used preplant burndown in combination with glyphosate to increase the control spectrum and address glyphosate-resistant weeds, such as horseweed. Herbicides labels for 2,4-D containing products require 30- to 90-days between herbicide application and cotton planting for cultivars not resistant to 2,4-D. Dicamba containing herbicide labels require an accumulation of 2.5 cm of rain plus 21 d per 280 g ae ha^{-1} between herbicide application and cotton planting for cultivars not resistant to dicamba. Previous research has shown that cotton injury caused by dicamba applied 14 d before planting was transient and had little effect on cotton yield. Likewise, similar research has shown that 2,4-D has little effect on cotton when applied 7 d prior to planting. Injury caused by dicamba and 2,4-D is inversely related to rainfall received between herbicide application and cotton planting. Experiments were conducted to evaluate cotton tolerance to halauxifen-methyl, a new Group 4 herbicide, applied at shorter intervals than the 30 d label requirement. Experiments were established near Painter, VA, Suffolk, VA, Belvidere, NC, Clayton, NC, Eure, NC, Lewiston, NC, and Rocky Mount, NC during the 2017 and 2018 growing seasons. Herbicide treatments included halauxifen, dicamba, and 2,4-D applied 4 weeks before planting (WBP), 3 WBP, 2 WBP, 1 WBP, and at-planting. Visible estimates of cotton injury (growth reduction, chlorosis, necrosis, and total injury recorded separately) were collected 1, 2, and 4 wk after cotton emergence (WAE). Cotton stand and percentage of plants with distorted leafs were collected 2 and 4 WAE. Cotton plant heights were measured and recorded 4 and 8 WAE. Halauxifen (9%)

was less injurious than dicamba (26%) and 2,4-D (21%) 2 WAE when the herbicides were applied at-planting. In addition, cotton stand reduction 2 WAE by halauxifen was less than dicamba and 2,4-D applied at-planting. Injury observed from herbicides applied 1, 2, 3, and 4 WBP was minor and no significant differences in cotton stand were observed. Early season cotton injury was transient and seedcotton yield was unaffected.

Since conservation compliance provisions were implemented in the 1985 farm bill, conservation tillage has been widely adopted. During 2004, nearly 22% of U.S. cotton acreage was devoted to conservation tillage (CTIC 2004). With decreasing tillage, preplant herbicides have become essential for controlling weeds in conservation tillage systems (York et al. 2004). Glyphosate and paraquat have traditionally been relied upon to control most weeds preplant. Prior to development of glyphosate-resistant horseweed (*Conyza canadensis* L.), glyphosate provided excellent horseweed control (87 to 100%), preplant control of weeds is important for beginning the season weed free (Bruce and Kells 1990; Scott et al. 1998). Paraquat offers adequate control of smaller horseweed, however paraquat resistance biotypes have been identified (Keeling et al 1989; Eubank et al 2008; Heap 2018). Due to development of glyphosate- and ALS-resistant horseweed, cotton producers turned to synthetic auxin herbicides to control this troublesome weed preplant (Wilson and Worsham 1988; Bruce and Kells 1990; York et al. 2004). Dicamba and 2,4-D are the most widely used synthetic auxins for herbicide-resistant horseweed control prior to planting cotton (Byker et al. 2013; Flessner et al. 2015, Kruger et al. 2010). These herbicides are often applied 3 to 4 wks prior to cotton planting in combination with glyphosate and flumioxazin to control emerged horseweed and other winter annual weeds and include preemergence, residual weed control (Cahoon et al. 2014). However, 2,4-D does not consistently control horseweed that has bolted and is taller than 10 cm (Keeling et al. 1989).

Halauxifen-methyl (Elevore™, Dow AgroSciences, Indianapolis, IN.) is a new Group 4, synthetic auxin herbicide and a member of the pyridine-2-carboxylate (or arylpicolinate) herbicide family (Epp et al. 2016; WSSA 2018). Other members of the pyridine-2-carboxylate family include picloram, clopyralid, and aminopyralid (Epp et al. 2016). Halauxifen is being marketed for use preplant burndown targeting broadleaf annual weeds under the trade name Elevore™ (Anonymous 2018a). Halauxifen is also being marketed in a pre-mix with florasulam, an ALS-inhibiting herbicide, for postemergence control of broadleaf weeds in wheat, barley, and triticale (Anonymous 2018b).

