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Narrow-row soybean and a cereal rye cover crop suppress glyphosate-resistant horseweed (*Conyza canadensis*)

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Abstract

Alternative strategies are needed for management of glyphosate-resistant (GR) horseweed in soybean. Integrating a cereal rye cover crop with soybean planted in narrow rows may improve control and reduce herbicide selection pressure for herbicide-resistant horseweed biotypes. Four site-years of experiments were conducted in Michigan to determine whether fall-planted cereal rye terminated with glyphosate 1 wk prior to (early termination) or 1 wk after (planting green) planting in combination with narrow-row soybean improved GR horseweed management. At postemergence (POST) herbicide application, horseweed biomass was reduced by 71% to 90% when soybean was planted into cereal rye, regardless of termination time, compared with no cover across all row widths. Planting green or narrow-row soybean suppressed horseweed through soybean harvest. When glyphosate was applied POST (noneffective), horseweed biomass was 36% to 46% lower when planting green compared with early terminated cereal rye and no cover. Similarly, planting soybean in 19- and 38-cm rows reduced horseweed biomass by 48% and 28%, respectively, compared with 76-cm rows. Cereal rye did not affect soybean yield pooled over 3 of 4 site-years; however, narrow row soybean yielded 11% to 18% higher than 76-cm rows. Soybean yield was 11% higher when an effective POST herbicide was applied. In conclusion, fall-seeded cereal rye or narrow-row soybean suppressed horseweed compared with no cover and 76-cm rows; however, the effects of early termination did not last throughout the growing season in most cases. Delaying cover crop termination by planting green reduced horseweed biomass and density through soybean harvest, but reduced yield in 1 site-year due to an increased incidence of white mold. These cultural practices have a positive influence on suppressing horseweed that should be part of an overall horseweed management strategy; however, the use of an effective POST herbicide is still needed for complete season-long horseweed management.

Introduction

Horseweed, a facultative winter annual, is one of the most serious weed management issues in Michigan soybean fields. If not controlled, horseweed can reduce soybean yield 83% (Bruce and Kells 1990). In a recent Michigan grower survey 86% of participants listed horseweed as their number one weed concern (E Burns and C Sprague, Michigan State University, personal communication, 2022). This ranking follows very closely to surveys conducted by the Weed Science Society of America (WSSA) via which researchers ranked horseweed as the second most common and troublesome weed in U.S. soybean production (Van Wychen 2019). The widespread occurrence is partially attributed to horseweed producing up to 200,000 seeds per plant. These seeds are adapted for wind dispersal through an attached pappus and can travel more than 550 km from the mother plant (Bhowmik and Bekech 1993; Shields et al. 2006). In Michigan, horseweed emergence has shifted from fall to primarily spring and early summer emergence (Schramski et al. 2021a). Schramski et al. (2021b) reported that peak horseweed emergence (>80%) occurred when 50 to 100 growing degree days (GDDs; base, 10 C) accumulated in the spring with adequate soil moisture, although horseweed continued to emerge throughout the summer following rainfall events. Horseweed is best managed when small in size (Loux and Johnson 2010; Mellendorf et al. 2013), but this is not always feasible with its extended and variable emergence pattern.

An obstacle in horseweed control is herbicide resistance. As of 2021, horseweed has evolved resistance to at least one herbicide site of action in 18 different countries (Heap 2021). Biotypes in Michigan are resistant to acetolactate synthase (ALS) inhibitors (WSSA Group 2); photosystem II inhibitors (WSSA Group 5); glyphosate, the 5-enolpyruvate-shikimate-3-phosphate inhibitor (EPSP; WSSA Group 9); and paraquat, a photosystem I electron diverter (WSSA Group 22), and resistance to multiple sites of action has also been reported (Heap 2021). In

Michigan, most horseweed populations are resistant to the ALS-inhibiting herbicides and glyphosate (Hill 2020), which limits herbicide options.

Extended horseweed emergence patterns and the increased prevalence of herbicide-resistant biotypes means that herbicides alone are not enough to protect soybean yield from horseweed competition. Integrating cover crops into the cropping system is a potential solution. Across the United States, cover crop hectarage increased by 50% between 2012 and 2017, totaling nearly 6.2 million hectares in 2017. Government cost-sharing to plant cover crops, ecosystem services, and weed suppression are reasons for this increase (SARE 2021; USDA-ERS 2021). Cover crops offer two periods of weed suppression, early on when the cover crop is actively growing, and later when the cover crop residue creates a mulch layer on the soil surface (Mirsky et al. 2013; Teasdale 1996). During the period of active growth, cover crops compete with weeds for resources such as light and nutrients, they delay soil warming, and some cover crop species can produce secondary plant metabolites that inhibit weed germination (Creamer et al. 1996; Davis and Liebman 2003; Shearin et al. 2008; Teasdale and Mohler 1993, 2000; Teasdale et al. 2007), causing reductions in weed density and biomass (Haramoto 2019; Hayden et al. 2012; Werle et al. 2017). After termination, cover crop residues reduce light penetration to the soil surface, hindering weed seedling growth and development (Teasdale and Mohler 2000; Wells et al. 2013). However, cover crop residues often do not persist long enough to provide season-long weed suppression (Osipitan et al. 2018; Schramski et al. 2021b).

