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Contributions of shading, soybean (*Glycine max*) row width, and planting green on horseweed (*Conyza canadensis*) management compared with soil-applied residual herbicides

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Abstract

Glyphosate-resistant (GR) horseweed is a problematic weed for Michigan soybean growers. Additionally, rosette- and upright-horseweed growth types have been observed co-emerging during mid- to late summer in several Michigan fields. In the greenhouse, shade levels from 35% to 92% reduced rosette- and upright-horseweed biomass 31% to 99% compared with the upright growth type grown under 0% shade. Greater reductions in biomass occurred under 69% and 92% shade. Thus, increased shading by planting in narrow rows and/or planting green into cereal rye may improve horseweed suppression. A field experiment conducted over 3 site-years compared the effect of fall-planted cereal rye terminated with glyphosate 1 wk after planting (WAP; planting green) with a preemergence residual herbicide program (glyphosate + 2,4-D + flumioxazin + metribuzin) on horseweed control in soybean planted in three row widths (19, 38, and 76 cm). Planting green or applying a residual herbicide program across all row widths reduced horseweed biomass 86% to 91% and 95% to 99%, respectively, compared with soybean planted with no cover in 76-cm rows, 4 to 6 WAP. At soybean harvest, when a noneffective postemergence herbicide (glyphosate) was applied, horseweed biomass was 42% and 81% lower by planting green or applying a residual-herbicide program compared with no cover, respectively. Similarly, planting soybean in 19-cm rows reduced horseweed biomass compared with 38- and 76-cm rows. When an effective postemergence program was applied, similar horseweed biomass reductions were observed by planting green or applying a residual herbicide across all row widths. Additionally, soybean yield and economic returns were similar between planting green and applying a residual herbicide in 1 of 2 site-years. Integrating planting green and an effective postemergence herbicide program offers an alternative horseweed management strategy to applying a residual preemergence herbicide program.

Introduction

Horseweed is one of the most problematic weeds in Michigan and is ranked as the second most common and troublesome weed in U.S. soybean production (E. Burns and C. Sprague, Michigan State University, personal communication, 2021; Van Wychen 2019). Horseweed can tolerate a variety of environmental conditions and thrives in undisturbed areas, such as reduced-tillage or no-tillage production systems, making management more challenging (Weaver 2001). Each plant can produce up to 200,000 seeds that have an attached pappus adapted for wind dispersal for up to 550 km from the source plant (Bhowmik and Bekeck 1993; Shields et al. 2006). Considered a facultative winter annual, horseweed emergence is observed throughout the growing season (Buhler and Owen 1997; Tozzi and Van Acker 2014; Weaver 2001). In Michigan, Schramski et al. (2021b) reported that horseweed plants exhibited a summer annual life cycle, with initial emergence occurring between late April and mid-May and that peak emergence (>80%) occurred when 50 to 100 growing degree days (GDDs) (base, 10 C) accumulated with adequate soil moisture. Additional emergence occurred through the spring and early summer, and late emergence into July followed rainfall events. Both rosette- and upright-horseweed growth types have been observed co-emerging in mid- to late summer in Michigan (Schramski et al. 2021a). Horseweed is best managed when small (Loux and Johnson 2015; Mellendorf et al. 2013); however, because of its extended and variable emergence pattern, variability in size has complicated management efforts.

Horseweed germination is not affected by light intensity or quality (Gorski et al. 1977; Nandula et al. 2006); however, decreasing light intensity from 100% to 25% of full sunlight has reduced biomass of rosette horseweed (Bekech 1988). In the same study horseweed rosettes eventually bolted, and the average plant height decreased from 192 to 92 cm as shade levels increased. Weed biomass reductions in other weed species are also observed as irradiance levels are reduced. Steckel et al. (2003) reported that each additional increase in shade (0, 40%, 68%, and 99%) reduced common waterhemp (*Amaranthus rudis* Sauer) biomass by 24%, 49%, and >99% for an early-emerging cohort (May) and by 37%, 51%, and 99% for a later emerging cohort (June). However, common waterhemp height was similar among shade treatments, except with the 99% shade level, regardless of emergence cohort (Steckel et al. 2003). Similarly, Bello et al. (1995) reported that velvetleaf (*Abutilon theophrasti* Medik.) biomass, branch number, leaf number, and plant height were consistently lower when grown under 76% shade compared with 0% and 30% shade.

One way to increase shade levels and lower light interception under a canopy is to plant soybean in narrow rows. Narrow-row soybean produces more biomass and provides earlier canopy development. The resulting interception of the solar radiation needed to stimulate weed seed germination reduces weed emergence and growth. (Yelverton and Coble 1991). Summer annual weed biomass and density were lower when soybean was planted in 19- and 38-cm rows compared with 76-cm rows, 3 to 5 wk after glyphosate application, as a result of earlier canopy closure that increased leaf area index (Harder et al. 2007). Similarly, Rich and Renner (2007) reported that eastern black nightshade (*Solanum ptycanthum* Dun.) biomass was lower in soybean planted in 19-cm rows compared with 76-cm rows; however, density was more variable and was often not affected.

Horseweed is resistant to at least one herbicide site of action in 18 countries (Heap 2023). However, in Michigan glyphosate-resistant (GR) (WSSA Group 9) horseweed biotypes are the most widespread, and there are numerous biotypes that are also resistant to the acetolactate synthase inhibitors (WSSA Group 2) (Hill 2020). Horseweed management requires effective control of plants prior to crop planting and a residual soil-applied herbicide to control later emerging plants (Loux et al. 2006). Previously, glyphosate alone was used in preplant burndown or preemergence applications to control emerged horseweed prior to soybean emergence. However, the widespread occurrence of GR and multiple-resistant horseweed has greatly reduced glyphosate effectiveness and limited options for control with preemergence and postemergence herbicides without the use of newer herbicide-resistant soybean traits. For example, Simpson et al. (2017) reported that the addition of dicamba (WSSA Group 4) or 2,4-D (WSSA Group 4) to glyphosate improved horseweed control to 93% and 85%, respectively, compared with glyphosate alone (54%). Additionally, glufosinate (WSSA group 10) alone or in combination with 2,4-D resulted in 85% and 92% control, respectively, 4 wk after a preplant application. These herbicides could not be used in soybean without the development of herbicide-resistant traits. The use of preemergence residual herbicides such as metribuzin (WSSA group 5), flumioxazin, or sulfentrazone (WSSA group 14) provided horseweed control for up to 8 wk after application (Davis et al. 2007, 2009; Eubank et al. 2008). However, residual herbicides often have lengthy rotation intervals because of their persistence in the soil. In a diverse agricultural state such as Michigan, rotation restrictions limit grower options for season-long horseweed control. Therefore, additional management strategies are needed.