Previous research determined halauxifen controlled horseweed similar to 2,4-D and dicamba (Zimmer et al. 2018a; Zimmer et al 2018b; McCauley and Young 2016; Ellis et al. 2017). Similar to these observations, Zimmer and others (2018a, 2018b) observed 87 to 97% control of glyphosate-resistant horseweed from treatments containing halauxifen. In another study, halauxifen and dicamba controlled glyphosate-resistant horseweed, up to 30 cm in height, 80% whereas 2,4-D controlled the weed 50% or less (McCauley and Young 2016)

Most labels for 2,4-D containing products used preplant require application 30 d prior to cotton planting (Anonymous 2018c, Anonymous 2018d; Anonymous 2018e). Other 2,4-D products require 90 d between application and planting of a non-labeled crop (Anonymous 2018f; Anonymous 2018g; York et al. 2004). Enlist Duo™ and Enlist One™, products containing 2,4-D choline, are labelled for application prior to and at planting and postemergence use in cotton with the Enlist™ trait (Anonymous 2018h; Anonymous 2018i). Dicamba formulations labeled prior to planting cotton (Anonymous 2018j; Anonymous 2018k; Anonymous 2018l; Anonymous 2018m; York et al. 2004). These products require 2.5 cm of rainfall or overhead irrigation followed by 21 d per 280 g acid equivalent (ae) ha^{-1} prior to planting non dicamba-resistant cotton (Anonymous 2018j; Anonymous 2018k; Anonymous 2018l; Anonymous 2018m). Engenia®, FeXapan™ herbicide plus VaporGrip™ technology, and XtendiMax® with VaporGrip® technology products labeled for preplant, preemergence, and postemergence use in XtendFlex® cotton. Previous research determined cotton injury from dicamba (280 g ae ha^{-1}) applied preplant seemed to be inversely correlated with rainfall received (Ferguson 1996). No cotton injury was observed when at least 2.5 cm of rainfall fell between herbicide applications and cotton planting, how, dicamba injured cotton greater than 2,4-D when < 2.5 cm of rainfall was received between application and cotton planting (Guy and Ashcraft 1996). York and others (2004) observed similar results; dicamba, was more injurious than 2,4-D when applied sooner than 21 d prior to planting cotton. However, early season injury caused by dicamba was transient, and had little effect on cotton yield when applied 2 or more wks before planting especially at 280 g ae ha^{-1}. In the same study, 2,4-D injured cotton at one location only when applied 1 wk prior to planting. Similar to findings by Ferguson (1996) and Guy and Ashcraft (1996), York and others (2004) noted cotton injury from preplant applied 2,4-D and dicamba at a few locations was inversely related to rainfall received between herbicide applications and cotton planting. Halauxifen currently has a 14 d rotational interval to corn and soybean and a 30 d rotational interval to cotton (Anonymous 2018a). While cotton response to 2,4-D and dicamba applied preplant sooner than product labels allow is well understood, research is limited on cotton tolerance to halauxifen applied less than 30 d prior to planting. The objective of this study was to evaluate cotton tolerance to halauxifen when applied preplant burndown at intervals shorter than 30 d prior to planting.

Materials and Methods

Experiments were conducted at the Eastern Shore Agriculture Research and Extension Center near Painter, VA (37.58° N, 75.78° W), at the Tidewater Agriculture Research and Extension Center near Suffolk, VA (36.7282° N, 76.5836° W), at the Central Crops Research Station near Clayton, NC (35.6507° N, 78.4564° W), and at the Upper Coastal Plain Research Station near

Rocky Mount, NC (35.9382° N, 77.7905° W) during the 2017 growing season. During the 2018 growing season, experiments were conducted at the Tidewater Agronomics Research Farm near Belvidere, NC (36.2688° N, 76.5358° W), a producer's field near Eure, NC (36.4202° N, 76.6875° W), at the Peanut Belt Research Station near Lewiston, NC (36.1229° N, 77.1766° W), and at the Upper Coastal Plain Research Station near Rocky Mount, NC (35.9382° N, 77.7905° W). Soil descriptions are listed in Table 14. The experiment was arranged in a randomized complete block design with treatments replicated four times. Treatment structure was a four by five factorial arrangement of four herbicide treatments by five preplant burndown timings. Plots were 4 rows wide at all locations, plot sizes varied by location and are presented in Table 14.

Stoneville cotton cultivars "ST 4946GLB2" or "ST 5020GLT (Bayer CropScience, Research Triangle Park, NC), resistant to glufosinate and glyphosate, were planted at all locations on dates listed in Table 14. Cultivars were selected to avoid auxin resistance, so that there would be no chance of halauxifen tolerance. Cotton in Virginia and at the Eure location was planted using a strip-tillage system (Edmisten et al. 2018a), however, strip-tillage occurred prior to any herbicide applications as not to disturb herbicides. At Clayton, Lewiston, and Rocky Mount 2017 and 2018 locations, cotton was planted no-till. At Belvidere location, cotton was planted using conventional tillage. Trials in Clayton and Suffolk received glyphosate at 1260 g ae ha^{-1} plus glufosinate at 655 g ai ha^{-1} applied immediately prior to planting whereas Rocky Mount received paraquat applied at 840 g ai ha^{-1}. Plots were maintained weed-free at all locations using glyphosate plus glufosinate at the rates listed above as needed. Experiments in Clayton and Rocky Mount 2017 received aldicarb (2-methyl-2-(methylthio)propionaldehyde O-(methylcarbamoyl)oxime) insecticide (Temik®, Bayer CropScience, Research Triangle Park, NC) applied in-furrow at 5600 g ai ha^{-1}. Experiments in Eure and Belvidere received imidacloprid (1-[(6-Chloro-3-pyridinyl)methyl]-*N*-nitro-2-imidazolidinimine) (Admire Pro™, Bayer CropScience, Research Triangle Park, NC) applied in-furrow at 370 g ai ha^{-1}. Other locations did not receive an insecticide in-furrow. All other agronomic practices varied among locations but were consistent with recommendations for the region (Edmisten et al. 2018b).