Cereal rye is the primary cover crop used in conjunction with soybean because of its flexible planting window, cold tolerance, high biomass production, and consistent weed suppression (Clark 2007; Hayden et al. 2012; Sherman et al. 2020). Delaying cover crop termination allows for greater biomass accumulation and improves weed suppression (Cholette et al. 2018; Finney et al. 2016; Ryan et al. 2011; Smith et al. 2011; Wallace et al. 2019). Reed et al. (2019) found delaying cover crop termination 4 to 30 d by planting green increased cover crop biomass 94% to 181% relative to early termination. Previous research observed that fall-planted cover crops reduced spring horseweed density prior to cover crop termination in soybean (Pittman et al. 2019; Schramski et al. 2021b; Wallace et al. 2019). No differences in horseweed density and biomass were observed between early termination and planting green across most site-years (Schramski et al. 2021b). However, at the time of postemergence (POST) herbicide application (5 wk after planting), soybean planted green in cereal rye reduced horseweed biomass 52% to 85% more compared with early terminated cereal rye across most site-years (Schramski et al. 2021b). However, cereal rye residue, regardless of termination time, was not persistent enough to suppress horseweed through soybean harvest (Schramski et al. 2021b).

Earlier canopy closure in narrow rows can suppress weeds that escape herbicide application or that emerge late in the growing season (Mickelson and Renner 1997). Harder et al. (2007) observed reduced summer annual weed biomass and density in 19- and 38-cm rows compared with 76-cm rows following glyphosate application 3 to 5 wk after treatment (WAT). Similarly, Hay et al. (2019) reported that planting soybean in 19- or 38-cm into an early terminated winter wheat cover reduced Palmer amaranth (*Amaranthus palmeri* S. Wats.) density by 65% to 67% and biomass by 83% compared with soybean planted in 76-cm rows with no cover 3 wk after planting (WAP). Comparable density reductions were observed 8 WAP; however, suppression was not evaluated at the end of the season. Conversely, Rogers (2017) observed no interaction between cereal rye, regardless of termination time, and soybean row width on Palmer amaranth density or biomass. However, similar research has not been conducted on the effect of narrow row soybean on horseweed suppression.

Fall-planted cereal cover crops improve early-season horseweed management, but cover residues are often not persistent enough to provide season-long horseweed suppression. Meanwhile, narrow-row soybeans reduce the biomass of many weeds. Can the two practices be integrated for season-long horseweed suppression in soybean? The objectives of this research were to 1) evaluate the effects of a fall planted cereal rye terminated 1 wk before and 1 wk after soybean planting on horseweed suppression; 2) determine the contribution of soybean row width on horseweed suppression by comparing soybean planted in 19-, 38-, and 76-cm rows; and 3) compare the integrated approaches of cover crop and soybean row width with and without an effective POST herbicide application on horseweed management.

Materials and Methods

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) and at the MSU Kellogg Biological Station (KBS) near Hickory Corners, Michigan in 2021 (42.4022°N, 85.3773°W) on no-tillage fields with known populations of GR horseweed. The soil series at MSU-A and MSU-B were a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludals), pH 6.2 and 7.4, and with 3.2% and 2.6% organic matter, respectively; and at MSU-C the soil was a Colwood-Brookston loam (fine-loamy, mixed, active, mesic Typic Haplaquolls), pH 5.9, and with 2.8% organic matter. The soil series at KBS was a Kalamazoo loam (fine-loamy, mixed, active, mesic Typic Hapludalfs), pH 6.8, and 1.9% organic matter.