Due to the prevalence of herbicide-resistant weed populations, cover crops are being reinvestigated as an additional weed management tool. Cover crops suppress weeds by competing for light and nutrients, and specific cover-crop species generate secondary metabolites that inhibit weed germination, causing reductions in weed density and biomass (Creamer et al. 1996; Davis and Liebman 2003; Haramoto 2019; Hayden et al. 2012; Shearin et al. 2008; Teasdale and Mohler 1993, 2000; Teasdale et al. 2007; Werle et al. 2017). The primary cover crop used in soybean is cereal rye because of its flexible planting window, cold tolerance, vast amounts of biomass production, and consistent suppression of weeds (Clark 2007; Hayden et al. 2012; Sherman et al. 2020). In several studies, fall-planted cereal rye reduced horseweed density and/or biomass compared with no cover prior to cover-crop termination in the spring (Pittman et al. 2019; Schramski et al. 2021b; Wallace et al. 2019). Other studies compared cereal rye terminated prior to soybean planting to preplant residual herbicides on horseweed management. Schramski et al. (2021c) reported that a preplant application of flumioxazin + metribuzin provided greater horseweed suppression than early-terminated cereal rye, 5 wk after planting (WAP). Similarly, Essman et al. (2020) observed greater reductions in horseweed density in June when a preplant residual herbicide was applied compared with early-terminated cereal rye with a preemergence herbicide application of flumioxazin.

Previous research found that weed suppression by cereal cover crops improves with increasing cover-crop biomass (Finney et al. 2016; Ryan et al. 2011; Smith et al. 2011). One way to increase cover-crop biomass is by planting green. Planting green is the agronomic practice of planting into a growing cover crop, allowing it to accumulate more cover biomass, and terminating it after planting (SARE 2020). Mirsky et al. (2011) reported that cereal rye biomass increased 37% with each 10-d delay. Additionally, Schramski et al. (2021b) reported soybean planted green into cereal rye reduced horseweed biomass 52% to 85% compared with early-terminated cereal rye. However, cereal rye residue did not persist long enough, regardless of termination time, to provide season-long horseweed suppression. Currently, there is a lack of research on horseweed management comparing the practice of planting green with preplant residual herbicides in soybean and/or no-tillage production systems.

The extended and variable emergence of horseweed and prevalence of herbicide-resistant biotypes has created many challenges in the management of horseweed. Preplant residual-herbicide applications provide excellent control of horseweed; however, this increases the selection pressure for horseweed that is resistant to more sites of action, and there are often lengthy rotation intervals that may limit grower options. Fall-planted cereal cover crops improve early-season horseweed management; however, cover residue is often not persistent enough to provide season-long horseweed suppression. Additionally, it has been reported that narrow soybean rows contribute to reductions in summer annual weed density and biomass. Many studies have investigated the effects of fall-seeded cover crops on horseweed management, but research is absent on integrating a cereal rye cover crop and narrow soybean rows. Therefore, the objectives of this research were to (i) determine the effect of shade on the growth of rosette- and upright-horseweed growth types, and (ii) examine horseweed suppression when planting green in combination with narrow soybean rows compared with a preemergence residual herbicide.

Materials and Methods

Greenhouse Experiment

Horseweed seed collected from Lansing, MI (42.6845° N, 84.4887° W) was used to generate two growth types, rosette and

Table 1. Cereal rye seeding and termination dates, growing degree days (GDDs)[a] until planting-green termination, preemergence (PRE) herbicide application, soybean planting, postemergence (POST) herbicide application, and soybean harvest dates for the three experimental locations.

	Site		
Operation	MSU-A	MSU-B	MSU-C
Cereal rye seeding	October 4, 2019	October 16, 2020	November 9, 2020
PRE application	June 4, 2020	May 13, 2021	May 13, 2021
Soybean planting	June 1, 2020	May 25, 2021	May 25, 2021
Planting-green termination	June 6, 2020	June 2, 2021	June 2, 2021
GDDs (base, 4.4 C)[b]	791	764	661
GDDs (base, 10 C)[c]	287	289	289
POST application	June 24, 2020	June 24, 2021	July 7, 2021
Soybean harvest	October 31, 2020	October 18, 2021	October 18, 2021

[a]Abbreviation: MSU, Michigan State University.
[b]GDDs (base, 4.4 C) accumulated from the time of cereal rye planting until termination.
[c]GDDs (base, 10 C) accumulated from January 1 until cover termination for horseweed emergence.

upright. Horseweed seeds were planted on the surface of 30 × 30 cm flats filled with potting medium (Suremix Perlite; Michigan Grower Products, Inc., Galesburg, MI) and watered. Flats were placed in a vernalization chamber set at 4 C with an 8-h photoperiod for 4 wk to stimulate the upright growth type. After 4 wk, vernalized flats and flats planted with seed from the same parent plant (to generate the rosette siblings) were placed in the greenhouse set at 25 ± 5 C, with a midday light intensity of 1,000 μmol m^{-2} s^{-1}, and a 16-h photoperiod. Upright and rosette flats were subjected to four shade treatments: 0, 30%, 60%, and 90%. Shade environments were created by covering structures with forest green–colored woven shade cloth (Agriculture Solutions, Strong, ME) for the 30% and 60% shade treatments, and with a black shade cloth (Shatex Corporation, Delta, BC) rated for 90% shade. Seedlings were transplanted 3 wk after emergence into 10 × 10 × 12 cm pots filled with potting medium, one horseweed plant per pot. Photosynthetically active radiation (PAR) was measured at plant height using a MultispeQ (PhotoSynQ; East Lansing, MI). PAR was converted to a percent of the nonshaded control to determine the estimated shade percent from each cloth. Based on weekly PAR measurements, actual percent shade for the 30%, 60%, and 90% cloth was 35%, 69%, and 92%, respectively. Plants were watered and fertilized as needed to promote optimum plant growth. Aboveground biomass was harvested at 6, 7, 8, and 9 WAP. Biomass was dried for 7 d at 60 C and weighed. Dry weights were converted to a percent of the final weight of the no shade (0%) upright growth type. Horseweed height and diameter were collected at 9 WAP. All treatments were replicated five times and repeated in time.

