Weed Technology

www.cambridge.org/wet

Delayed cover-crop termination and reduced herbicide inputs produce trade-offs in soybean phase of US Northeast forage-grain rotation

Teala S. Ficks[1], Heather D. Karsten[2] and John M. Wallace[3]

[1]Graduate Student, Plant Science Department, Pennsylvania State University, University Park, PA, USA; [2]Associate Professor, Pennsylvania State University, University Park, PA, USA and [3]Assistant Professor, Pennsylvania State University, University Park, PA, USA

Research Article

Cite this article: Ficks TS, Karsten HD, Wallace JM (2023) Delayed cover-crop termination and reduced herbicide inputs produce trade-offs in soybean phase of US Northeast forage-grain rotation. Weed Technol. **37**: 132–140. doi: 10.1017/wet.2023.18

Received: 10 November 2022
Revised: 16 February 2023
Accepted: 24 February 2023
First published online: 13 March 2023

Associate Editor:
Rodrigo Werle, University of Wisconsin

Nomenclature:
Horseweed; *Erigeron canadensis* (L.); cereal rye; *Secale cereale* L.; soybean; *Glycine max* (L.) Merr.

Keywords:
Cereal rye; cover crop; horseweed; integrated weed management; planting green; soybean

Corresponding author:
John M. Wallace, Assistant Professor, Plant Science Department, Pennsylvania State University, 116 ASI Building, University Park, PA 16802. (E-mail: jmw309@psu.edu)

Abstract

Region- and system-specific research is needed to understand the viability of delayed cover-crop termination (i.e., planting green) as an integrated weed management (IWM) tactic in no-till soybean. In a 3-yr field experiment, we evaluated the potential for planting green to facilitate elimination of soil-applied, preemergence residual herbicides within a soybean phase of a 6-yr grain–forage cropping systems experiment in Pennsylvania. This IWM tactic was contrasted with a Standard treatment, which included 14 to 21 d pre-plant termination of cereal rye and a two-pass herbicide program with preemergence herbicides. A 63% increase in cereal rye biomass production was observed within the IWM treatment in 2019, but only a 22% and 33% increase in 2020 and 2021, respectively. In 2020, significantly lower volumetric water content (%VWC) was observed within the IWM treatment in dates closest to planting and greater %VWC at multiple dates in June and July compared to the Standard treatment. No differences occurred in soybean populations, but soybean biomass at the V4 growth stage was reduced in the Standard treatment compared to the IWM treatment, which we attribute to injury from preemergence applications. The Standard treatment resulted in greater soybean yield (2,590 kg ha^{-1}) than the IWM treatment (1,870 kg ha^{-1}) in 2020, but yields were similar in other years. The IWM treatment resulted in 58% fewer herbicide inputs, as measured by the number of active ingredients applied, compared to the Standard over the 3-yr study. Yet, peak weed biomass did not differ between treatments. However, the IWM treatment resulted in greater total horseweed density and the number of horseweed plants that exceeded recommended size-based height thresholds (10 cm) compared to the Standard treatment just prior to postemergence applications (35–42 d after planting) in 2020 and 2021, underscoring the importance of integrating surface mulch residues with effective herbicide sites of action.

Introduction

Effective combinations of herbicide-based and cultural weed control tactics are needed to foster sustainable weed management approaches within conservation tillage systems (Liebman 2018; Mortensen et al. 2012; Norsworthy et al. 2012). Cover crops are increasingly integrated and incentivized in annual cropping systems to improve soil health and target conservation goals (Schipanski et al. 2014), which represents an opportunity to optimize their performance as a cultural weed management tactic in no-till systems. Cover crops are an effective cultural weed control tactic in the US Northeast, particularly when utilized in combination with herbicide-based tactics (Bunchek et al. 2020; Vollmer et al. 2020; Wallace et al. 2019).

Currently, there is increasing interest in intensifying cover-crop management within the northeastern United States by using planting green tactics in no-till systems. Planting green is the delay of cover-crop termination until after cash crop planting (Reed et al. 2019), which enables more growth and biomass production than typical 10- to 14-d pre-plant burndown termination tactics. The most common crop sequence in which planting green tactics are used is no-till planting of soybean into cereal rye. In the northeastern United States, delaying termination of cereal rye by 10 to 14 d can result in significant biomass gains (Mirsky et al. 2009; Reed and Karsten 2022), which has been shown to correlate directly with weed suppression levels (Nord et al. 2011, 2012).

Intensification of cover-crop management with use of planting green tactics may facilitate a reduction in herbicide inputs while maintaining crop protection goals. However, the efficacy of reduced-herbicide programs will depend on (i) species traits such as herbicide-resistance level, emergence periodicity, and seed mass (Beam et al. 2021; Bunchek et al. 2020; Ficks et al. 2022), and (ii) the method of herbicide input reduction, including elimination of preemergence applications, a postemergence pass, or a reduction in the total number of active ingredients utilized within a growing season. In theory, high-residue cover-crop surface mulches provide early-season weed suppression, which is the intended management goal when applying preemergence herbicides at or near cash crop planting. Consequently, excluding preemergence herbicides when delaying termination of cover crops may be a viable strategy for reducing herbicide inputs, and would encourage adoption of an IPM framework, where early-season scouting permits the grower to plan postemergence herbicide application passes.

Region- and system-specific research is needed to understand the viability of planting green as an IWM tactic, as well as the agronomic trade-offs that will affect adoption rates. Cropping systems that integrate annual or perennial forage phases may provide opportunities to reduce herbicide inputs within summer annual grain crops, because asynchronous disturbance events created by planting and harvesting winter annual or perennial forages within the rotation disrupt life cycles of summer annual weed species (Cavigelli et al. 2008; Davis et al. 2012; Weisberger et al. 2019). Within the US Northeast, herbicide banding and high-residue, inter-row cultivation can be viable tactics to reduce herbicide inputs in corn (*Zea mays* L.) and soybean phases of a grain and forage cropping system (Snyder et al. 2016; Summers et al. 2021). However, constraints based on labor and equipment have led few producers to express interest in adopting these tactics. In contrast, there is significant interest in delayed cover-crop termination tactics within no-till grain production systems (Reed et al. 2019), which may be adopted in more diverse grain and forage cropping systems as a method for reducing herbicide inputs.