Trials were arranged in a split-split plot design with four replications. Plots measured 3 m wide by 11 m long. The main plot factor was cover treatment, the subplot factor was soybean row width, and the sub-subplot factor was POST-applied herbicide. The main plots consisted of three cover treatments: cereal rye terminated 1 wk prior to planting (early termination), cereal rye terminated 1 wk after soybean planting (planting green), and no cover. Cereal rye was terminated by applying glyphosate (Roundup PowerMAX; Bayer CropScience, St. Louis, MO) at 1.27 kg ae ha^{-1} plus ammonium sulfate (AMS; Actamaster; Loveland Products, Inc., Greeley, CO) at 2% wt wt^{-1}. The subplots consisted of three soybean row widths: 19, 38, and 76 cm. The sub-subplot factors were two POST herbicide application strategies: an effective POST herbicide application for GR horseweed and other weed control, or a noneffective POST herbicide application to control other weeds, but not GR horseweed. The effective POST herbicide treatment consisted of glufosinate (Liberty; BASF Corporation, Research Triangle Park, NC) at 0.66 kg ai ha^{-1} plus 2,4-D choline (Enlist One; Corteva Agriscience, Indianapolis, IN) at 1.12 kg ae ha^{-1} plus AMS at 2% wt wt^{-1}. The noneffective POST herbicide application was glyphosate at 1.27 kg ae ha^{-1} plus AMS at 2% wt wt^{-1}.

'Wheeler' cereal rye was drilled at 67 kg ha^{-1} in 19-cm rows using a no-till drill (John Deere, Moline, IL) the fall prior to data collection. Dates for all field operations are listed in Table 1. The following spring, cereal rye was terminated, and main plots were established 1 wk prior to (early termination) or 1 wk after (planting

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Table 1. Cereal rye seeding and termination dates, GDDs until cereal rye termination, soybean planting, POST herbicide application, and soybean harvest dates for the four experimental locations.[a]

	Site			
Operation	MSU-A	MSU-B	MSU-C	KBS
Cereal rye seeding	October 4, 2019	October 16, 2020	November 9, 2020	October 12, 2020
Early termination	May 24, 2020	May 13, 2021	May 13, 2021	May 14, 2021
GDDs (base, 4.4C)	561	521	418	560
GDDs (base, 10 C)	138	142	142	146
Soybean planting	June 1, 2020	May 25, 2021	May 25, 2021	May 24, 2021
Planting green termination	June 8, 2020	June 2, 2021	June 2, 2021	June 3, 2021
GDDs (base, 4.4 C)[b]	791	764	661	812
GDDs (base, 10 C)[c]	287	289	289	300
POST application	June 29, 2020	June 24, 2021	July 7, 2021	July 1, 2021
Soybean harvest	October 31, 2020	October 18, 2021	October 18, 2021	October 19, 2021

[a]Abbreviations: GDDs, growing degree days; MSU, Michigan State University; KBS, Kellogg Biological Station; POST, postemergence.
[b]GDDs (base, 4.4 C) accumulated from the time of cereal rye planting in the fall until termination.
[c]GDDs (base, 10 C) accumulated from January 1 until cover termination for horseweed emergence.

green) planting soybean. Glyphosate, glufosinate, and 2,4-D choline-resistant soybean 'P25T09E' or 'P24T35E' was planted at 500,000, 437,500, 375,000, or 500,000, 450,000, and 387,500 seeds ha^{-1}, respectively, in 2020 and 2021 in 19-, 38-, and 76-cm rows. Higher seeding rates were used in 2021 due to dry conditions at planting. POST herbicide applications were made 4 to 6 WAP when soybean was at the V2 to V4 growth stage in the no-cover plots. Herbicides were applied 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 air 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 closest to each trial (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 each cereal rye termination timing, aboveground cereal rye biomass, and weed density and biomass were collected from two randomly placed 0.25-m^2 quadrats per plot. In addition to GR horseweed, shepherd's purse [*Capsella bursa-pastoris* (L.) Medic], common chickweed [*Stellaria media* (L.) Vill.], whitlowgrass (*Draba verna* L.), purple deadnettle (*Lamium purpureum* L.), henbit (*Lamium amplexicaule* L.), and dandelion (*Taraxacum officinale* F. H. Wigg.) were present at early termination at all sites in 2021. In 2020, only GR horseweed was present at early termination. 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 Corporation, St. Joseph, MI). Percent ground cover was measured using line-transects (Laflen et al. 1981) laid diagonally across each plot at the planting green termination. The presence of cover crop, GR horseweed, other weeds, or no vegetation was recorded at every 30-cm point along an 11-m transect and converted to a percentage. When soybean reached the V2 growth stage in the no-cover plots, percent ground cover was measured again with the addition of marking the presence of soybean. At the time of POST herbicide application and prior to soybean harvest, GR horseweed density and biomass were collected from two randomly placed 0.25-m^2 quadrats per plot. Height of 20 random plants per plot was also measured. Biomass samples were dried for approximately 7 d at 65 C and weighed. Soybean growth and development was evaluated biweekly until soybean reached the R1 stage based on the hybrid method (Pedersen 2009).