Field Experiment

Field experiments were conducted at the Michigan State University (MSU) Agronomy Farm in Lansing, Michigan in 2020 (MSU-A = 42.6872° N, 84.4914° W) and 2021 (MSU-B = 42.6845° N, 84.4887° W; MSU-C = 42.6889° N, 84.4904° W) in no-tillage fields with known populations of GR horseweed. The soil types at MSU-A and MSU-B were a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludals) with pH 6.2, 7.4 and 3.2%, 2.6% organic matter, respectively, and a Colwood-Brookston loam (fine-loamy, mixed, active, mesic Typic Haplaquolls) with pH 5.9 and 2.8% organic matter at MSU-C.

In 2020, the experiment was arranged in a randomized complete-block split-plot design with four replications. In 2021, the experiment was arranged in a randomized complete-block split-split plot design with four replications. Plots measured 3 m wide by 11 m long. The main plot factor was early-season management strategy consisting of (i) cereal rye terminated 1 wk after soybean planting with glyphosate (Roundup PowerMAX; Bayer CropScience, St. Louis, MO) at 1.27 kg ae ha^{-1} + ammonium sulfate at 2% w w^{-1} (AMS) (Actamaster; Loveland Products, Inc., Greeley, CO) (planting green); (ii) a no-cover plus preemergence residual-herbicide program that included glyphosate at 1.27 kg ae ha^{-1} + 2,4-D (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.12 kg ae ha^{-1} + flumioxazin (Valor; Valent U.S.A. Corporation, Walnut Creek, CA) at 0.07 kg ai ha^{-1} + metribuzin (Metribuzin 75; Winfield Solutions, St. Paul, MN) at 0.31 kg ha^{-1} + AMS at 2% wt/wt, and (iii) a no-cover control that was treated with glyphosate at 1.27 kg ae ha^{-1} + AMS at 2% wt/wt preemergence. The subplot factor was soybean row width: 19, 38, and 76 cm. The sub-subplot factor in 2021 was postemergence herbicide program consisting of an effective postemergence program of glufosinate (Liberty; BASF Corp., Research Triangle Park, NC) at 0.66 kg ai ha^{-1} + 2,4-D at 1.12 kg ae ha^{-1} + AMS at 2% wt/wt, or a noneffective postemergence program of glyphosate at 1.27 kg ae ha^{-1} + AMS at 2% wt/wt to only control other weeds, but not GR horseweed. In 2020 at MSU-A, only glyphosate at 1.27 kg ae ha^{-1} + AMS at 2% wt/wt was applied postemergence to all plots.

The fall prior to data collection, 'Wheeler' cereal rye was drilled at 67 kg ha^{-1} in 19-cm rows using a no-till drill (John Deere, Moline, IL). Dates for all field operations can be found in Table 1. The next spring, glyphosate-, glufosinate-, and 2,4-D-resistant soybean 'P25T09E' or 'P24T35E' was planted at 500,000, 437,500, 375,000 seeds ha^{-1}, or 500,000, 450,000, and 387,500 seeds ha^{-1} in 2020 and 2021, respectively, in 19-, 38-, and 76-cm rows. Higher seeding rates were used in 2021 because of dry conditions. The burndown-plus-residual treatments were established 3 d after soybean planting (DAP) or 1 wk prior to soybean planting in 2020 and 2021, respectively. Cereal rye was terminated 1 wk after soybean planting the following spring. Postemergence herbicide applications were made 4 to 6 WAP when horseweed was 10 cm tall in the control. At MSU-C, postemergence herbicides applications were delayed as a result of weather, and average horseweed height was 20 cm tall. All herbicide applications were made using a tractor-mounted, compressed-air sprayer calibrated to deliver 177 L ha^{-1} at 207 kPa of pressure through 11003 AIXR nozzles (TeeJet, Spraying Systems CO., Wheaton, IL).

Throughout the growing season, temperature and precipitation data were collected from the Michigan Automated Weather

Network (http://www.agweather.geo.msu.edu/mawn/, Michigan State University, East Lansing, MI) stations located in East Lansing (data not shown). Temperature and precipitation 30-yr averages were collected from the National Oceanic and Atmospheric Administration (https://www.noaa.gov) (data not shown).

Data Collection

At planting-green termination, aboveground cereal rye biomass and weed density and biomass were collected from two randomly placed 0.25-m^2 subsamples per plot. Subsamples of cereal rye biomass were analyzed for C/N ratios by A&L Great Lakes Laboratories, Inc. (Fort Wayne, IN) using a TruMac CNS Macro Analyzer (LECO Corp., St. Joseph, MI). Horseweed density and biomass were also collected at the time of postemergence herbicide application and prior to soybean harvest. Biomass samples were dried for approximately 7 d at 65 C and weighed.

Canopy closure was measured in the preemergence residual treatments 6, 7, 8, 10, and 11 WAP using the mobile-device application Canopeo (Oklahoma State University, Stillwater, OK). In these treatments, no weeds were present at the time of data collection. Three images were taken randomly per plot using the Canopeo application on a smartphone (iPhone X, Apple®) held 5 ft above the soybean canopy. Images were then analyzed for percent green cover based on selection of pixels according to ratios of R/G, B/G (Paruelo et al. 2000; Liang et al. 2012), and the excess green index (Richardson et al. 2007; Chen et al. 2010) with a threshold setting of 0.95. Green cover ranged from 0 (no green cover) to 1 (100% green cover). Soybean was harvested for yield using a small-plot research combine (Massey-Ferguson 8XP; AGCO, Duluth, GA). Yields were adjusted to 13% moisture.

Economic Analysis

The net economic returns in response to each treatment were calculated by subtracting estimated treatment cost from gross income. Gross income was calculated in USD ($) ha^{-1} by multiplying soybean yield by soybean prices of $0.37 kg^{-1} ($10.00 bu^{-1}) and $0.55 kg^{-1} ($15.00 bu^{-1}). The cost of each treatment was calculated by using the average soybean seed, cereal rye seed, herbicide, and adjuvant prices from June 2021 and January 2022 price sheets provided by major agricultural retailers in the Midwest. Soybean seed cost for 140,000 seeds was estimated at $60.00, and cereal rye seed cost plus custom planting was estimated at $58.52 for 67 kg ha^{-1}. A custom application fee of $22.23 ha^{-1} was included for each herbicide application timing in the program.