We conducted a field experiment to evaluate the potential for delayed cereal rye termination (i.e., planting green) to facilitate elimination of soil-applied residual (preemergence) herbicides within a soybean phase of a diverse 6-yr grain–forage rotation within a long-term cropping systems study in Pennsylvania. This IWM strategy was compared to standard pre-plant termination of cover crops (14 to 21 d) and herbicide programs (two-pass program with preemergence herbicides). We hypothesized that use of planting green tactics without preemergence herbicides would maintain weed control and soybean yield performance, while contributing to herbicide resistance management goals, including reduced recruitment rates of summer annual weed species and size of individuals at the time of postemergence herbicide applications.

Materials and Methods

Experimental Design and Field Operations

A field experiment was conducted at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) near Rock Springs, PA (40.118333°N, 76.427500°W) in the soybean phase of the Pennsylvania State University Sustainable Dairy Cropping Systems Project for three growing seasons (2019–2021). This cropping system experiment involves a 6-yr rotation, including a 3-yr annual grain/forage phase and a 3-yr perennial forage phase [alfalfa (*Medicago sativa* L.) – orchardgrass (*Dactylis glomerata* L.)] that is imposed with a full-entry design and four replicate blocks, where each crop phase is present each year in main plots (18 m by 30 m). Two alternative weed management treatments (Standard, IWM) are imposed at the split-plot level (9 m by 30 m) using a single-factor, paired comparison. In the 3-yr annual grain/forage phase, the Standard treatment included a corn silage/corn silage/cereal rye–soybean phase, and the IWM treatment included a corn silage/sorghum sudangrass (*Sorghum bicolor* × *S. bicolor* var. sudanese)/cereal rye (*Secale cereale* L.)–soybean phase.

Within the soybean phase, weed management treatments included the following: (i) Standard: cereal rye termination (14 to 21 d pre-plant, DPP) and a two-pass herbicide program that included preemergence herbicides; and (ii) IWM: delayed cereal rye termination (1 d post-plant) and a one-pass herbicide program (postemergence only; Table 1). At the postemergence application timing (35–42 d after planting, DAP), an IPM approach was carried out by scouting weeds and adjusting the herbicide program accordingly based on the emerged weed community. Given that glyphosate was the planned postemergence application, scouting focused on the presence of either glyphosate-resistant species or species that require the addition of herbicides with other sites of action in combination with glyphosate to achieve adequate control.

Cereal rye ('Aroostook') was established each fall before the soybean phase with a no-till drill (Great Plains, Salina, KS) in early October using a 135 kg ha^{-1} seeding rate in both treatments (Table 2). Because weather conditions across years were variable, cereal rye was terminated 21 DPP in 2019 and 2021 growing seasons and 14 DPP in the 2020 growing season within the Standard treatment (Table 2). Soybeans were planted using a John Deere 1720 MaxEmerge no-till planter (Deere & Company, Moline, IL) at a rate of 371,000 seeds ha^{-1} in 76-cm-wide rows (Table 2). Soybean trait platforms differed among years as a result of regional availability (2019–2020, Xtend®; 2021, XtendFlex®; Bayer Crop Science, Leverkusen, Germany). Cereal rye was roll-crimped and soybean planted in a single pass in the IWM treatment using ZRX integrated roller-crimpers and double-disk row cleaners (Dawn Equipment, Sycamore, IL). The roll-crimper was not used in the Standard treatment at soybean planting. We suggest that residue management and planter configuration differences between treatments represent best-management practices currently being utilized by early adopters of planting green tactics (Reed et al. 2019).

Data Collection

Aboveground cereal rye biomass was collected in two randomly placed 0.25-m^2 quadrats per split plot one day prior to cover-crop termination. Cereal rye residue and soybean biomass was collected just prior to the postemergence application at the V4 soybean growth stage within one randomly placed 0.5-m^2 quadrat. Biomass samples were oven-dried at 65 C for 7 d and weighed. Soybean stand counts were conducted at the V4 soybean growth stage in a representative 2.66 m of the middle two rows per split plot. Soybean yields were evaluated by harvesting the middle two rows of each split plot with a small-plot harvester and moisture corrected to 13.5%.

Soil moisture conditions were monitored in split plots to better characterize effects of delayed cover-crop termination on soybean growing conditions and early-season weed dynamics. We measured soil volumetric water content (%VWC) at a 7.62-cm depth in three random inter-row locations per split plot on a weekly interval for 14 wk after soybean planting using a Campbell Scientific HydroSense II soil moisture probe (Campbell Scientific, Inc., Logan, UT).

Weed abundance was evaluated in two different sampling zones. The effect of Standard and IWM treatments on weed abundance was evaluated in mid-August each year within each split plot by harvesting aboveground weed biomass from two randomly placed 0.25-m^2 quadrats in the center planting pass, corresponding with soybean yield strips. Samples were sorted to species, oven-dried at 65 C for 7 d, and weighed. As a result of field scouting prior

https://doi.org/10.1017/wet.2023.18 Published online by Cambridge University Press

Table 1. Herbicide inputs across treatments (Standard and integrated weed management, IWM) and crop growing season (2019–2021). Standard treatments include products applied 14 to 21 d pre-plant for cover-crop termination and weed control, preemergence soil-applied residuals (preemergence) applied 1 d after planting (DAP), and a postemergence pass 35–42 DAP. IWM treatments include cover-crop termination 1 DAP and a postemergence pass 35–42 DAP.

	Standard			IWM		
Herbicide inputs	2019	2020	2021	2019	2020	2021
Cover-crop termination						
Glyphosate (1.26 kg ae ha^{-1})	X	X	X	X	X	X
2,4-D ester (0.53 kg ae ha^{-1})	X	X	X			
Preemergence soil residual (1 DAP)						
Glyphosate (1.26 kg ae ha^{-1})	X	X	X			
Flumioxazin (0.09 kg ai ha^{-1})	X	X	X			
Pyroxasulfone (0.11 kg ai ha^{-1})	X	X	X			
Postemergence (35–42 DAP)						
Glyphosate (1.73 kg ae ha^{-1})	X	X	X	X	X	X
Cloransulam-methyl (0.04 kg ai ha^{-1})		X			X	
Glufosinate-ammonium (0.66 kg ai ha^{-1})						X
Total number of active ingredients	6	7	6	2	3	3

Table 2. Field operations dates and environmental conditions for each experimental year.