Soil moisture was measured with a Field Scout TDR 300 Soil Moisture Meter (FieldScout; Spectrum Technologies, Aurora, IL) by collecting five measurements per plot at a depth of 7.6 cm at the time of soybean planting and at 4 to 6 WAP. Prior to soybean planting and again after soybean harvest, soil samples (30-cm depth) from each cover treatment were collected and analyzed for soil nitrate levels (Soil and Plant Nutrient Laboratory, Michigan State University). Soybean was harvested using a small-plot research combine (Massey-Ferguson 8XP; AGCO, Duluth, GA). Yields were adjusted to 13% moisture.

Statistical Analysis

Data analysis was performed using the GLIMMIX procedure and SAS OnDemand software (SAS Institute Inc., Cary, NC) at $\alpha = 0.05$. The statistical model consisted of cover treatment, soybean row width, POST 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 cover treatment and replication nested within environments, and the interaction between cover treatment 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. Normality of residuals were examined using the UNIVARIATE procedure ($\alpha \leq 0.05$). Squared and absolute value residuals were examined with Levene's test to confirm homogeneity of variances ($\alpha \leq 0.05$). Data were combined over main effects when interactions were not significant. Treatment means were separated using Fisher's Protected LSD at $\alpha \leq 0.05$ when ANOVA indicated a significant main effect or interaction. Non-transformed means for horseweed density and biomass are presented because the arcsine and square root transformation did not improve the normality of the data.

Table 2. Cereal rye biomass and C:N ratios at each termination time, and cereal rye ground cover and the effect of cereal rye on horseweed density and biomass at planting green termination.[a,b]

Cover treatment	Cereal rye			Horseweed	
	Biomass	C:N ratio	Groundcover	Density	Biomass
	kg ha^{-1}		%	plants m^{-2}	g m^{-2}
No cover	NA	NA	NA	49 a	7 a
Early termination	1,842 b	27:1 b	46 b	17 b	2 b
Planting green	4,280 a	42:1 a	58 a	21 b	2 b
Effects (P-values)					
Cover treatment	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[a]Abbreviations: C:N, carbon:nitrogen ratio; NA, not applicable.
[b]Means followed by the same letter within a column are not statistically different at $\alpha \le 0.05$.

Results and Discussion

Early-Season Horseweed Suppression

At the time of early termination, the presence of cereal rye reduced horseweed density and biomass by 3-fold compared with no cover, where 31 plants m^{-2} and 3 g m^{-2} of horseweed biomass were present (data not shown). Additionally, in 2021, the biomass of other weeds was reduced by 76% where cereal rye was present compared with no cover (42 g m^{-2}); however, other weed density was not affected by cereal rye (14 to 20 plants m^{-2}). Horseweed diameter at the time of early termination averaged 2 cm; there was not a substantial amount of horseweed biomass present (<3 g m^{-2}). Although there can be some fall horseweed emergence, in Michigan annual cropping systems and peak horseweed emergence (>80%) generally occurs when 50 to 100 GDDs (base, 10 C) have accumulated and soil moisture is adequate (Schramski et al. 2021b). However, horseweed can continue to emerge throughout the summer following rainfall events. GDD accumulation from the first of the year through early termination was 138 to 146 GDDs (base, 10 C; Table 1) in this study; however, due to reduced precipitation in April (28 to 73 mm) and May (6 to 110 mm), peak emergence did not take place until late May to mid-June. Total precipitation across site-years was 10 to 50 mm and 0 to 87 mm less in April and May than the 30-yr average (data not shown).

Cereal rye at the time of early termination was at Feekes stage 8 with 1,842 kg ha^{-1} of biomass, and GDD accumulation from rye planting to termination ranged between 418 to 561 GDDs (base, 4.4 C; Table 1). Previous research has reported slightly lower (756 to 1,359 kg ha^{-1}) aboveground biomass in early terminated cereal rye in Michigan, likely due to less GDD accumulation (315 to 326 GDD; base, 4.4 C; Schramski et al. 2021b). Horseweed biomass was reduced by 71% at the early termination timing where cereal rye had been used (Table 2). Schramski et al. (2021b) reported horseweed biomass was reduced by 59% to 70% by cereal cover crops compared with no cover, similar to what was observed in this study. Christenson (2015) reported slightly higher horseweed biomass reductions of 84% to 92% when cereal rye was terminated prior to planting soybean compared with no cover.