Statistical Analysis

Upright- and rosette-horseweed biomass response and canopy closure data were analyzed using the drc package in R v. 4.0.2 (R Development Core Team 2020). Three-parameter log logistic models (Equation 1) were fitted for each shade level by growth-type combination and soybean row width as selected by the drc modelFit function using the lack-of-fit test. The effective time to reach 25% (T_{25}) biomass compared with the 0% shade upright growth type was determined using the ED function for the rosette- and upright-type within each shade level. For canopy closure, the effective time to reach 75% (T_{75}) and 90% (T_{90}) canopy closure was determined using the ED function for each row width. Time is the d after planting (DAP) for the shade and canopy closure data, respectively

$$y = c + \frac{d - c}{1 + exp[(b(log(x) - log(e))]} \quad [1]$$

For this equation, y is the biomass response (percent of the 0% shade upright type) or the % canopy closure; x is the time (DAP), c and d are the lower and upper limits, respectively, b is the relative slope around e, and e is the T_{25} (Streibig 1988). Shade level by growth type differences in T_{25} values and row-width differences in T_{75} and T_{90} values (based on a t-statistic with $\alpha \leq 0.05$) were compared using the EDcomp function.

Final biomass, upright height, and rosette diameter were analyzed using ANOVA in the lmer function of R v. 3.6.0 (R Development Core Team 2020). Fixed factors were shade level and growth type, and their respective interaction. Random factors included replication and shade level by replication. Normality assumption was checked by examining histogram and normal probability plots of the residuals. Unequal variance assumption was assessed by visual inspection of the side-by-side box plots of the residuals followed by Levene's test for unequal variances. Treatment means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$.

Field experiment data analysis was performed using PROC GLIMMIX in SAS OnDemand (SAS Institute, 2014) at $\alpha = 0.05$. The statistical model consisted of early-season management strategy, soybean row width, postemergence-herbicide application, and their interactions as fixed effects. Each year–location combination was considered an environment sampled at random from a population as suggested by Carmer et al. (1989). Environment (individual year and location), replication nested within environments, the interaction between early-season strategy and replication nested within environments, and the interaction between early-season strategy and soybean row width nested within environments were considered random effects. Replications were used as an error term for testing the effects of environment, and data were combined over all environments for each measurement except for soybean yield and economic return. Data for horseweed density and biomass at harvest, soybean yield, and economic return were analyzed separately by postemergence-herbicide treatment. Normality of residuals were examined using the UNIVARIATE procedure. Squared and absolute value residuals were examined with Levene's test to confirm homogeneity of variances. Data were combined over main effects when interactions were not significant. Treatment means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$. Nontransformed means for horseweed density and biomass are presented because the arcsine and square root transformation did not improve the normality of the data.

Results and Discussion

Horseweed Response to Shade

Shade had a significant effect on the growth of rosette- and upright-horseweed plants. As shade level increased, the rate of biomass accumulation for the upright growth type decreased (Figure 1) with 1.66× and 2.42× slower biomass accumulation under 35% and 69% shade, respectively (Table 2). These increased shade levels also led to an additional 2 and 19 d to reach 25% (T_{25}) biomass accumulation in relation to the upright growth type under 0% shade. The rate of biomass accumulation for the rosette type grown under 0% shade was 2.27× slower compared with the upright growth type under 0% shade (Table 2). There were no

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Table 2. Rate of biomass accumulation, biomass accumulation T_{25} (±SE)[a], and final height, diameter, and biomass for the upright and rosette growth types of horseweed in a greenhouse study.

Growth type	Shade level	Rate[b]		Biomass T_{25}[c]		Height	Diameter	Final biomass
	%	——% d^{-1}——		——d——		——cm——		g $plant^{-1}$
Upright	0	11.34	(±0.97)	45	(±0.72)	33 a[e]	–	2.52 a
	35	6.84	(±0.58)	47	(±0.96)	29 b	–	1.74 b
	69	4.69	(±1.19)	64	(±2.07)	15 c	–	0.58 cd
	92	0	(–)[d]	>63		2 d	–	0.0087 e
Rosette	0	4.99	(±0.48)	46	(±1.21)	–	16 a	1.44 b
	35	4.16	(±0.61)	53	(±1.63)	–	17 a	0.96 c
	69	3.88	(±1.91)	>63		–	12 b	0.30 de
	92	0	(–)[d]	>63		–	2 c	0.0038 e
Effects (P values)								
Shade		–		–		<0.0001	<0.0001	<0.0001
Growth type		–		–		–	–	<0.0001
Shade level × growth type		–		–		–	–	<0.0001

[a]Abbreviations: SE, standard error.
[b]Rate is the % biomass accumulation per day (d).
[c]T_{25} is the time required to reach 25% biomass accumulation relative to upright growth type under 0% shade.
[d]SE could not be calculated for 92% shade because no biomass was accumulated.
[e]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

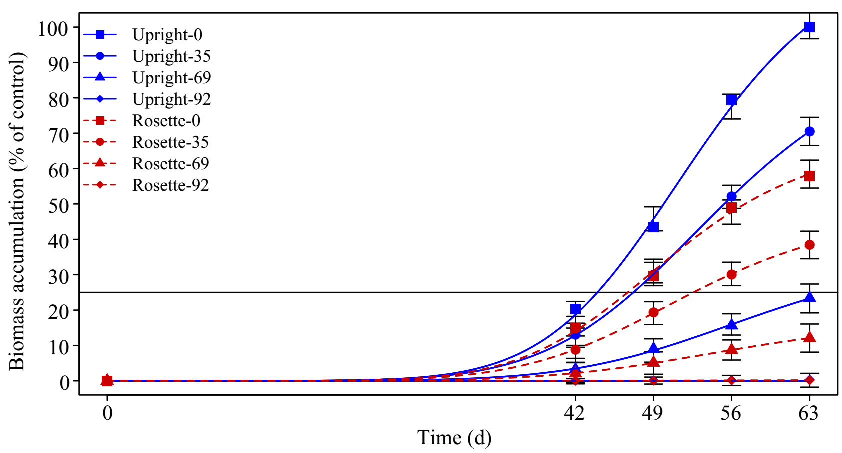

Figure 1. Time to reach 25% biomass accumulation of rosette- and upright-horseweed plants grown under 0%, 35%, 69%, and 92% shade. Biomass is presented as a percent of the biomass of the upright growth type grown under 0% shade at 63 d.

differences in rates for the rosette growth type the 0%, 35%, and 69% shade treatments, but the higher shade levels caused significant delays in the time to reach 25% biomass accumulation, and these delays were generally longer for the rosette compared with the upright growth type. At the highest shade level (92%), neither growth type reached 25% biomass accumulation by the end of the experiment. High shade levels (>40%) were reported to slow the growth rate of other weeds, such as common waterhemp (Steckel et al. 2003).