Field operation	2018–2019	2019–2020	2020–2021
Cereal rye seeding	October 17	September 25	September 23
Cereal rye termination (Standard[a])	April 30	May 5	April 27
Soybean planting	May 22	May 20	May 18
Cereal rye termination (IWM[a])	May 22	May 21	May 19
Soybean harvest	October 11	October 23	October 21
Fall GDD[b]	79	358	456
Spring GDD (Standard)	239	262	252
Spring GDD (IWM)	481	367	435
IWM GDD difference relative to Standard	242	105	183

[a]Standard treatment consisted of cereal rye termination 14 to 21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP.
[b]Abbreviation: GDD, cumulative growing degree days; base temperature set at 4.4 C (Mirsky et al. 2011) and calculated from seeding to termination date.

to postemergence applications, horseweed density, and heights were additionally sampled from two randomly placed 0.25-m^2 quadrats per split plot 35–42 DAP in 2020 and 2021; horseweed sampling was not conducted in 2019, because there were no emerged populations at the postemergence herbicide application timing.

In addition, preemergence herbicide exclusion subplots (1 m^2) were established within each split plot to isolate the effect of delayed cover-crop termination on suppression of summer annual weeds. Artificial weed seedbanks were seeded each December following cereal rye seeding to create preemergence herbicide exclusion subplots using 800 redroot pigweed (*Amaranthus retroflexus* L.) seeds and 200 large crabgrass [*Digitaria sanguinalis* (L.) Scop.] seeds from local populations. At the time of preemergence applications within the Standard treatment, subplots were covered with a plastic tarp, allowed to dry following the application, and then removed. Density and height of large crabgrass and redroot pigweed populations were recorded within subplots at the V4 soybean growth stage, just prior to postemergence herbicide applications.

Statistical Analysis

Statistical analyses were conducted using R v. 3.6.1 (R Core Team 2019). For each response, variable, mixed-effects models were fit using weed management treatment (Standard, IWM), site-year, and their interaction as fixed effects, and block as a random effect. Biomass data (cereal rye, weeds, soybean), soybean population and yield, and soil %VWC data were analyzed using linear mixed-effect models in the *nlme* package (Pinheiro et al. 2019). A repeated-measures ANOVA with an autoregressive correlation structure was used to test for interactions between sampling date and management strategy in models of soil %VWC by experimental year. Soil %VWC was expressed as the difference relative to the Standard treatment, sampling date was fit as a fixed effect, and a plot identifier was used as the within-subject term. Summer annual weed and horseweed density data were analyzed with generalized linear mixed-effect models (GLMMs) using a negative binomial distribution and a log link function (*glmer.nb*) in the *lme4* package (Bates et al. 2015). Significance of fixed effects within GLMMs was evaluated using log-likelihood ratio tests (Wald χ) to compare full versus reduced models using the *anova* function. The *emmeans* package was used to obtain least-square means on the response scale and pairwise comparisons for significant interactions (Lenth 2019). Back-transformed means (± SE) are presented in results.

Results and Discussion

Cereal Rye Performance

Greater aboveground cereal rye biomass at termination was observed in the IWM treatment compared to the Standard treatment (14 to 21 d pre-plant termination) in 2 of 3 yr ($F = 10.9$; $P < 0.01$; Figure 1A). However, the magnitude of the response varied among years. We observed a 63% increase in cereal rye biomass production within the IWM treatment in 2019, but only a 22% and 33% increase in 2020 and 2021, respectively. Differences in magnitude may be partially explained by differences in cumulative growing degree days (GDD) between termination timings. Delayed termination in the IWM treatments resulted in a 242, 105, and 183 GDD increase in 2019, 2020, and 2021, respectively, compared to the Standard treatment (Table 2).

Previous research has shown that delaying termination of cereal rye is an effective means for significantly increasing biomass potential within the US Northeast. Mirsky et al. (2011) reported that cereal rye biomass increased approximately 2,000 kg ha^{-1} for each 10-d incremental delay in spring termination. A recent study has reported 76% to 96% increases in cereal rye biomass production

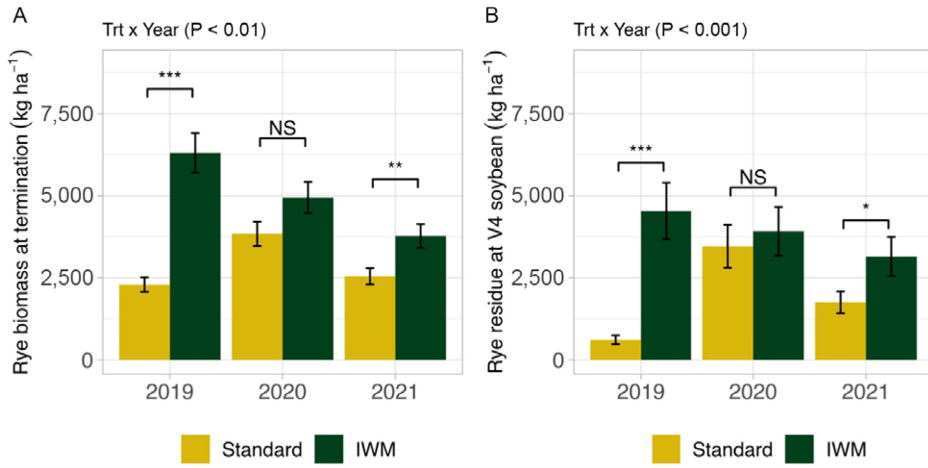

Figure 1. The effect of experimental year (2019–2021) and integrated weed management (IWM) treatment (Standard, IWM) on (A) cereal rye aboveground biomass at termination and (B) cereal rye surface residue at the V4 soybean growth stage. Standard treatment was cereal rye termination 14 to 21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP. Pairwise comparisons with a significant treatment (Trt)-by-year interaction are displayed (NS, nonsignificant at P < 0.05; * P < 0.05; ** P < 0.01; *** P < 0.001).

when delaying termination by 10 to 14 d during the same time-period (late April through mid-May) within the Northeast (Reed and Karsten 2022). Within this study, termination timings were based on targeted soybean planting date (May 15–20), and in 2 yr (2020–2021) Standard pre-plant termination of cereal rye occurred after initiation of stem elongation, which significantly increases biomass accumulation. We attribute more moderate increases (22% to 33%) in biomass accumulation to these phenological patterns.