At soybean planting, mean volumetric soil moisture content was 9% to 11%. Moisture was not affected by cereal rye, regardless of termination time, likely due to below average precipitation during this time (data not shown). At planting, cereal rye was terminated for 1 wk in the early terminated plots and was at Feekes stage 10.5 in the planting green plots. Prior to soybean planting, precipitation was 6 to 110 mm in May across site-years (data not shown). Previous research in Michigan has reported that cereal rye, regardless of termination time, did not influence soil moisture at the time of soybean planting (Rogers 2017; Schramski et al. 2021b). Cereal rye, regardless of termination time, caused a reduction in soil nitrate (NO_3-N) of 8 to 14 kg N ha^{-1} compared with no cover (24 kg N ha^{-1}) at soybean planting. Similarly, Hill et al. (2016) found that soil inorganic N was up to 13 kg N ha^{-1} at the time of dry bean planting when a cereal rye cover crop was present. By reducing available nitrogen to the plant, cereal rye may be more competitive and suppress weeds, which is an asset in legume crops such as soybean, which fix their own nitrogen and grow well in soils with low nitrogen (Wells et al. 2013).

Delaying termination 15 to 20 d by planting green resulted in an additional 230 to 252 GDDs compared with early termination (base, 4.4 C). Cereal rye was at Feekes growth stage 10.5.1 (Table 1), which resulted in an increase of cover biomass by 132% to 4,280 kg ha^{-1} and provided 12% more ground cover compared with early termination (Table 2). Similarly, Reed et al. (2019) reported that delaying cover crop termination 4 to 30 d by planting green produced up to 181% greater cover-crop biomass production compared with early termination. During this timeframe, delaying termination by planting green increased the C:N ratio of cereal rye to 42:1 compared with 27:1 for the early termination timing (Table 2). In contrast, Schramski et al. (2021b) reported C:N ratios below 24:1 when cereal rye was terminated early at Feekes growth stage 5 to 6, and C:N ratios of 16:1 and 30:1 when terminated a week after planting at Feekes 10.4 to 10.5. Higher C:N ratios in this study may be due to slightly advanced cereal rye development at the time of cover termination. The optimum C:N ratio is 24:1 because this is the ideal diet for soil microorganisms (USDA-NRCS 2011). Plant residue below this ratio will decompose more rapidly compared with C:N ratios larger than 24:1 (Jahanzad et al. 2016; Odhiambo and Bomke 2001; USDA-NRCS 2011), providing a potentially longer period of horseweed suppression by planting green. Greater cover biomass production and higher C:N ratios likely contributed to nitrogen immobilization in the cereal rye treatments at soybean planting.

There was a significant increase in cover biomass by planting green; however, there was no increase in horseweed suppression at the time of planting green termination compared with early termination. This was likely due to delayed horseweed emergence as a result of the dry conditions. At the early and planting green termination timings, horseweed density and biomass were both reduced when cereal rye had been planted. Cereal rye reduced horseweed density 57% to 65% compared with no cover (Table 2). Likewise, previous studies found that cover crops reduced horseweed density by 41% to 97% at the time of termination compared with no cover (Essman et al. 2020; Pittman et al. 2019; Schramski et al. 2021b; Wallace et al. 2019). Horseweed biomass was reduced by 71% by planting cereal rye, regardless of termination time, compared with no cover (Table 2). Similarly, Schramski et al. (2021b) reported that a cereal cover, regardless of termination time, resulted in reduced horseweed biomass at the time of termination. Less variable plant sizes and smaller horseweed plants at the time of preplant soybean herbicide application were linked with residue from a cereal rye cover crop (Wallace et al. 2019). Additionally, horseweed size at the time of herbicide application affects selection intensity for glyphosate resistance within resistant populations (Wallace et al. 2019). The ability of cereal rye to reduce horseweed size could reduce the selection pressure for resistant individuals providing growers with greater horseweed control at the time of burndown application.

Mid-Season Horseweed Suppression

In late June, approximately 4 WAP, when soybean was at the V2 growth stage in the no-cover treatment, cereal rye ground cover was 12% higher by planting green (51%) compared with early termination (data not shown). Horseweed ground cover was similar between early terminated cereal rye and planting green (7-9%) but was significantly lower in both compared with no cover (17%; data not shown). Additionally, soybean planted in narrow rows reduced horseweed ground cover by 5% compared with that in 76-cm rows (14%; data not shown). At this time, soybean was at the VC stage in the planting green treatments, one to two growth stages behind the early terminated and no-cover treatments. This delay lasted until the R1 soybean stage. Delays in soybean growth were likely due to nitrogen deprivation, shading, or differences in light quality from planting green cover crop residue because cereal rye did not affect soil moisture, which ranged from 13% to 15% at 4 to 6 WAP (data not shown). Wells et al. (2013) reported that cereal rye created an exceedingly low nitrogen environment that resulted in nitrogen deprivation in pigweed and in soybean before nodulation; however, soybean plants recovered from nitrogen deficit once nodulation became active, whereas pigweed continued to be negatively affected and reductions in pigweed density were observed.