Final horseweed height and biomass was reduced for the upright growth type with increasing shade level (Table 2). Biomass was 30% and 77% lower when the upright growth type was grown under 35% and 69% shade, respectively. For rosettes, final diameter was not different between the 0% and 35% shade; although biomass was 33% less. At 69% shade, there was no difference in horseweed biomass between the upright and rosette growth types. Horseweed, regardless of growth type, grown under 92% shade produced very little biomass and was >99% lower than the 0% shade treatments. Previous research showed that decreasing light intensity from 100% to 25% of full sunlight reduced biomass of rosette horseweed (Bekech 1988). Similarly, Steckel et al. (2003) reported less common waterhemp biomass with increased shading; however, there was no difference in final height.

Overall, increased shading up to 69% slowed the rate of horseweed growth in the upright, but not the rosette, growth type. However, higher shade levels delayed the time to reach 25% biomass accumulation within each growth type, and the time required was longer for the rosette compared with the upright growth type. Higher shade levels also reduced final horseweed height and biomass.

Horseweed Suppression at Planting Green

Cereal rye suppressed horseweed to a similar extent as the preemergence residual herbicide treatment at the time of planting-green termination (1 WAP). At this time, cereal rye was at Feekes stage 10.5.1 with a dry biomass of 4,384 kg ha^{-1} and a C/N ratio of 41:1 (data not shown). Horseweed density was 54% and 80% lower by planting green or applying a residual herbicide, compared with the no-cover control (Table 3). Likewise, horseweed biomass was not different between the planting-green and residual-herbicide treatments (10–20 g m^{-2}). At termination, biomass was extremely low as a result of the relatively small size of horseweed plants (<2.5 cm average diameter), and horseweed biomass for the planting-green treatment was not different from the no-cover

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Table 3. Main effect of early-season strategy on horseweed density and biomass at the time of planting-green termination, 1 wk after planting.

Early-season management strategy[a]	Horseweed density	Horseweed biomass
	No. plants m^{-2}	g m^{-2}
No cover	56 a[b]	42 a
No cover + preemergence residual	11 b	10 b
Planting green (cereal rye)	26 b	20 ab
Effects (P value)		
Early-season management strategy	<0.0001	0.0153

[a]Abbreviations: No-cover control, glyphosate only; no cover + preemergence residual, glyphosate + 2,4-D + flumioxazin + metribuzin.
[b]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

Table 4. Interaction between early-season strategy and soybean row width on horseweed density and biomass at the time of postemergence herbicide application (4 to 6 wk after planting).

		Horseweed	
Early-season management strategy[a]	Row width	Density	Biomass
	cm	No. plants m^{-2}	g m^{-2}
No cover	19	71 b[b]	41 b
	38	75 b	44 b
	76	171 a	76 a
No cover + preemergence residual	19	2 e	1 e
	38	6 de	3 de
	76	7 d	4 de
Planting green (cereal rye)	19	29 c	7 cd
	38	45 bc	10 c
	76	60 b	11 c
Effects (P values)			
Early-season management strategy		<0.0001	<0.0001
Row width		0.0038	0.0052
Early-season management strategy × row width		<0.0001	0.0002

[a]Abbreviations: No-cover control, glyphosate only; No cover + preemergence herbicide with residuals, glyphosate + 2,4-D + flumioxazin + metribuzin.
[b]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

control. However, the residual-herbicide treatment reduced horseweed biomass by 76% compared with no-cover control (Table 3). Previous studies reported horseweed densities reductions of 41% to 97% from fall-planted cover crops at the time of early termination compared with no cover (Essman et al. 2020; Schramski et al. 2021b; Pittman et al. 2019; Wallace et al. 2019). Similarly, Owen et al. (2009) reported >86% horseweed control 21 d after application of various preplant residual-herbicide programs. Pittman et al. (2019) reported greater horseweed density reductions from fall-planted cover crops compared with fall-applied metribuzin + chlorimuron-ethyl.

Horseweed Suppression at Postemergence Application

Horseweed continued to emerge after cereal rye termination. Horseweed density increased 3-fold between cereal rye termination and the postemergence herbicide application in the no-cover control with soybean planted in 76-cm rows (Tables 3, 4). Schramski et al. (2021b) reported prolonged horseweed emergence until 450 to 600 GDD (base, 10 C), depending on rainfall. In our research, GDD accumulation at the time of planting-green termination was 287 to 289 (base, 10 C) (Table 1), and at the time of postemergence-herbicide application, 500 to 703 GDDs (base, 10 C) had accumulated (data not shown). Prior to planting-green termination in June, rainfall was 3–20 mm; however, later rainfall events totaling 71 to 157 mm occurred throughout the rest of June, likely stimulating horseweed emergence (data not shown).

At the time of postemergence-herbicide application, each early-season strategy-by-soybean row width combination reduced horseweed density and biomass compared with soybean planted in 76-cm rows in the no-cover control (Table 4). Soybean planted in narrow rows (19 or 38 cm) reduced horseweed density and biomass by over 2- and 1.7-fold, respectively, compared with 76-cm rows when no early-season horseweed management strategy was in place. Rich and Renner (2007) found that planting soybean in 19-cm rows reduced eastern black nightshade biomass compared with 76-cm rows. The preemergence-residual treatment of metribuzin + flumioxazin provided the greatest horseweed suppression for all three soybean row widths. Horseweed density was lower in 19- than 76-cm rows; however, reductions in horseweed biomass were not different among soybean row widths (96% to 99%). Schramski et al. (2021c) observed similar reductions in horseweed density and biomass at the time of postemergence-herbicide application in soybean when a residual herbicide was applied. Across all row widths, planting green reduced horseweed density and biomass 65% to 83% and 86% to 91%, respectively, compared with soybean planted in 76-cm rows with no cover (Table 4). Planting soybean in 19-cm rows reduced horseweed density 2-fold more than 76-cm rows in the planting-green treatments; however, there were no differences in horseweed biomass among row widths. Similar horseweed biomass reductions were observed between the combination of planting green in 19-cm rows and the residual-herbicide treatment with soybean planted in 38- and 76-cm rows. Only the 19-cm row-by-preemergence residual-herbicide combination suppressed horseweed biomass more. Similar weed density reductions were reported in narrow row-by-cover crop combinations. Hay et al. (2019) reported soybean planted in 19- and 38-cm rows into an