Herbicide treatments included nontreated, 2,4-D dimethylamine salt applied at 1060 g ae ha^{-1}, dicamba diglycolamine salt applied at 280 g ae ha^{-1}, and halauxifen applied at 5 g ae ha^{-1}. Herbicide sources are listed in Table 15. All herbicide treatments were applied 4 wks before planting (WBP), 3 WBP, 2 WBP, 1 WBP, and 0 WBP (immediately prior to planting, but allowed to dry for 1 hr before planting).

Interest in halauxifen + florasulam applied preplant burndown for control of herbicide-resistant horseweed and other winter annual weeds is increasing. However, current labels for halauxifen + florasulam premix products prohibit planting cotton within 3 months of the herbicide (Anonymous 2018b). To determine when halauxifen + florasulam premix can be safely applied, preplant burndown prior to planting cotton, halauxifen + florasulam premix applied 2 and 4 WBP were added to experiments during 2018. Halauxifen + florasulam premix was applied at a rate delivering 5.5 g ae ha^{-1} halauxifen and 5.3 g ai ha^{-1} florasulam.

Herbicides were applied using a CO_2-pressureized backpack sprayer equipped with flat-fan tips (TTI 110015 Turbo TeeJet® Induction flat spray tip, TeeJet Technologies, Wheaton, IL.) Applications were made at 140 L ha^{-1} of solution delivered at 206 kPa.

Weekly rainfall totals prior to cotton planting and for the first 10 d after planting and accumulated rainfall between each application and cotton emergence can be found in Table 16.

Visible cotton injury (growth reduction, chlorosis, necrosis, and total injury recorded separately) were evaluated according to Frans et al. (1986) and were collected 1, 2, and 4 w after cotton emergence (WAE). Cotton stand and percentage of plants with distorted leafs were collected 2 and 4 WAE. Cotton stand was collected by counting all cotton plants the middle two rows of each plot. Percentage of plants with distorted leafs (leaf distortion) were collected by counting the number of plants with distorted leaves in the middle 2 rows of each plot and dividing that by the total number of plants in each row. Cotton plant heights were measured and recorded 4 and 8 WAE. Cotton plant heights were collected from ten plants in the middle 2 rows of each plot. Plots were harvested on dates listed in Table 14 with a John Deere cotton picker modified for small-plot research and weighed to determine seedcotton yield.

Data were subjected to ANOVA using the PROC GLIMMIX procedure in SAS software (version 9.4, SAS Institute Inc., Cary, NC). Application timing and herbicide treatment were considered fixed factors, whereas location and replications were treated as random. The main effect of application timing and herbicide treatment as well as the two-way interaction of application timing by herbicide treatment were significant for cotton growth reduction, total injury, distorted leaf, and stand 2 and 4 WAE. However, little injury was observed from herbicides applied 1, 2, 3, and 4 WBP whereas herbicides applied immediately prior to cotton planting (0 WBP) were more injurious. Exclusion of data for 0 WBP timing allowed injury and stand data for 1, 2, 3, and 4 WBP to be pooled. Therefore, injury and stand data are presented pooled over timings 1, 2, 3, and 4 WBP with data for timing 0 WBP presented separately. The two-way interaction of application timing and herbicide treatment was not significant for cotton height and seedcotton yield. Data for these parameters are presented pooled over all application timings. Means were separated using Fisher’s protected LSD a P= 0.05 when appropriate.

Results and Discussion

Cotton response to herbicides applied at planting. Cotton response was greatest when synthetic auxin herbicides were applied at-planting. Dicamba applied at-planting caused 20 and 10% growth reduction 2 and 4 WAE, respectively, and was the greatest among herbicides evaluated (Table 17). Growth reduction in response to 2,4-D applied 0 WBP was slightly less injurious than dicamba; 2,4-D reduced cotton growth 17% 2 WAE and 8% 4 WAE. Halauxifen was the safest of all auxin herbicides evaluated, reducing cotton growth 3 and 0% 2 and 4 WAE, respectively. Total cotton injury followed a similar trend as growth reduction. Dicamba applied at-planting caused 26% total injury 2 WAE and was more injurious than 2,4-D (21%) and halauxifen (9%). Overall, injury decreased as the season progressed. At 4 WAE, dicamba and 2,4-D caused similar injury (11 to 12%). Early cotton injury caused by halauxifen was transient with no injury observed 4 WAE.