At the time of POST herbicide application, 4 to 6 WAP, there was an interaction between cover treatment and soybean row width on horseweed density and biomass. All treatment combinations reduced horseweed density compared with soybean planted in 76-cm rows with no cover. However, horseweed density was reduced most (67% to 80%) when soybean was planted in narrow rows into cereal rye, regardless of termination time (Table 3). Similarly, Hay et al. (2019) reported soybean planted in 19- and 38-cm rows into an early terminated winter wheat cover crop reduced Palmer amaranth density by 49% to 55% compared with soybean planted in 76-cm rows with no cover 8 WAP. Earlier soybean canopy closure in narrower rows likely suppressed horseweed compared with that in 76-cm rows. In contrast, Schramski et al. (2021b) and Wallace et al. (2019) reported no reduction in horseweed density at the time of POST herbicide application when a cereal rye cover crop was present.

Horseweed biomass was 71% to 90% lower when soybean was planted into cereal rye across all row widths, compared with no cover (Table 3). The greatest biomass reductions were with planting green in all row widths compared with early terminated cereal rye in 76-cm rows and no cover for all row widths. Similarly, Schramski et al. (2021b) reported soybean planted green into a cereal rye or winter wheat cover crop reduced horseweed biomass 46% to 93% compared with no cover at the time of POST herbicide application. Averaged over soybean row width, horseweed height was 8 and 10 cm shorter in early terminated cereal rye and planting green plots compared with no cover, respectively (Table 3). Peak emergence was estimated to have taken place between planting green termination and POST herbicide application (data not shown). Horseweed density was similar between early terminated cereal rye and planting green, but the planting green cover was more competitive and more able to reduce horseweed growth. Reductions in horseweed size at the time of POST herbicide application may also improve herbicide effectiveness when managing GR horseweed.

Table 3. Interaction between cover treatment and soybean row width on horseweed density, biomass, and height at the time of POST herbicide application, 4 to 6 WAP.[a,b]

Cover treatment	Row width	Density	Biomass	Height[c]
	cm	plants m^{-2}	g m^{-2}	cm
No cover	19	51 bc	43 b	19
	38	51 bc	44 b	19
	76	116 a	63 a	19
Early termination	19	32 cd	13 cde	11
	38	38 cd	14 cd	11
	76	60 b	18 c	11
Planting green	19	23 d	6 f	8
	38	34 cd	8 ef	9
	76	43 bc	9 def	10
Effects (P-values)				
Cover treatment		<0.0001	<0.0001	<0.0001
Row width		0.0018	0.0173	0.8843
Cover treatment × row width		0.0137	0.0386	0.8651

[a]Abbreviations: POST, postemergence; WAP, weeks after planting.
[b]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.
[c]The main effect of cover treatment was significant for horseweed height. Horseweed height was reduced 8 and 10 cm by terminating cereal rye early (11 cm) and planting green (9 cm), respectively.

Late-Season Horseweed Suppression

Prior to soybean harvest, horseweed density was 42% lower in the planting green treatments compared with no cover, regardless of soybean row width or POST herbicide treatment (Table 4). In contrast, Schramski et al. (2021b) reported that cereal rye and winter wheat cover crop residue did not persist long enough to provide horseweed suppression through soybean harvest. This was likely due to lower C:N ratios (<30:1) and less biomass production in that study. Although there were no interactions with cover treatment, there was an interaction between soybean row width and POST herbicide treatment on horseweed density. Horseweed density was reduced by 59% and 32%, respectively, when soybean was planted in 19- and 38-cm rows, compared with 76-cm rows when a noneffective POST herbicide was applied (Table 4). The addition of an effective POST herbicide resulted in greater reductions in horseweed density in 19-cm rows than in 76-cm rows. Additionally, there was an interaction between cover treatment and POST herbicide, as well as soybean row width and POST herbicide on horseweed biomass. When a noneffective POST herbicide was applied, horseweed biomass was 36 to 46% lower by planting green compared with early terminated cereal rye and no cover (Table 4). Greater reductions (69%) in horseweed biomass were observed when planting into cereal rye, regardless of termination time, compared with no cover (39 g m^{-2}) when an effective POST herbicide was applied. In contrast, Schramski