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Table 5. Interaction between early-season strategy and soybean row width on horseweed density and biomass at the time of soybean harvest for plots treated with and without an effective postemergence application of glufosinate and 2,4-D.[a]

Early-season management strategy	Row width	Noneffective		Effective	
		Density	Biomass[b]	Density	Biomass
	cm	No. plants m^{-2}	g m^{-2}	No. plants m^{-2}	g m^{-2}
No cover	19	13 cd[c]	133	4 bc	33 bc
	38	17 bc	169	8 b	58 b
	76	35 a	184	22 a	141 a
No cover + preemergence residual	19	1 e	6	0 c	0 d
	38	3 e	31	1 c	7 cd
	76	4 de	55	1 c	1 cd
Planting green (cereal rye)	19	6 de	47	0 c	0 d
	38	18 bc	100	4 bc	25 cd
	76	26 ab	135	5 bc	28 bcd
Effects (P values)					
Early-season management strategy		<0.0001	<0.0001	<0.0001	<0.0001
Row width		0.0045	0.0026	0.0309	0.0492
Early-season management strategy × row width		0.0229	0.8834	<0.0001	<0.0001

[a]Abbreviations: Noneffective, glyphosate; effective, 2,4-D + glufosinate; no-cover control, glyphosate only; no cover + preemergence herbicide with residuals, glyphosate + 2,4-D + flumioxazin + metribuzin.

[b]The main effects of early-season strategy and row width were significant for horseweed biomass when a noneffective postemergence was applied. Horseweed biomass was reduced 42% and 81% by planting green (94 g m^{-2}) or applying a residual herbicide (31 g m^{-2}) compared with no-cover control (162 g m^{-2}), respectively. Horseweed biomass was reduced 38% to 50% by planting soybean in 19-cm rows (62 g m^{-2}) compared with 38- and 76-cm rows (100 to 125 g m^{-2}).

[c]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

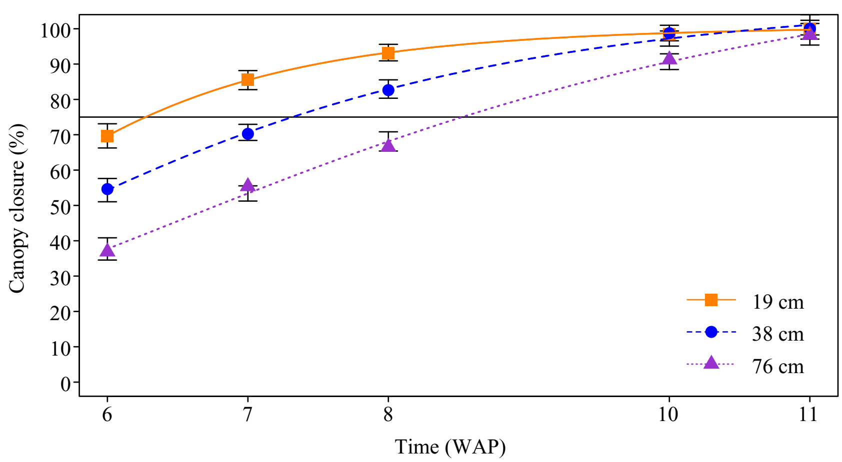

Figure 2. Canopy closure from 6 to 11 wk after planting (WAP) for soybean planted in 19-, 38-, and 76-cm rows combined over 3 site-years.

early-terminated winter wheat cover crop reduced Palmer amaranth (*Amaranthus palmeri* S. Wats.) density 49% to 55% compared with soybean planted in 76-cm rows with no cover.

The advantage of soybean planted in narrow rows for horseweed suppression was likely a result of quicker canopy development. Soybean planted in 38- and 19-cm rows reached 75% (T_{75}) canopy closure 1 and 2.5 wk ahead of 76-cm rows, respectively (Figure 2). The soybean canopy reached 90% closure 7.5 WAP for 19-cm rows. It took an additional 1.25 and 2.5 wk for the 38- and 76-cm rows to reach this point, respectively. Greater horseweed suppression from earlier canopy closure in narrow-row soybean was supported by our greenhouse research. At 69% shade, which would have occurred prior to 6 WAP in 19-cm rows in our field study, biomass of both rosette- and upright-horseweed growth types was reduced by greater than 75% (Table 2). Any horseweed emerging after 90% canopy closure would likely not produce much biomass. Earlier canopy closure by planting in narrower rows likely contributed to greater reductions in horseweed density and biomass at the time of postemergence-herbicide application. Additionally, planting-green cover residue was persistent enough to suppress horseweed until the time of postemergence-herbicide application, but the magnitude of suppression was less evident compared with applying a preemergence-residual herbicide.

Horseweed Suppression at Soybean Harvest

At soybean harvest, early-season strategy and soybean row width continued to have a significant effect on horseweed density and biomass when a noneffective postemergence herbicide was applied. Planting soybean in 19- and 38-cm rows suppressed horseweed density 2.7× and 2× more than soybean planted in 76-cm rows, respectively, when no early-season horseweed management strategy was in place (Table 5). The effect of row width on horseweed density was also important for soybean planted green. The 19-cm row width was the only spacing that reduced horseweed density within the planting-green treatments, although the 38-cm row width planted green had lower horseweed numbers than soybean planted in 76-cm rows with no cover. Soybean planted green in 19-cm rows also had similar horseweed numbers to the

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Table 6. Main effects of early-season strategy and soybean row width on soybean yield for plots treated with either a noneffective or effective postemergence herbicide application for horseweed control.[a]

	Soybean yield			
	MSU-A and MSU-B (combined)	MSU-B[b]	MSU-C[c]	
Main effects	Noneffective	Effective	Noneffective	Effective
Early-season management strategy	kg ha^{-1}			
No cover	3,373 b[d]	3,319 b	3,643 b	4,200 ab
No cover + preemergence residual	4,078 a	4,199 a	4,536 a	4,452 a
Planting green (cereal rye)	3,568 b	3,980 a	3,862 b	3,851 b
Row width (cm)				
19	3,955 a	4,070 a	4,264	4,109
38	3,738 a	3,727 b	4,200	4,193
76	3,327 b	3,702 b	3,578	4,202
Effects (P values)				
Early-season management strategy	0.0012	0.0012	0.0010	0.0168
Row width	0.0009	0.0039	0.0762	0.7834
Early-season management strategy × row width	0.8538	0.5781	0.3184	0.1090