The IWM treatment also resulted in greater surface residue biomass compared to the Standard treatment at the V4 soybean growth stage in 2 of 3 yr (F = 12.8; P < 0.001), with the magnitude of difference in each year closely tracking biomass patterns observed at the time of termination (Figure 1B). The average mass loss in cereal rye residue from termination until the V4 growth stage ranged from 17% to 28% in the IWM treatments, with greater variation in mass loss observed in the Standard treatments (10% to 74%) across years.

Cereal rye residue persistence is an important factor that contributes to weed suppression potential and is mediated by total biomass production and the C:N ratio at termination (Poffenbarger et al. 2015). Relative humidity and precipitation in the first 60 d following cover-crop termination are important drivers of cereal rye decomposition, with both soil moisture and N availability to soil microorganisms limiting decomposition rates during the growing season (Thapa et al. 2022). It is likely that differences in C:N ratios and precipitation patterns between cereal rye termination timings among years contributed to the observed variability in surface residue mass loss within Standard treatments in our 3-yr study.

Indirect Effects on Soil Moisture

Delaying cereal rye termination can influence soil moisture dynamics by creating early-season soil moisture deficits due to greater transpiration loss and later-season soil moisture conservation due to prevention of evaporative loss due to greater surface mulch persistence (Williams et al. 1998; Reed et al. 2019). This trend was observed in only the 2021 growing season, where comparatively lower %VWC was observed within the IWM treatment at dates closest to planting, and greater %VWC was observed at multiple dates in June and July (Figure 2). Relative to other study years, 2021 received above-average (30-yr) precipitation across the growing season and soil moisture fluctuated between 15% and 30% VWC. In comparison, precipitation was below 30-yr averages by mid-June in 2020 and reached drought-level status through the month of July, with soil moisture declining from 30% VWC in mid-June to 10% by mid-July (Table 3). Though not statistically significant, trends suggest that %VWC was lower in the IWM planting green treatment during this drought period.

Soybean Performance

Soybean populations within the IWM treatment did not differ compared to the Standard treatment, but populations did vary among years (F = 4.3; P < 0.05; Figure 3A). Soybean biomass was greater (F = 16.9; P < 0.01) in the IWM treatment compared to the Standard treatment at the V4 growth stage (Figure 3B). Though the magnitude of the effect was small, the relationship was consistent among years. Field observations suggest that early-season soybean growth rates were reduced due to flumioxazin injury, which was applied only in the Standard treatment. Flumioxazin, a component of the soil-applied herbicide treatment, can result in ephemeral injury to emerging soybeans, particularly in lower residue environments (J.M. Wallace, personal observation). Weed management treatment effects on soybean grain yield differed among years (F = 4.1; P < 0.05). The Standard treatment resulted in greater soybean yield (2,587 kg ha^{-1}) than the IWM treatment (1,873 kg ha^{-1}) in 2020, but yields were similar in other years (Figure 3C).

Recent soybean research has found either no effect (Reed et al. 2019) or a small yield penalty (3% to 4%; Reed and Karsten 2022) when planting green. In both studies, delaying rye termination until soybean planting resulted in cooler soil temperatures compared to Standard pre-plant termination tactics, which corresponded to observations of delayed soybean seedling emergence and maturation. Reduced soybean populations due to inadequate seed placement and closure of seed furrows have historically been a constraint to no-till planting into high levels of cover-crop surface mulch (Liebl et al. 1992; Mirsky et al. 2013; Williams et al. 1998).

https://doi.org/10.1017/wet.2023.18 Published online by Cambridge University Press

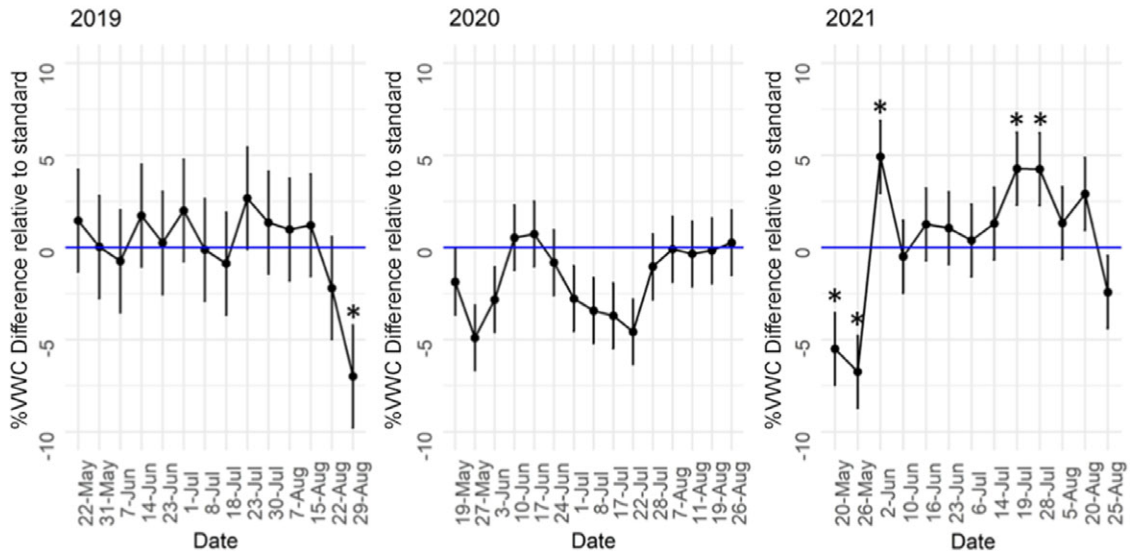

Figure 2. Effect of IWM treatment on soil volumetric water content (VWC%; 7.6-cm depth) relative to the Standard treatment across three growing seasons (2019–2021). Standard treatment was cereal rye termination 14 to 21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP. Data are treatment means (± 1 SE) averaged across replicates. Asterisks indicate significant %VWC differences ($P < 0.05$) relative to Standard termination timing.