Table 4. Interactions between cover treatment and POST herbicide application, and soybean row width and POST herbicide treatment on horseweed density, biomass, and height at soybean harvest.[a]

Cover treatment	POST treatment	Density[b]	Biomass	Height[c]
		plants m^{-2}	g m^{-2}	cm
No cover	Noneffective	18	153 a	108 a
Early termination		16	129 a	99 a
Planting green		11	82 b	62 b
No cover	Effective	6	39 c	36 c
Early termination		3	12 d	13 d
Planting green		2	12 d	15 d
Row width (cm)				
19	Noneffective	9 c[d]	83 c	81
38		15 b	119 b	91
76		22 a	161 a	98
19	Effective	2 e	10 e	14
38		3 de	15 de	15
76		6 cd	37 d	35
Effects (P-values)				
Cover treatment		0.0202	0.0001	<0.0001
Row width		0.0064	0.0033	0.0315
POST		<0.0001	<0.0001	<0.0001
Cover treatment × row width		0.6906	0.7995	0.7447
Cover treatment × POST		0.3782	0.0148	0.0002
Row width × POST		0.0148	0.0158	0.4184
Cover treatment × row width × POST		0.8387	0.4891	0.3798

[a]Abbreviation: POST, postemergence.
[b]The main effect of cover treatment was significant for horseweed density. Density was reduced 42% by planting green (7 plants m^{-2}) compared with no cover (12 plants m^{-2}).
[c]The main effect of row width was significant for horseweed height. Height was reduced 13 to 18 cm by planting in narrower rows (48 to 53 cm).
[d]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.

Table 5. Main effects of cover treatment, soybean row width, and POST herbicide treatment on soybean yield and soil nitrate at harvest.[a,b]

	Soil nitrate	Soybean yield	
Main effects	Combined sites	3 site-years	MSU-C[c,d,e]
Cover treatment	kg N ha^{-1}	kg ha^{-1}	
No cover	32	4,098	3,930
Early termination	30	4,362	4,010
Planting green	27	4,077	3,888
Row width (cm)			
19	NA[a]	4,493 a[b]	4,095
38	NA	4,237 a	4,036
76	NA	3,807 b	3,697
POST			
Noneffective	NA	3,960 b	3,793
Effective	NA	4,399 a	4,092
Effects (P-values)			
Cover treatment	0.1189	0.1315	0.6274
Row width	NA	0.0099	0.2307
POST	NA	0.0004	0.0080
Cover treatment × row width	NA	0.7871	0.1171
Cover treatment × POST	NA	0.9215	0.0353
Row width × POST	NA	0.7487	0.0166
Cover treatment × row width × POST	NA	0.9707	0.2305

[a]Abbreviations: NA, not applicable, 3 site-years = MSU-A, MSU-B, and KBS.
[b]Means followed by the same letter within a column are not statistically different at $\alpha \leq 0.05$.
[c]There was a high incidence of white mold in the planting green and narrow-row treatments at MSU-C; therefore, it was separated from the remaining site-years.
[d]There was an interaction between cover treatment and POST. When a noneffective POST was applied, yield was similar between cover treatments (3,643 to 3,934 kg ha^{-1}). However, when an effective POST was applied, early terminated cereal rye (4,217 kg ha^{-1}) yielded 10% higher compared with planting green (3,842 kg ha^{-1}).
[e]There was an interaction between row width and POST. Yield was similar in narrow rows, regardless of POST herbicide application (3,911 to 4,162 kg ha^{-1}); however, yield was 21% higher in 76-cm rows with an effective POST (4,055 kg ha^{-1}) compared with 76-cm rows with a noneffective POST application (3,339 kg ha^{-1}).

et al. (2021b) did not observe an effect of cover crop or termination time on horseweed biomass at soybean harvest when an effective POST herbicide was applied. Planting soybean in 19- and 38-cm rows reduced horseweed biomass by 48% and 26% compared with that in 76-cm rows, respectively, when a noneffective POST was applied (Table 4). Planting soybean in 19-cm rows reduced horseweed biomass more compared with planting in 76-cm rows when an effective POST herbicide treatment was applied. In contrast, previous research found that narrower rows (19 and 38 cm) did not reduce summer annual weed biomass prior to soybean harvest (Harder et al. 2007). Similarly, Rogers (2017) reported no difference in Palmer amaranth control between 19- and 76-cm rows at soybean harvest.