[a]Abbreviations: Noneffective, glyphosate; effective, 2,4-D + glufosinate; no-cover control, glyphosate only; No cover + preemergence herbicide with residuals, glyphosate + 2,4-D + flumioxazin + metribuzin.
[b]Effective postemergence herbicide only applied at MSU-B and -C.
[c]There was a high incidence of white mold in the planting-green and narrow-row soybean treatments at MSU-C; therefore, it was separated from the remaining site-years.
[d]Means followed by the same letter within a column are not statistically different at α ≤ 0.05.

preemergence residual treatments for all three soybean row widths, which provided the greatest horseweed suppression. Unlike horseweed density, only main effects were significant for early-season strategy and soybean row width on horseweed biomass. Horseweed biomass was reduced most with the preemergence residual-herbicide treatment (81%), and planting green reduced horseweed biomass 67% compared with no cover across all three row widths (Table 5). Across all early-season strategies, horseweed biomass was only reduced when planting soybean in 19-cm rows. Soybean planted in 19-cm rows reduced horseweed biomass 38% and 50% compared with 38- and 76-cm rows, respectively. Similarly, Schramski et al. (2021c) reported an 84% reduction in horseweed density when a preemergence herbicide with residuals and a noneffective postemergence herbicide application took place compared with no cover. However, he observed no effect of cereal rye terminated early on horseweed density or biomass prior to soybean harvest. In our study, the cereal rye C/N ratio was relatively high at 42:1 when planting green, whereas Schramski et al. (2021c) had cereal rye C/N ratios of <24:1. Therefore, the residue in our study was likely more persistent through soybean harvest, resulting in a longer horseweed suppression period.

Although it is important to know what effects early-season strategies will have on horseweed control throughout the season, growers are likely going to need an integrated approach that includes an effective postemergence herbicide application for season-long horseweed management. Therefore, each early-season strategy-by-soybean row width combination was also treated with an effective postemergence herbicide of glufosinate + 2,4-D. For these treatments, there was an interaction between early-season strategy and soybean row width on horseweed density and biomass (Table 5). Planting soybean in 19- and 38-cm rows when no early-season horseweed management strategy was in place suppressed horseweed density and biomass 2.7- to 5.5-, and 2.4- to 4.2-fold, respectively, compared with 76-cm rows when an effective postemergence herbicide was applied. Across all row widths, horseweed density and biomass were reduced most when a preemergence residual herbicide was applied or when soybean was planted green. Similar horseweed density reductions were observed among the combination of planting soybean in 19-cm rows with no cover and applying a preemergence herbicide with residuals and planting green across all row widths. Our results show that when an effective postemergence herbicide is integrated, horseweed control is similar between planting green and applying a preemergence residual herbicide.

Soybean Yield and Economic Return

As a result of a high incidence of white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary], MSU-C was analyzed separately from MSU-A and MSU-B for soybean yield and economic returns. Combined over MSU-A and MSU-B, there was a main effect of early-season strategy and soybean row width on soybean yield when a noneffective postemergence herbicide was applied. By applying a preemergence residual herbicide, soybean yield was 14% to 21% higher compared with the no-cover control and planting green (Table 6). Yield was also 19% and 12% higher when soybean was planted in 19- and 38-cm rows compared with 76-cm rows, respectively. When an effective postemergence herbicide was applied, horseweed control was higher in the planting-green treatments. Thus, soybean yield was similar for planting green and applying a preemergence herbicide with residuals. Planting soybean in 19-cm rows yielded 9% to 10% higher than soybean planted in 38- and 76-cm rows (Table 6). These findings support Schramski et al. (2021c), who reported that soybean yield was 52% to 145% higher when a preplant residual herbicide treatment was applied with a noneffective postemergence compared with a no-cover control; however, they observed no effect on soybean yield by planting into an early-terminated cereal rye cover. Additionally, Harder et al. (2007) reported that soybean planted in 19-cm rows yielded higher than soybean planted in 38- and 76-cm rows.

A high incidence of white mold was observed at MSU-C in the planting-green and narrow-row soybean treatments. This was likely due to above average rainfall in June, July, and August in 2021 that totaled 356 mm compared with the 30-yr average of 259 mm (data not shown). As a result, the cover residue by planting green and narrow soybean rows created a moist soil surface beneath the closed canopy favorable for sclerotia germination. In addition, this site was bordered by corn and a woodlot that may have reduced air flow creating a larger risk for infection. When a

Table 7. Treatment costs (June 2021) for horseweed management programs for plots treated with either a noneffective or effective postemergence herbicide application for horseweed control.[a,b]

		Postemergence	
Early-season management strategy	Row width	Noneffective	Effective
	cm	——USD $ ha^{-1}——	
No cover	19	294.97	336.33
	38	271.15	312.50
	76	244.67	286.02
No cover + preemergence residual	19	358.77	400.13
	38	334.94	376.30
	76	308.47	349.83
Planting green (cereal rye)	19	353.49	394.85
	38	329.67	371.02
	76	303.19	344.55

[a]Total treatment costs = soybean seed costs + cereal rye seed and planting costs + herbicide costs + adjuvant costs + application costs. Average prices of seed, herbicide, and adjuvants were calculated from multiple price lists. Herbicide application cost = $22.31 ha^{-1}.
[b]Abbreviations: Noneffective, glyphosate; effective, 2,4-D + glufosinate; No-cover control, glyphosate only; No cover + preemergence herbicide with residuals, glyphosate + 2,4-D + flumioxazin + metribuzin.

noneffective postemergence herbicide was applied, there was a main effect of early-season strategy on soybean yield. Much as with MSU-A and MSU-B, by applying the preemergence residual herbicide treatment soybean yield was 17% and 25% higher compared with planting green and no cover, respectively (Table 6). In contrast to MSU-A and MSU-B, there was no effect of soybean row width on yield, regardless of postemergence herbicide application. The higher incidence of white mold in the 19- and 38-cm rows likely diminished the yield advantage of narrower rows compared with 76-cm rows at this location. Grau and Radke (1984) reported greater white mold severity in narrow-row soybean compared with wide rows, resulting in significant yield loss. At MSU-C, soybean yield was similar between the no-cover control and the preemergence residual herbicide treatment when an effective postemergence herbicide was applied; however, yield was 13% lower by planting green compared with applying a residual herbicide, likely because of the high incidence of white mold.