Table 3. Total monthly precipitation and average monthly temperature in each soybean growing season compared to 30-yr averages (1981–2010) at Rock Springs, PA.

Month	Precipitation				Temperature			
	2019	2020	2021	30 yr	2019	2020	2021	30 yr
	mm				C			
May	158	91	116	92	16	14	14	15
June	91	125	109	103	19	20	21	20
July	63	35	146	96	23	25	22	22
August	67	51	123	105	21	23	23	21
September	47	57	223	100	18	17	18	17
October	114	83	89	87	12	11	15	11

We attribute the lack of difference in populations between treatments to improved planter technologies, including integrated roller-crimpers on parallel linkage coupled with double-disk row cleaners, as well as automatic adjustment of hydraulic downforce pressure on individual row units. Improved planter technologies should further increase relative fitness of emerging soybean seedlings relative to co-emerging weed species within surface mulch residues (Mohler 1996; Ficks et al. 2022; Williams et al. 1998).

Weed Control Performance

The IWM treatment resulted in 58% fewer herbicide inputs, as measured by the number of active ingredients applied, compared to the Standard treatment over the 3-yr study (Table 1). Variation in the selection of postemergence herbicide inputs was primarily driven by abundance of glyphosate-resistant horseweed populations. In 2019, no additional active ingredients were mixed with glyphosate programs because of minimal recruitment of horseweed at the study, whereas cloransulam-methyl was applied in 2020 in dicamba-tolerant soybean (Xtend®) and glufosinate was applied in 2021 in dicamba/glufosinate-tolerant soybean (XtendFlex®) to target emerged horseweed populations.

Just prior to postemergence applications (35–42 DAP), the IWM treatment resulted in greater total horseweed density ($\chi^2 = 14.9$; $P < 0.001$) and the density of horseweed plants that exceeded recommended size-based height thresholds (10 cm; $\chi^2 = 20.1$; $P < 0.001$) compared to the Standard treatment in 2020 and 2021 (Figure 4A, B). Peak weed biomass did not differ ($F = 1.1$; $P = 0.31$) between IWM and Standard treatments (Figure 4C). Mean biomass levels in mid-August were below 50 kg ha^{-1} within each treatment and year. The most discernible species-level trend between treatments was greater abundance of horseweed and large crabgrass within IWM treatments. The trend toward greater total peak biomass within IWM treatment in 2020 can be attributed to reduced efficacy of cloransulam-methyl treatments on horseweed relative to 2021, when use of a glufosinate-tolerant soybean variety permitted use of postemergence glufosinate applications and resulted in acceptable levels of horseweed control.

Fall-sown cereal rye can significantly reduce horseweed populations at the time of a pre-plant burndown application (Bunchek et al. 2020; Essman et al. 2020; Schramski et al. 2021; Wallace et al. 2019). However, field observations suggest that greater horseweed populations in planting green treatments 35–42 DAP resulted from the lack of an effective pre-plant burndown active ingredient to control the population cohort that had emerged in fall and persisted in the cereal rye cover crop, whereas Standard treatments included 2,4-D ester in pre-plant burndown applications. Use of Enlist® soybean traits permits use of 2,4-D choline when terminating cereal rye in a planting green scenario (1 DAP), but additional research is needed to understand how roll-crimped surface residues affect weed control efficacy for horseweed cohorts near the soil surface where foliar coverage may be compromised (Wallace et al. 2019).

Surface Mulch Effect on Weed Suppression

Preemergence-herbicide exclusion subplots were utilized to isolate the effect of the surface mulch differences between treatments on recruitment and early-season growth rates of summer annual grass and broadleaf weed species. No difference in redroot pigweed total

https://doi.org/10.1017/wet.2023.18 Published online by Cambridge University Press

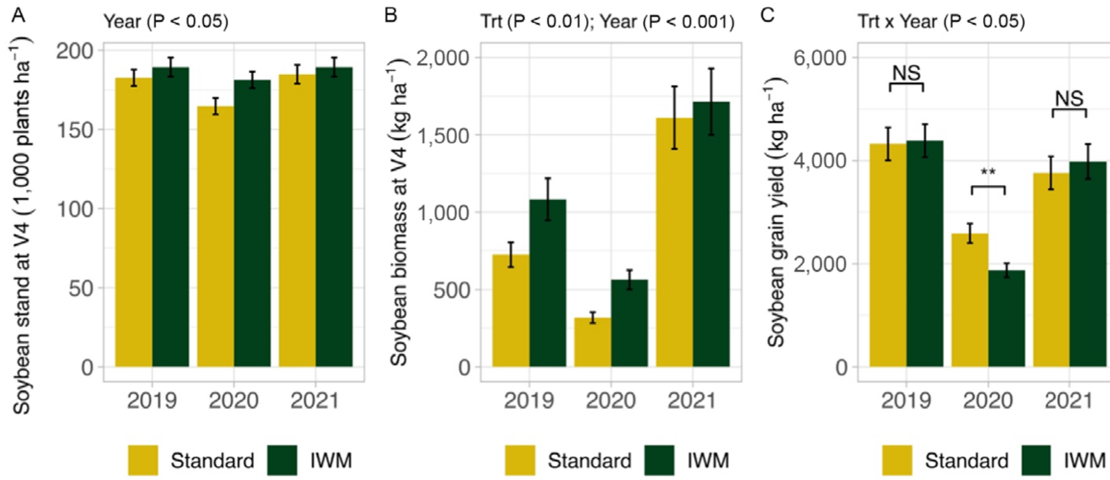

Figure 3. The effect of experimental year (2019–2021) and integrated weed management (IWM) treatment (Standard, IWM) on soybean (A) population and (B) aboveground biomass at the V4 growth stage, and (C) soybean grain yield. Standard treatment was cereal rye termination 14–21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP. Pairwise comparisons with a significant treatment (Trt)-by-year interaction are displayed (NS, nonsignificant at P < 0.05; * P < 0.05; ** P < 0.01; *** P < 0.001).