Typical injury from low doses of synthetic auxin herbicides or preplant applications of these herbicides includes malformed leaves, twisting and bending of stems, and cracked or swollen stems (Al-Khatib and Peterson 1999; Andersen et al. 2004; Auch and Arnold 1978; Guy and Ashcraft 1996; Kelley et al. 2005; Sciumbato et al. 2004; Solomon and Bradley 2014; Wax et al. 1969; York et al. 2004). To capture this injury in these experiments, percentage of plants with visible leaf distortion were determined similar to methods outlined by York and others (2004). Dicamba (22%) caused the greatest percentage of cotton plants with distorted leaves 2 WAE whereas fewer plants exhibited visible leaf distortion resulting from 2,4-D (9%) and halauxifen (6%) (Table 17). Cotton leaf distortion caused by halauxifen differed from dicamba and 2,4-D 4 WAE. While 2,4-D and dicamba produced leaf strapping and leaf cupping, respectively, halauxifen caused cotton leaves to curl or roll upward more similar to early cotton symptomology resulting from aminopyralid exposure (Rhodes et al. 2015). At 4 WAE, dicamba continued to cause some leaf distortion; leaf distortion in response to dicamba at this time was 5% whereas leaf distortion caused by 2,4-D was less (2%). No leaf distortion was observed from halauxifen 4 WAE.

Cotton treated with dicamba and 2,4-D at planting was slower to emerge than cotton treated with halauxifen at the same timing and nontreated checks. Cotton stand totaled 87 plants 10 m row^{-1} in nontreated checks 2 WAE and was similar to cotton stand in plots treated with halauxifen at planting (83 plants 10 m row^{-1}) (Table 17). Relative to the nontreated, dicamba and 2,4-D applied at plating reduced cotton stand 15 to 17% 2 WAE. Compared to cotton stand 2 WAE, although not statistically significant, numerical trends for cotton stand were similar 4 WAE. Likewise, York and others (2004) reported dicamba (280 g ae ha^{-1}) and 2,4-D (1060 g ae ha^{-1}) reduced cotton stand when applied 1 WBP in a strip-till system. These researchers did not investigate cotton response to these herbicides applied at-planting.

Cotton response to herbicides applied prior to planting. Cotton response was minimal from herbicides applied 1, 2, 3, and 4 WBP; therefore, data were pooled across these ratings. Cotton growth reduction and total injury was 2% or less 2 WAE and early season cotton injury dissipated quickly (Table 18). No cotton growth reduction or total injury was observed 4 WAE when synthetic auxin herbicides were applied 1 WBP or earlier in the spring. In contrast to percentage of cotton plants with distorted leaves observed when herbicide were applied at planting, herbicides applied 1 WBP or earlier produced 3% or less cotton leaf distortion (data not shown). Likewise, cotton stand was not influenced by 2,4-D, dicamba, or halauxifen applied 1 to 4 WBP. Cotton stand in response to all herbicide treatments applied 1 to 4 WBP ranged 83 to 85 plants 10 m row^{-1} 2 WAE and 86 to 88 plants 10 m row^{-1} 4 WAE; cotton stand in response to synthetic auxin herbicides applied 1 to 4 WBP was similar to nontreated checks. York and others (2004) noted 10% or less cotton plants with distorted leaves at 5 of 7 locations when dicamba (280 g ae ha^{-1}) and 2,4-D (1060 g ae ha^{-1}) were applied 1 to 6 WBP. At the remaining locations in this study, dicamba at 280 g ae ha^{-1} produced 12 to 40% and 0 to 30% plants with distorted leaves when applied 1 and 2 WBP, respectively. Percentage of cotton plants with distorted leaves in response to 2,4-D at 1060 g ae ha^{-1} applied 1 to 2 WBP ranged 0 to 29%. Differences in cotton injury across locations observed by York and others (2004) was likely influenced by rainfall. The risk of cotton injury from synthetic auxin herbicides applied preplant burndown is reduced when moderate rainfall accumulates between herbicide application and cotton planting (Anonymous 2018c; Anonymous 2018d; Anonymous 2018j; York et al. 2004). At locations where York and others (2004) observed the most cotton injury, accumulated rainfall for the 3 wk preceding cotton planting was least. Other researchers have noted a similar relationship between accumulated rainfall and cotton response to synthetic herbicides applied prior to planting (Ferguson 1996; Guy and Ashcraft 1996). North Carolina and Virginia both experienced abnormally wet springs during 2017 and 2018, which explains limited injury observed by synthetic auxin herbicides applied prior to cotton planting. In these experiments, accumulated rainfall following herbicides applied 1, 2, 3, and 4 WBP and cotton planting ranged 3.5 to 21.6 cm (Table 16). Following synthetic auxin herbicides applied at planting, rainfall the first 10 d after planting totaled at least 1.7 cm and was less than rainfall prior to cotton planting.