Horseweed height was 13 to 18 cm shorter in soybean planted in narrower rows compared with that in 76-cm rows (66 cm) prior to soybean harvest (Table 4). Moreover, there was an interaction between cover and POST herbicide treatments. Planting green reduced horseweed height by 37% to 43% compared with early termination and no cover when a noneffective POST herbicide was applied. Regardless of termination time, horseweed height was reduced by 58% to 64% when cereal rye had been planted as a cover compared with no cover when an effective POST herbicide was applied (36 cm; Table 4). Horseweed biomass reductions were also observed with a cereal rye cover compared with no cover with an effective POST herbicide application. In this study, horseweed plants with flower heads were often above the soybean canopy in treatments with a noneffective POST herbicide application or when soybean was planted in 76-cm rows (personal observation). Horseweed plants that produce flower heads above the soybean canopy in August to October can contribute upward of 88% to total seed production (Davis and Johnson 2008). Shorter horseweed plants at the end of the growing season may result in less seed production and reduce the seed bank.

Soybean Yield

Due to a high incidence of white mold [*Sclerotinia sclerotiorum* (Lib.) de Bary], MSU-C was separated from the remaining site-years. Combined over MSU-A, MSU-B, and KBS, cereal rye, regardless of termination time, did not affect soybean yield, which ranged from 4,077 to 4,362 kg ha^{-1} (Table 5). Likewise, other researchers reported no effect on soybean yield from a cereal rye cover crop (Pittman et al. 2019; Schramski et al. 2021b). In addition, cereal rye did not affect soil NO_3-N concentrations (Table 5), supporting what Hill et al. (2016) reported in dry beans that were planted into early terminated cereal rye. We also observed that soybean planted in 19- and 38-cm rows yielded 11% to 18% higher compared with soybean in 76-cm rows (Table 5). Harder et al. (2007) reported soybean yielded was greater in 19-cm rows compared with 38- and 76-cm rows. Furthermore, by applying an effective POST herbicide application yield was 11% greater compared with a noneffective POST herbicide application (Table 5).

There was a cover treatment and POST herbicide application interaction at MSU-C. When a noneffective POST herbicide was applied, yield was similar among cover treatments (3,643 to 3,934 kg ha^{-1}), likely due to greater horseweed competition.

However, when an effective POST herbicide was applied, early terminated cereal rye yielded 10% more than planting green (3,842 kg ha^{-1}; Table 5). This was likely due to a high incidence of white mold within the planting green treatments. There was also a soybean row width and POST herbicide application interaction at MSU-C. Yield was lower when soybean was planted in 76-cm rows with a noneffective POST herbicide application compared with all other treatments (Table 5), whereas yield was similar in narrower rows, regardless of POST herbicide application (3,911 to 4,162 kg ha^{-1}). The above average rainfall in June, July, and August that totaled 356 mm compared with the 30-yr average of 259 mm (data not shown) likely contributed to the high incidence of white mold in the planting green and narrow row soybean treatments. As a result, these treatments created an environment beneath the closed canopy that was favorable for sclerotia germination. This site was also surrounded by corn and a woodlot that may have limited air flow, thereby creating a greater risk for infection. The higher incidence of white mold in narrow row soybean compared with 76-cm rows at this location likely diminished the yield advantage of narrow rows. Previous research has reported higher white mold disease severity in narrow row soybean causing significant yield loss (Grau and Radke 1984).

Overall, planting soybean in narrow rows into a cereal rye cover crop is a promising horseweed management tool; however, growers should be cautious of favorable environmental conditions for white mold development created by planting green or narrow soybean rows. The addition of a cereal rye cover crop reduced horseweed emergence and density at cover crop termination. By the time of POST herbicide application, narrow-row soybean planted into cereal rye, regardless of termination time, reduced horseweed density by 67% to 80% compared with density in 76-cm rows with no cover, whereas soybean planted green in narrow rows reduced horseweed size by 90% compared with that in 76-cm rows with no cover. Reductions in horseweed size at the time of burndown and POST herbicide applications may improve herbicide effectiveness and potentially reduce the selection pressure for further development of herbicide-resistant populations. In contrast to previous research, planting green suppressed horseweed through soybean harvest, likely due to higher cereal rye biomass (4,280 kg ha^{-1}) and later growth stages at termination, thus resulting in a more persistent residue due to a higher C:N ratio. At soybean harvest, horseweed biomass was reduced by 91% or more by planting into cereal rye or by planting in 19-cm rows when an effective POST herbicide was applied. Narrow-row soybean or soybean planted green with an effective herbicide program can be implemented as an additional horseweed management strategy for early- and late-season horseweed suppression.

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