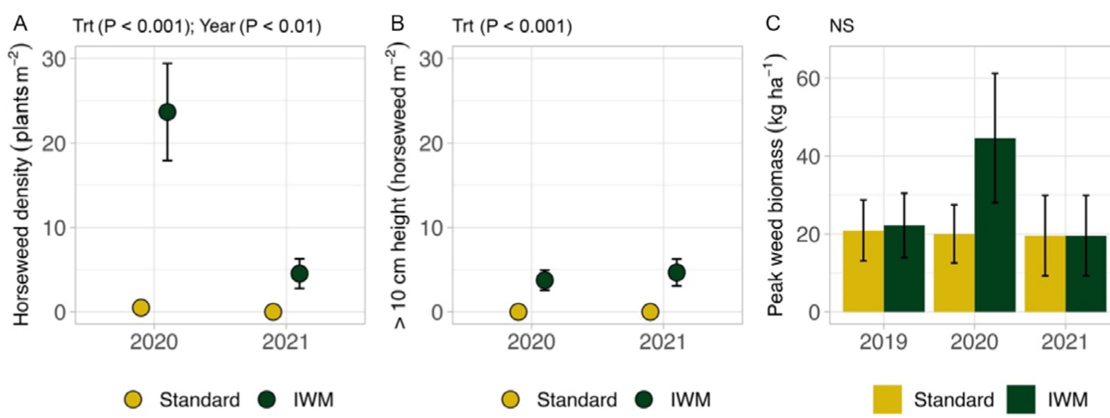

Figure 4. The effect of experimental year (2019–2021) and integrated weed management (IWM) treatment (Standard, IWM) on horseweed (A) total density and (B) horseweed individuals >10 cm height 35–42 d after planting (DAP), and (C) total peak weed biomass. Standard treatment consisted cereal rye termination 14 to 21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP.

density or individuals exceeding size thresholds were detected between treatments ($P < 0.05$) just prior to postemergence applications (35–42 DAP), though a trend toward lower densities in the IWM treatment was observed (Figure 5A, B). Treatment effects differed across years in analysis of large crabgrass total density just prior to postemergence applications ($\chi^2 = 16.7$; $P < 0.001$), where greater densities were observed in IWM treatments in 2 of 3 yr (Figure 5C), but no differences were observed in analysis of the number of large crabgrass individuals exceeding size-based thresholds just prior to postemergence applications (Figure 5D). Based on field observations, large crabgrass recruitment patterns can be attributed, in part, to greater in-row disturbance within IWM treatments. Large crabgrass recruitment was concentrated within areas disturbed by row cleaning, which tended to be more aggressive within IWM than the Standard treatment. Row cleaning in combination with roll-crimping is carried out to optimize soybean seed placement and establishment rates but necessarily creates in-row soil disturbance that influences weed recruitment rates. Future research should consider strategies for balancing such trade-offs when utilizing planting green tactics in higher cover-crop residue systems.

Delaying cereal rye termination can reduce total summer annual weed densities (Nord et al. 2011) and size of individual weeds at key within-season herbicide application timings (Bunchek et al. 2020). In our experiment, moderate increases (22% to 63%) in cereal rye biomass likely contributes to the lack of strong trends in summer annual weed recruitment rates between treatments. However, several factors can influence the magnitude of the effect beyond differences in biomass accumulation, including seedbank size, species traits, and indirect effects of delayed termination on pedoclimatic factors influencing weed seedbank dynamics. For example, Nord et al. (2012) demonstrated that weed seedbank density levels mediate the effects of cereal rye biomass and termination timings on weed suppression potential, with greater relative weed suppression levels observed when seedbank density was low (<300 seeds m^{-2}). Small-seeded broadleaf species, such as redroot pigweed, are more susceptible to seedling mortality during the establishment phase in cereal surface mulch than summer annual grass species (Ficks et al. 2022). Germination periodicity also mediates surface residue effects on population recruitment at the species level (Nord et al. 2011). Cover-crop surface residues affect microsite conditions that mediate weed seed dormancy and germination cues in the

https://doi.org/10.1017/wet.2023.18 Published online by Cambridge University Press

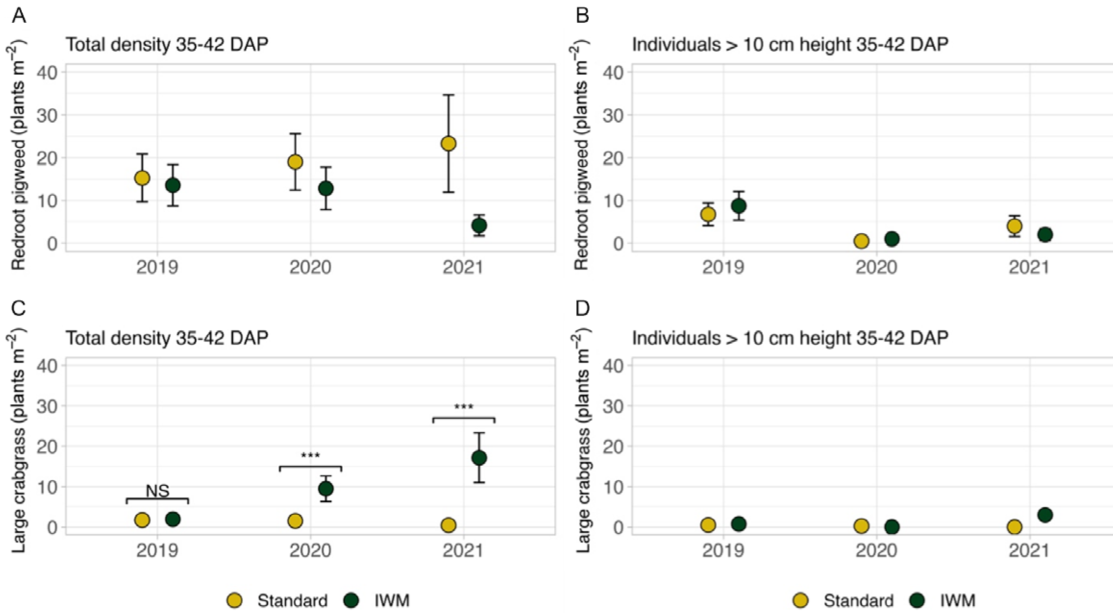

Figure 5. The effect of experimental year (2019–2021) and integrated weed management (IWM) treatment (Standard, IWM) on redroot pigweed (A) density and (B) individuals >10 cm height, and large crabgrass (C) density and (D) individuals >10 cm height 35–42 d after planting (DAP). Standard treatment was cereal rye termination 14 to 21 d pre-plant, preemergence herbicide applied 1 d after planting (DAP), postemergence herbicide 35–42 DAP; IWM treatment was cereal rye termination 1 DAP, postemergence herbicide 35–42 DAP. Pairwise comparisons with a significant treatment (Trt)-by-year interaction are displayed (NS, nonsignificant at $P < 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).