Cotton height and seedcotton yield. The two-way interactions of application timing by herbicide treatment for cotton height and seedcotton yield were not significant; therefore, data for these parameters are presented by herbicide treatment pooled over all application timings. Despite early season growth reduction, synthetic auxin herbicides had little effect on cotton height 4 WAE (Table 19). Cotton in nontreated plots averaged 26 cm in height and was slightly larger than cotton treated with 2,4-D, dicamba, and halauxifen (25 cm). At 8 WAE, cotton height ranged 63 to 64 cm and no difference between herbicide nor the nontreated check were observed. York and others (2004) reported cotton height and number of main-stem nodes in mid-July were not affected by 2,4-D or dicamba applied prior to cotton planting. Akin to cotton height, seedcotton yield was not influenced by early season cotton injury or stand reduction. Seedcotton yield totaled 3020 to 3450 kg ha^{-1} and plots treated with 2,4-D, dicamba, and halauxifen yielded similarly to nontreated plots. State average cotton lint yield during 2017 were 1090 kg ha^{-1} and 1250 kg ha^{-1} for North Carolina and Virginia, respectively (USDA-NASS 2017a: USDA-NASS 2017b). Cotton is an indeterminate plant capable of simultaneous vegetative and reproductive growth, giving the plant to the ability to recover well from early season stressors including drought, insects, diseases, weed competition, and herbicide injury (Edmisten and Collins 2018). Cotton lint yields during 2017 and 2018 are evidence of plentiful rainfall during these years and may explain why seedcotton yield in these experiments were not affected by minimal to moderate cotton injury observed early in the season.

Cotton tolerance to halauxifen + florasulam premix. Halauxifen + florasulam premix was applied 2 and 4 WBP during 2018 only. Cotton response to halauxifen + florasulam was minimal. The herbicide combination applied 2 or 4 WBP caused 3% or less cotton growth reduction and 2% or less total injury (data not shown). Similar to cotton response to 2,4-D, dicamba, and halauxifen applied at the same application timings, halauxifen + florasulam did not affect cotton stand, cotton height, or seedcotton yield compared to the nontreated check (data not shown). No published research is available on cotton tolerance to halauxifen or florasulam applied prior to planting.

In general, results from these experiments, and other research from North Carolina and Georgia (York et al. 2004), confirm cotton can be safely planted following 2,4-D and dicamba applied preplant burndown if label requirements for plant back interval and rainfall or soil moisture are met. Current labels for halauxifen and halauxifen + florasulam containing products require at least 30 and 90 d between application of these herbicides and cotton planting, respectively. Much shorter plant-back intervals were investigated in this research. Cotton tolerance to halauxifen applied preplant burndown was greater than 2,4-D and dicamba. Early season cotton injury caused by halauxifen was transient with no injury observed in response to the herbicide 4 WAE. Furthermore, regardless to timing, halauxifen did not affect cotton stand or seedcotton yield. Likewise, halauxifen + florasulam applied 2 and 4 WBP during 2018 caused little injury and did not affect cotton stand or seedcotton yield. Therefor this research confirms halauxifen and halauxifen + florasulam can be safely applied prior to planting cotton at currently required plant-back intervals and indicates plant-back intervals may be shortened. These herbicides applied at least 2 WBP injured cotton 2% or less. Because cotton tolerance to halauxifen + florasulam was only investigated during 2018, more research on cotton tolerance to this premix applied prior to planting is needed. Due to wet conditions during April and May of each year, cotton tolerance to halauxifen applied preplant when conditions are dry between application and cotton planting should also be investigated.

Literature Cited

Al-Khatib K and Peterson D (1999) Soybean (Glycine max) response to simulated drift from selected sulfonylurea herbicides, dicamba, glyphosate, and glufosinate. Weed Technology 13:264–270

Andersen SM, Clay SA, Wrage LJ, and Matthees D (2004) Soybean foliage residues of dicamba and 2,4-D and correlation to application rates and yield. Agronomy Journal 96:750–760

Anonymous (2018a) Elevore™ herbicide product label. Dow AgroSciences. Indianapolis, IN: http://www.cdms.net/ldat/ldE1J001.pdf. Accessed February 14, 2018.

Anonymous (2018b) Quelex™ herbicide product label. Dow AgroSciences. Indianapolis, IN: http://www.cdms.net/ldat/ldDBL000.pdf. Accessed February 15, 2018.

Anonymous (2018c) Barrage® HF herbicide product label. Helena Chemical Company, Collierville, TN. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Barrage_HF_Label1h.pdf. Accessed February 15, 2018

Anonymous (2018d) Salvo® herbicide product label. Loveland Products, Inc. Loveland, CO. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Salvo_Label5.pdf. Accessed February 15, 2018

Anonymous (2018e) Savage® herbicide product label. Loveland Products, Inc. Loveland, CO. https://s3-us-west-1.amazonaws.com/www.agrian.com/pdfs/Savage_Label7.pdf. Accessed February 15, 2018

Anonymous (2018f) Weedar® 64 herbicide product label. Nufarm, Inc. Alsip, IL. http://www.cdms.net/ldat/ld08K002.pdf. Accessed February 15, 2018.