Program costs based on June 2021 pricing ranged from $244.67 to $358.77 kg ha^{-1} for those that included a noneffective postemergence herbicide treatment and were $286.03 to $400.13 kg ha^{-1} for those that included an effective postemergence herbicide treatment (Table 7). Economic returns generally followed the same trend as soybean yield. There were no significant differences in economic returns among treatments whether soybean was marketed at $0.37 kg^{-1} ($10.00 bu^{-1}) or $0.55 kg^{-1} ($15.00 bu^{-1}); therefore, economic return is based on a market price of $0.37 kg^{-1}. Additionally, the impact of increased herbicide costs arising from glyphosate and glufosinate shortages during the 2022 growing season were examined; however, this did not change the differences between treatments compared with 2021 herbicide costs (data not shown).

When a noneffective postemergence herbicide was applied at MSU-A and MSU-B, economic return was highest by applying a preemergence residual herbicide ($1,165 ha^{-1}) (Table 8). Regardless of postemergence herbicide application, higher economic return was observed when soybean was planted in 19-cm rows compared with 76-cm rows. The application of an effective postemergence herbicide improved soybean yield in the planting-green treatments; therefore, economic return was similar between planting green and applying a preemergence residual herbicide ($1,092 to 1,167 ha^{-1}).

Table 8. Economic return for horseweed management programs for soybean marketed at $0.37 kg^{-1} ($10.00 bu^{-1}) using price lists from June 2021 for plots treated with and without an effective postemergence herbicide application.[a–d]

	Economic return			
	MSU-A and MSU-B	MSU-B[e]	MSU-C[f]	
Main effects	Noneffective	Effective	Noneffective	Effective
Early-season strategy	——USD $ ha^{-1}——			
No-cover control	970 b[g]	908 b	1,068 b	1,232 a
No cover + preemergence residual	1,165 a	1,167 a	1,333 a	1,260 a
Planting green (cereal rye)	982 b	1,092 a	1,117 b	1,045 b
Row width (cm)				
19	1,117 a	1,118 a	1,257	1,133
38	1,062 ab	1,016 b	1,231	1,187
76	938 b	1,033 b	1,029	1,218
Effects (P values)				
Early-season strategy	0.0089	0.0082	0.0059	0.0125
Row width	0.0028	0.0161	0.0921	0.3183
Early-season strategy × row width	0.8593	0.5781	0.4947	0.1090

[a]Net return = (yield × price) – treatment costs. Crop selling price = $10.00 bu^{-1}.
[b]No differences in mean separation when crop selling price = $15.00 bu^{-1}.
[c]No differences in mean separation using January 2022 price lists.
[d]Abbreviations: Noneffective, glyphosate; effective, 2,4-D + glufosinate; no-cover control, glyphosate only; No cover + preemergence herbicide with residuals, glyphosate + 2,4-D + flumioxazin + metribuzin.
[e]Effective postemergence herbicide only applied at MSU-B and -C.
[f]There was a high incidence of white mold in the planting-green and narrow-row soybean treatments at MSU-C; therefore, it was separated from the remaining site-years.
[g]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

Like MSU-A and MSU-B, applying a preemergence residual herbicide resulted in the highest economic return when a noneffective postemergence herbicide was applied at MSU-C. Because of white mold, the yield advantage of narrow rows was diminished, resulting in no effect of row width on soybean yield, regardless of postemergence herbicide application. Additionally, applying an effective postemergence did not improve soybean yield in the planting-green treatments, and economic return was $187 ha^{-1} lower than the no-cover control and $215 ha^{-1} lower than preemergence residual herbicide treatments (Table 8). Overall, planting green resulted in similar soybean yields and economic return to applying a preemergence residual-herbicide treatment when integrated with an effective postemergence herbicide program in 1 site-year. To diminish the risks of white mold development, variety resistance, soil type, field history, and the environment surrounding the field should be assessed.

In conclusion, planting green suppressed horseweed season-long. However, suppression was not to the magnitude of applying a preemergence herbicide with residuals unless soybean was planted green in 19-cm rows. When a residual herbicide was applied across all row widths, there was 96% to 99% horseweed suppression at the time of postemergence herbicide application. In comparison, horseweed density was only reduced 65% to 83% by planting green; however, horseweed biomass was 86% to 91% lower, which likely improved postemergence herbicide efficacy. Planting soybean in narrow rows contributed to greater reductions in horseweed density and biomass at postemergence herbicide application and soybean harvest as a result of earlier canopy closure. However, this effect was diminished when a residual herbicide was applied. Greenhouse experiments demonstrated that rosette- and upright-type horseweed were greatly affected by shade, and as shade levels increased, greater reductions in biomass were observed. Thus, earlier canopy closure can play a substantial role in reducing horseweed growth as well as suppressing late-season emergence. Soybean yield and economic return was similar when planting green or applying a preemergence herbicide with residuals in 1 site-year when integrated with an effective postemergence herbicide program. Conversely, reduced soybean and economic return occurred in 1 site-year when planting green or in narrow-row soybean because of a high incidence of white mold. Thus, planting green is a practical alternative horseweed management strategy for growers, especially for those whose crop rotation limits residual herbicide options.

Practical Implications

Our research demonstrates that glyphosate-resistant horseweed can be managed in soybean by planting green into cereal rye similarly to applying a preemergence residual herbicide when an effective postemergence-herbicide program is applied. By planting green, horseweed density and biomass were reduced at the time of postemergence-herbicide applications through soybean harvest. As a result, less selection pressure is applied on horseweed to develop herbicide resistance to sites of action that are currently effective, and it also widens the postemergence herbicide application window by reducing plant size. This is of value when weather conditions may not allow for timely herbicide application. The economics of an integrated weed management approach that included a cereal rye cover crop were also analyzed, and it was determined that the return on investment by planting green was equal to applying a preemergence herbicide when an effective postemergence herbicide was applied. Our study offers growers another option to manage glyphosate-resistant horseweed outside of preemergence herbicides and remain profitable. This is especially important in diverse agricultural states, such as Michigan, where rotation restrictions limit growers' options for horseweed control.

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