upper soil profile within no-till systems, including %VWC and soil temperature (Nichols et al. 2015; Williams et al. 1998). For example, Reed et al. (2019) reported that soil was 7% to 24% drier and 0.9 C cooler when delaying termination of cereal rye until soybean planting compared to earlier pre-plant termination timings. Delayed termination also influences cereal rye C:N ratios, which can indirectly affect fitness of nitrophilic weeds, including redroot pigweed, in no-till soybean systems (Wells et al. 2013). Finally, Champagne et al. (2019) reported that the level of in-row disturbance that results from planter configurations in high-residue no-till systems can influence summer annual weed recruitment rates.

Management Implications

Previous northeastern United States studies have shown that there is a positive relationship between cover-crop biomass and several ecosystem services, including weed suppression and N retention (Finney et al. 2016; Mirsky et al. 2017). Earlier fall planting dates, supplementing fall N fertility, and delaying termination are all means for increasing cereal rye biomass potential (Mirsky et al. 2017). In this study, we investigated delayed cereal rye termination as an IWM tactic that facilitates reduced herbicide inputs in a soybean phase of a diversified grain–forage system. Use of delayed cover-crop termination and postemergence herbicide programs reduced the number of herbicide active ingredients used in the soybean phase by >50% without influencing late-season weed abundance, which can be used as an indicator of weed seedbank returns. This result, however, should be viewed in context of our study system. First, herbicide exclusion microplots suggest that surface mulch levels resulting from planting green did not significantly reduce summer annual weed recruitment compared to Standard pre-plant germination, which we attribute to only moderate gains (22% to 63%) in biomass. Recent meta-analyses suggest that greater than 5,000 kg ha^{-1} of aboveground biomass is needed to reduce weed biomass by 75% (Nichols et al. 2020). In comparison, total aboveground biomass in planting green treatments ranged from 3,800 to 6,300 kg ha^{-1} in our study, exceeding this theoretical threshold (5,000 kg ha^{-1}) in only 1 of 3 yr. Although considerable context is required to relate weed suppression potential to cover-crop biomass thresholds, it is instructive to note that cereal rye biomass production following a 14- to 21-d delay in termination was still lower than what is commonly viewed as the threshold necessary for season-long weed suppression when relying on cover-crop surface mulch as a stand-alone weed control tactic.

Our results highlight several factors that should be considered to accurately characterize short- and long- term net returns when adopting planting green tactics. First, reductions in herbicide inputs (58% over the 3-yr study) achieved via use of cultural tactics such as planting green have the potential to significantly decrease costs of production. However, we suggest that reduced herbicide use without (i) a loss in weed control efficacy and (ii) increase in weed seedbank returns is more likely to be achieved when soybean is produced in diverse crop rotations, such as forage–grain systems, which are more likely to select for higher diversity and lower abundance weed communities (Davis et al. 2012). Nonetheless, our results underscore the importance of integrating nonchemical tactics with effective herbicide sites of action. In our study, additional active ingredients in postemergence application passes were needed to control glyphosate-resistant horseweed and increased early-season horseweed competition could have contributed, in part, to the observed yield reduction in 1 of 3 yr within the IWM treatment. Within forage–grain systems, future research may also consider contrasting net returns from using planting green tactics to reduce herbicide inputs with harvesting cereal rye for forage prior to no-till planting soybean, which is frequently utilized in a corn silage sequence (Binder et al. 2020) but has been less explored in a soybean sequence (Crowley et al. 2018). Finally, cost savings from reduced herbicide use may offset yield penalties driven by variable environmental conditions when planting green into higher residue cereal rye biomass. In our study, the

IWM treatment resulted in lower soybean yield in only 1 yr when drought conditions occurred throughout late June and July. Field-based observations suggest that greater early-season water use in the IWM treatment could have exacerbated later-season drought impacts on soybean yield. In conclusion, we suggest that the mediating effects of soil moisture dynamics on crop–weed competition that results from delayed termination tactics is an important factor that requires more research to inform adaptive cover-crop management decision making in no-till systems.

Practical Implications

Delaying cover-crop termination until at or after cash crop planting (i.e., planting green) represents a departure from long-held preplant burndown management recommendations. The benefit of planting green is the gain in cover-crop biomass production, which can result in better early-season weed suppression. This study focused on planting green in a cereal rye–soybean crop sequence within a grain–forage production system. Delaying cereal rye termination resulted in reduced soil moisture availability at the time of planting, which can be an agronomic benefit in wet springs, but may reduce soybean yields in dry growing seasons. Soybean populations were similar among planting green and Standard termination (14- to 21-d pre-plant burndown) tactics in our study, which we attribute to planter modifications designed to achieve optimal seed placement in higher levels of surface residues. Our research also shows that planting green may facilitate reductions in use of soil-applied herbicides without affecting soybean yield in the absence of glyphosate- or multiple herbicide–resistant summer annual weed species. However, careful consideration should be given to best-management practices for preventing evolution of resistance to postemergence herbicides. Ideally, cover-crop surface residues should reduce the size of emerged weed populations and the number of large individuals (>10 cm) within a population at the time of postemergence applications. Our study also demonstrated that scouting is necessary to design the appropriate preplant burndown application program when delaying cereal rye termination. Glyphosate-resistant horseweed populations that persisted in the understory of cereal rye stands were not adequately controlled and required additional inputs at the postemergence application timing. In summary, planting green is an adoption-ready integrated weed management (IWM) tactic but requires adaptive management decision making to balance weed control and conservation management goals.

Acknowledgments. This was supported by The Pennsylvania University College of Agriculture Sciences, LTAR ARS USDA 58-8070-8-008. No conflicts of interest have been declared. The authors would like to thank Tosh Mazzone, Jared Adam, Kaleb Wolfe, Tom Adams, and graduate and undergraduate students who provided assistance to complete this experiment.