Anonymous (2018g) Weedone® LV4 EC herbicide product label. Nufarm, Inc. Aslip, IL. http://www.cdms.net/ldat/ld5PB002.pdf. Accessed February 15, 2018

Anonymous (2018h) Enlist Duo™ herbicide product label. Dow AgroSciences. Indianapolis, IN. http://www.cdms.net/ldat/ldAEA005.pdf

Anonymous (2018i) Enlist One™ herbicide product label. Dow AgroSciences. Indianapolis, IN. http://www.cdms.net/ldat/ldAEA005.pdf

Anonymous (2018j) Clarity® herbicide product label. BASF. Research Triangle Park, NC. http://www.cdms.net/ldat/ld797012.pdf. Accessed February 15, 2018

Anonymous (2018k) Engenia® herbicide product label. BASF. Research Triangle Park, NC. http://www.cdms.net/ldat/ldDG8015.pdf

Anonymous (2018l) Xtendimax™ herbicide product label. Monsanto Company. St. Louis, MO. http://www.cdms.net/ldat/ldDF9000.pdf

Anonymous (2018m) FeXapan™ herbicide product label. DuPont. Wilmington, DE. http://www.cdms.net/ldat/ldDJ1011.pdf

Auch DE and Arnold WE (1978) Dicamba use and injury on soybeans (Glycine max) in South Dakota. Weed Science 26:471– 475

Bruce JA and Kells JJ (1990) Horseweed (*Conyza canadensis*) control in no-tillage soybeans (*Glycine max*) with preplant and preemergence herbicides. Weed Technology 4:62-647

Byker HP, Soltani N, Robinson DE, Tardif FJ, Lawton MB, and Sikklema PH (2013) Control of glyphosate resistant horseweed (*Conyza canadensis*) with dicamba applied preplant and postemergence in dicamba-resistant soybean. Weed Technology 27:492-496

Cahoon CW, York AC, Jordan DL, Everman WJ, and Seagroves RW (2014) An Alternative to Multiple Protoporphyrinogen Oxidase Inhibitor Applications in No-Till Cotton. Weed Technology 28:58-71

Conservation Technology Information Center (2004) National crop residue management survey: conservation tillage data. http://www.ctic.purdue.edu/media/pdf/National%20Summary%202008%20(Amendment).pdf. Accessed February 13, 2018.

Edmisten K and Collins G (2018) The Cotton Plant. Pages 5-15 *in* 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Edmisten K, Collin G, Vann RA, Foote B, and York AC (2018a) Cotton Production with Conservation Tillage. Pages 170-179 *in* 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service

Edmisten K, Collins G, Crozier C, Meijer A, York A, Hardy D, Reisig D, Bullen G, Thiessen L, and Vann R (2018b) 2018 Cotton Information. Publication AG-417. Raleigh, NC: North Carolina Cooperative Extension Service.

Ellis JM, Walton LC, Richburg JS, Haygood BA, Huckaba RM, Lovelace ML, Perry DH, and Peterson MA (2017) Utility of Elevore™ Herbicide with Arylex™ Active for Preplant Burndown Applications. Page 150 in Proceedings of the Southern Weed Science Society 70th Annual Meeting. Birmingham, AL.

Epp JB, Alexander AL, Balko TW, Buysse AM, Brewster WK, Bryan K, Daeuble JF, Fields SC, Gast RE, Green RA, Irvine NM, Lo WC, Lowe CR, Renga JM, Richburg JS, Ruiz JM, Satchivi NM, Schmitzer PR, Siddall TL, Webster JD, Wimer MR, Whiteker GT, and

Yerkes CN (2016) The discovery of Arylex™ active and Rinskor™ active: Two novel auxin herbicides. Journal of Bioorganic and Medicinal Chemistry 24:362-371

Eubank TW, Poston DH, Nandula VK, Koger CH, Shaw DR, and Reynolds DB (2008) Glyphosate-Resistant Horseweed (Conyza canadensis) Control Using Glyphosate-, Paraquat-, and Glufosinate-based Herbicide Programs. Weed Technology 22:16-21

Ferguson G (1996) Banvel SGF for preplant weed control in cotton. Pages 48-49 *In* Proceedings of the Beltwide Cotton Conference. Nashville, TN.

Flessner ML, McElroy JS, McCurdy JD, Toombs JM, Wehthe GR, Burmester CH, Price AJ, and Ducar JT (2015) Glyphosate-Resistant Horseweed (*Conyza canadensis*) Control with Dicamba in Alabama. Weed Technology 29:633-640

Frans RE, 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. Champaign, IL: Southern Weed Science Society

Guy CB and Ashcraft RW (1996) Horseweed and Cutleaf eveningprimrose control in no-till cotton. Page 1557 *In* Proceedings of the Beltwide Cotton Conference. Nashville, TN.

Heap I (2018) The International Survey of Herbicide Resistant Weeds. http://www.weedscience.org/Summary/Species.aspx?WeedID=61. Accessed on February 28, 2018

Keeling JW, Henniger CG, and Abernathy JR (1989) Horseweed (Conyza canadensis) Control in Conservation Tillage Cotton (Gossypium hirsutum). Weed Technology 3:399-401

Kelley KB, Wax LM, Hager AG, and Riechers DE (2005) Soybean response to plant growth regulator herbicides is affected by other postemergence herbicides. Weed Science 53:101–112

Kruger GR, Davis VM, Weller SC, and Johnson WG (2010) Control of Horseweed (*Conyza canadensis*) with Growth Regulator Herbicides. Weed Technology 24:425-429

Mehlich A (1984) Photometric determination of humic matter in soils, a proposed method. Communications in Soil Science and Plant Analysis 15:1417–1422

McCauley CL and Young B (2016) Control of Glyphsoate-Resistant Horseweed (*Conyza canadensis*) with Halauxifen-methyl Versus Dicamba and 2,4-D. Page 37 *In* Proceedings of the 71st Annual North Central Weed Science Society. Des Moines, IA.

Rhodes GN, Israel TD, and Steckel L (2015) Diagnosing Suspected Off-target Herbicide Damage to Cotton. https://cotton.ces.ncsu.edu/wp-content/uploads/2015/07/UT-Diagnosing-Suspected-Off-target-Herbicide-Damage-to-Cotton.pdf?fwd=no. Accessed November 21, 2018

Sciumbato AS, Chandler JM, Senseman SA, Bovey RW, and Smith KL (2004) Determining exposure to auxin-like herbicides. I. Quantifying injury to cotton and soybean. Weed Technology 18:1125–1134

Scott R, Shaw DR, and Barrentine WL (1998) Glyphosate Tank Mixtures with SAN 582 for Burndown or Postemergence Applications in Glyphosate-Tolerant Soybean (Glycine Max). Weed Technology 12:23-26

Solomon CB and Bradley KW (2014) Influence of Application Timings and Sublethal Rates of Synthetic Auxin Herbicides on Soybean. Weed Technology 28:454-464

USDA-NASS (2017a) 2017 State Agriculture Overview North Carolina. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NORTH%20CAROLINA. Accessed November 21, 2018

USDA-NASS (2017b) 2017 State Agriculture Overview Virginia. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=VIRGINIA. Accessed November 21, 2018

USDA-NASS (2018) Quick Stats Cotton Yield Projection. https://quickstats.nass.usda.gov/results/012A7167-43D4-306F-8766-B0EF88E302D1. Accessed November, 21, 2018

Wax LM, Knuth LA, and Slife FW (1969) Response of soybeans to 2,4-D, dicamba, and picloram. Weed Science 17:388–393

Weed Science Society of America (2018) Summary of Herbicide Mechanism of Action According to WSSA. http://wssa.net/wp-content/uploads/WSSA-Mechanism-of-Action.pdf. Accessed February 13, 2018

Wilson JS and Worsham AD (1988) Combinations of nonselective herbicides for difficult to control weeds in no-till corn, *Zea mays*, and soybeans, *Glycine max*. Weed Science 36:648-652

York AC, Culpepper AS, Stewart AM (2004) Response of Strip-tilled Cotton to Preplant Applications of Dicamba and 2,4-D. Journal of Cotton Science 8:213-222

Zimmer M, Young BG, and Johnson WG (2018a) Herbicide Programs Utilizing Halauxifen-Methyl for Glyphosate-Resistant Horseweed (*Conyza canadensis*) Control in Soybean. Weed Technology doi: 10.1017/wet.2018.60

Zimmer M, Young BG, Johnson WG (2018b) Weed Control with Halauxifen-Methyl Applied Alone and in Mixtures with 2,4-D, Dicamba, and Glyphosate. Weed Technology 32:597–602

Table 14. Locations, soil descriptions, planting dates, and harvest dates.

Location	Year	Soil series	Soil texture	pH	Humic matter[i]	Plot length	Planting date	Harvest date
						m		
Painter, VA	2017	Bojac[a]	Sandy loam	6.4	0.5	9.1	May 9	November 20
Suffolk, VA	2017	Kenansville[b]	Sandy loam	6.3	0.45	9.1	May 17	November 7
Clayton, NC	2017	Dothan[c]	Loamy sand	6.4	0.27	9.1	May 9	October 27
Rocky Mount, NC	2017	Aycock[d]	Sandy loam	5.9	0.36	15.2	May 9	October 3
Belvidere, NC	2018	Seabrook[e]	Loamy sand	5.7	1.08	7.6	May 16	October 10
Eure, NC	2018	Conetoe[f]	Loamy sand	6.2	0.27	7.6	May 24	October 30
Lewiston, NC	2018	Goldsboro[g]	Sandy loam	5.8	1.14	9.1	May 10	October 30
Rocky Mount, NC	2018	Norfolk[h]	Loamy sand	6.0	0.51	15.2	May 9	October 18

[a] Coarse-loamy, mixed, semiactive, thermic Typic Hapludults.
[b] Loamy, siliceous, subactive, thermic Arenic Hapludults.
[c] Fine-loamy, kaolinitic, thermic Plinthic Kandiudults.
[d] Fine-silty, siliceous, subactive, thermic Typic Paleudults.
[e] Loamy-sand, mixed, thermic Aquic Udipsamments.
[f] Loamy, mixed, semiactive, thermic Arenic Hapludults.
[g] Fine-loamy, siliceous, subactive, thermic Aquic Paleudults.
[h] Fine-loamy, kaolinitic, thermic Typic Kandiudults.
[i] Humic matter determined according to Mehlich (1984).