References

Bates D, Maechler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Statistical Software 67:1–48

Beam SC, Cahoon CW, Haak DC, Holshouser DL, Mirsky SB, Flessner ML (2021) Integrated weed management systems to control common ragweed (Ambrosia artemisiifolia L.) in soybean. Frontiers Agron 2:1–15

Binder JM, Karsten HD, Beegle DB, Dell CJ (2020) Manure injection and rye double cropping increased nutrient recover and forage production. Agron J 112:2968–2977

Bunchek JM, Wallace JM, Curran WS, Mortensen DA, VanGessel, MJ, Scott BA (2020) Alternative performance targets for integrating cover crops as a proactive herbicide-resistance management tool. Weed Sci 68:538–544

Cavigelli MA, Teasdale JR, Conklin AE (2008) Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron J 100:785–794

Champagne RJ, Wallace JM, Curran WS, Baraibar B (2019) Agronomic and economic tradeoffs between alternative cover crop and organic soybean sequences. Renew Agric Food Syst 36:17–25

Crowley KA, VanEs HM, Gomez MI, Ryan MR (2018) Trade-offs in cereal rye management strategies prior to organically managed soybean. Agron J 110:1492–1504

Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. PLOS ONE 7(10). 1–8

Essman AI, Loux MM, Lindsey AJ, Dobbels AF, Regnier EE (2020) The effects of integrating a cereal rye cover crop with herbicides on glyphosate-resistant horseweed (*Conyza canadensis*) in no-till soybean. Weed Sci 68: 527–533

Ficks TS, Lowry CJ, Wallace JM (2022) Weed seed mass affects seedling establishment and resource allocation patterns across a cereal rye surface residue gradient. Weed Res 62:49–58

Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron J 108:39–52

Lenth R (2019) emmeans: estimated marginal means, aka least-squares means. R package version 1.4.1. https://CRAN.R-project.org/package=emmeans

Liebl R, Simmons W, Wax LM, Stoller EW (1992) Effect of rye (Secale cereale) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol 6:838–846

Liebman M (2018) Cultural techniques to manage weeds. Pages 203–226 *in* Zimdahl RL, ed, Integrated Weed Management for Sustainable Agriculture. London: Burleigh Dodds Science Publishing

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

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

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

Mirsky SB, Spargo JT, Curran WS, Reberg-Horton SC, Ryan MR, Schomberg HH, Ackroyd, VJ (2017) Characterizing cereal rye biomass and allometric relationships across a range of fall available nitrogen rates in the eastern United States. Agron J 109:1520–1531

Mohler CL (1996) Ecological bases for the cultural control of annual weeds. J Prod Agric 9:468–474

Mortensen DA, Egan JF, Maxwell BD, Ryan MR, Smith RG (2012) Navigating a critical juncture for sustainable weed management. BioScience 62:75–84

Nichols V, Martinez-Feria R, Weisberger D, Carlson S, Basso B, Basche A (2020) Cover crops and weed suppression in the U.S. Midwest: a meta-analysis and modeling study. Agric Environ Lett 5:e0022

Nichols V, Verhulst N, Cox R, Govaerts B (2015) Weed dynamics and conservation agriculture principles: a review. Field Crops Res 183:56–68

Nord EA, Curran WS, Mortensen DA, Mirsky SB, Jones BP (2011) Integrating multiple tactics for managing weeds in high residue no-till soybean. Agron J 103:1542–1551

Nord EA, Ryan MR, Curran WS, Mortensen DA, Mirsky SB (2012) Effects of management type and timing on weed suppression in soybean no-till planted into rolled-crimped cereal rye. Weed Sci 60:624–633

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60:31–62

Pinheiro J, Bates D, Debroy S, Sarkar D (2019) nlme: linear and nonlinear mixed effects models. R package version 3.1–140. https://CRAN.R-project.org/package=nlme

Poffenbarger HJ, Mirsky SB, Teasdale JR, Spargo JT, Cavigelli MA, Kramer M (2015) Nitrogen competition between corn and weeds in soils under organic and conventional management. Weed Sci 63: 461–476

R Core Team (2019) R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing

Reed HK, Karsten HD, Curran WS, Tooker JF, Duiker SW (2019) Planting green effects on corn and soybean production. Agron J 111: 2314–2325

Reed H, Karsten H (2022) Does winter cereal rye seeding rate, termination time, and N rate impact no-till soybean? Agron J 144:1311–1323

Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K, Kaye JP, Kemanian AR, Mortensen DA, Ryan MR, Tooker J, White C (2014) A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric Syst 125:12–22

Schramski JA, Sprague CL, Renner KA (2021) Effects of fall-planted cereal cover-crop termination time on glyphosate-resistant horseweed (*Conyza canadensis*) suppression. Weed Technol 35:223–233

Snyder EM, Curran WS, Karsten HD, Malcolm GM, Duiker SW, Hyde JA (2016) Assessment of an integrated weed management system in no-till soybean and corn. Weed Sci 64:712–726

Summers H, Karsten HD, Curran W, Malcolm GM (2021) Integrated weed management with reduced herbicides in a no-till dairy rotation. Agron J 113:3418–3433

Thapa R, Tully K, Reberg-Horton C, Cabrera M, Davis BW, Fleisher D, Gaskin J, Hitchcock R, Poncet A, Schomberg HH, Seehaver SA, Timlin D, Mirsky SB (2022) Cover crop residue decomposition in no-till cropping systems: insights from multi-state on-farm litter bag studies. Agric Ecosyst Environ 326. https://doi.org/10.1016/j.agee.2021.107823

Vollmer KM, VanGessel MJ, Johnson QR, Scott BA (2020) Influence of cereal rye management on weed control in soybean. Frontiers Agron 2:1–7

Wallace, JM, Curran WS, Mortensen DA (2019) Cover crop effects on horseweed (*Erigeron canadensis*) density and size inequality at the time of herbicide exposure. Weed Sci 67:327–338

Weisberger D, Nichols V, Liebman M (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. PLoS ONE 14(7):e0219857

Wells MS, Reberg-Horton C, Smith AN, Grossman JM (2013) The reduction of plant-available nitrogen by cover crop mulches and subsequent effects on soybean performance and weed interference. Agron J 105:539–545

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