Table 15. Herbicides and adjuvants used in experiments.[a]

Herbicides and adjuvants	Trade name	Formulation concentration	Application rate	Manufacturer
			g ae or ai ha^{-1}	
Halauxifen-methyl	Elevore	69 g ae L^{-1}	5	Corteva Agriscience
Dicamba	Clarity	480 g ae L^{-1}	280	BASF
2,4-D	Weedar 64	456 g ae L^{-1}	1064	Nufarm Inc.
Halauxifen-methyl + florasulam	Quelex	10.4 + 10% wt wt^{-1}	5.5 + 5.3	Corteva Agriscience
Glyphosate	Roundup PowerMAX	540 g ae L^{-1}	1260	Monsanto Co.
Glufosinate	Liberty	280 g ai L^{-1}	655	BASF
Paraquat	Parazone	360 g ai L^{-1}	840	Adama

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

Table 16. Rainfall 1 to 28 d before planting (DBP) and for the first 10 d after at-planting (DAP) and accumulated rainfall between each application and cotton emergence.

		Rainfall[a]					Accumulated rainfall[b]				
Location	Year	22 to 28 DBP[a]	15 to 21 DBP	8 to 14 DBP	1 to 7 DBP	0 to 10 DAP[a]	4 WBP[a]	3 WBP	2 WBP	1 WBP	0 WBP
		cm									
Painter, VA	2017	0	2.4	1.4	6.0	6.4	16.2	16.2	13.8	12.4	6.4
Suffolk, VA	2017	2.7	0.9	1.7	1.8	6.2	13.3	10.6	9.7	8	6.2
Clayton, NC	2017	5.1	7.6	0	2.2	2.6	17.5	12.4	4.8	4.8	2.6
Rocky Mount, NC	2017	1.8	9.1	4.8	4.1	1.8	21.6	19.8	10.7	5.9	1.8
Belvidere, NC	2018	0	1.9	1.9	0.8	6.7	11.3	11.3	9.4	7.5	6.7
Eure, NC	2018	0.1	0	1.5	1.8	1.7	5.1	5	5	3.5	1.7
Lewiston, NC	2018	3.2	4.7	0	2.8	5.6	16.3	13.1	8.4	8.4	5.6
Rocky Mount, NC	2018	1.8	9.1	4.8	4.1	1.8	21.6	19.8	10.7	5.9	1.8

[a] Abbreviations: DBP, days before planting; DAP, days after planting; WBP, weeks before planting.[b]
[b] Cotton emergence occurred at least 10 days after planting.

Table 17. Cotton growth reduction, total injury, distorted leaf, and stand 2 and 4 weeks after emergence (WAE) in response to halauxifen, dicamba, and 2,4-D applied at planting at all locations.[a,b]

Herbicide[c]	Growth reduction		Total injury		Distorted leaf		Cotton stand	
	2 WAE[d]	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE
	%						—plants 10 m row^{-1}—	
Halauxifen	3 C	0 C	9 C	0 B	6 B	0 C	83 a	84 a
Dicamba	20 A	10 A	26 A	12 A	22 A	5 A	74 b	77 a
2,4-D	17 B	8 B	21 B	11 A	9 B	2 B	72 b	76 a
Nontreated	---	---	---	---	---	---	87 a	88 a

[a] Herbicides applied immediately prior to planting were allowed to dry for 1 hr prior to planting.
[b] Means within a column followed by the same letter are not different according to Fisher's protected LSD test at P = 0.05.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1060 g ae ha^{-1}, respectively. Herbicide sources can be found in Table 15.
[d] Abbreviation: WAE, weeks after emergence.

Table 18. Cotton growth reduction, total injury, and stand 2 and 4 weeks after emergence (WAE) in response to halauxifen, dicamba, and 2,4-D applied 1, 2, 3, and 4 wk prior to planting at all locations.[a,b]

	Growth reduction		Total injury		Cotton stand	
Herbicide[c]	2 WAE	4 WAE	2 WAE	4 WAE	2 WAE	4 WAE
					—plants 10 m row^{-1}—	
Halauxifen	1 B	0 A	1 A	0 A	85 a	88 a
Dicamba	2 A	0 A	2 A	0 A	83 a	87 a
2,4-D	1 B	0 A	1 A	0 A	84 a	87 a
Nontreated	---	---	---	---	84 a	86 a

[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] Data were pooled over application timings 1, 2, 3, and 4 wk before cotton planting.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1060 g ae ha^{-1}, respectively. Herbicide sources can be found in Table 15.

Table 19. Cotton height 4 and 8 weeks after emergence (WAE) and seedcotton yield in response to halauxifen, dicamba, and 2,4-D applied 0, 1, 2, 3, and 4 wk prior to planting at all locations.[a,b]

	Cotton height		
Herbicide[c]	4 WAE	8 WAE	Seedcotton yield
	cm		kg ha^{-1}
Halauxifen	25 B	63 A	3210 A
Dicamba	25 B	63 A	3020 A
2,4-D	25 B	66 A	3450 A
Nontreated	26 A	64 A	3200 A

[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] Data were pooled over application timings 0, 1, 2, 3, and 4 wk before cotton planting.
[c] Halauxifen, dicamba, and 2,4-D were applied at 5, 280, and 1060 g ae ha^{-1}, respectively. Herbicide sources can be found in Table 15.