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Cereal rye seeding rate does not affect magnitude of weed suppression when planting green within Mid-Atlantic United States

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Research Article

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Abstract

In the Mid-Atlantic United States, there is increasing interest in delaying cereal rye termination until after soybean planting (i.e., planting green). Improved understanding of cereal rye seeding rate effects is needed to balance weed and agronomic management goals. We investigated the effects of cereal rye seeding rates on weed control and crop performance when planting green in complementary experiments in two Mid-Atlantic regions. The Pennsylvania experiment was replicated at three site-years and the Delaware experiment at two site-years. In both experiments, population-level weed responses were evaluated across four cereal rye seeding rates: 0, 51, 101, and 135 kg ha^{-1}. The Delaware experiment also implemented a nitrogen treatment factor (0 and 34 kg N ha^{-1}; spring applied). Both experiments showed that integrating cereal rye in the fall significantly improved winter- and summer-annual weed suppression compared with the fallow control, but no differences in total cereal rye biomass production or weed suppression were found among alternative cereal rye seeding rates (51 to 135 kg ha^{-1}). Soybean yield did not differ among treatments in any of the studies. These results show there is no reason to increase cereal rye seeding rates for weed suppression services or to decrease seeding rates for agronomic reasons (i.e., soybean population and yield) when employing planting-green tactics in no-till soybean production within the Mid-Atlantic region of the United States.

Introduction

In the Mid-Atlantic United States, there is increasing interest in intensifying cover crop management with use of planting-green tactics in no-till soybean production systems. Planting green is the delay of cover crop termination until after cash crop planting (Reed et al. 2019), which often results in significantly greater biomass accumulation than standard 10- to 14-d preplant burndown tactics. Cereal rye is the most common cover crop species used when delayed termination tactics are employed in the Mid-Atlantic region due to its winter hardiness, nitrogen scavenging potential, and high biomass potential (Mirsky et al. 2009). Cereal rye management varies widely among early adopters of planting green tactics (Reed et al. 2019). Greater understanding of cultural tactics, including the role of seeding rate, will inform the decision-making process that weighs tradeoffs among weed control outcomes, input costs, and cash crop productivity.

The effect of cereal rye seeding rates on weed control outcomes likely depends on the life cycle of targeted weed species. Foundational research supports the theory that increasing the sowing density of fall-sown or spring-sown cereals generally increases competition for resources with weeds that have overlapping life cycles (Schwinning and Weiner 1998; Weiner et al. 2001). Light resource preemption is considered the primary driver of enhanced weed suppression potential when sowing density is increased (Weiner et al. 2001), and as a result, both early-season ground cover and total biomass production can be indicators of weed suppression potential.

In the context of fall-sown cover crops, previous research has shown a positive correlation between late fall and early spring ground cover with suppression of winter annual (Wallace et al. 2019) and early-emerging summer annual weed species (Ryan et al. 2011). Increasing cereal rye seeding rates can increase the amount of ground cover (Haramoto 2019; Ryan et al. 2011; Schramski et al. 2021). In comparison, total cover crop biomass production is viewed as the primary driver of summer annual weed species that emerge within terminated cover crop surface mulches (Mirsky et al. 2013; Nord et al. 2012, 2013). Fall growing degree days (GDDs; Essman et al. 2020; Feyereisen et al. 2006; Reed et al. 2019; Schramski et al. 2021; Vollmer et al. 2020) and plant-available nitrogen are the primary drivers of cereal rye biomass potential (Mirsky et al. 2017). Cultural tactics, such as increasing cereal rye seeding rate, have shown to have less impact on total cereal rye biomass potential (Bish et al. 2021; Haramoto 2019; Ryan et al. 2011). Consequently, it is likely that cereal rye seeding rates will be a more important

Table 1. Cereal rye management and growing conditions across experimental site-years.

Experimental site-year	Growing season	Cereal rye management and environmental conditions		
		Seeding date	Termination date	Cumulative GDD[a,b]
Rock Springs, PA	2018–2019	September 29	May 16	694
Rock Springs, PA	2019–2020	October 2	May 21	630
Landisville, PA	2019–2020	November 1	May 5	414
Georgetown, DE	2018–2019	October 17	May 9	1,204
Georgetown, DE	2019–2020	October 30	May 20	957

[a]Abbreviation: GDD, growing degree days.
[b]Base temperature was set at 4.4 C (Mirsky et al., 2011) and calculated from seeding to termination date.

cultural tactic for winter annual weed suppression compared to suppression of summer annual species that emerge after cover crop termination.

In practice, planting green mimics organic no-till soybean production practices, when soybean is no-till planted into a fall-sown cereal rye cover crop at anthesis and terminated with a roll-crimper. Best management practices in organic no-till production include early fall sowing dates and high (e.g., 135 kg ha^{-1}) cereal rye seeding rates to ensure rapid stand establishment and biomass accumulation (Mirsky et al. 2013; Wallace et al. 2017). High cereal rye seeding rate inputs may be unnecessary when planting-green tactics are integrated with herbicide-based weed control tactics. Some growers who have adopted planting-green tactics to target soil health goals use lower cereal rye seeding rates (e.g., <51 kg ha^{-1}), which keeps input costs low and reduces the likelihood of residue management challenges that can occur at planting (Haramoto 2019; Reed et al. 2019; Williams et al. 1998).

We conducted complementary field experiments in Pennsylvania and Delaware to evaluate cereal rye seeding rates when delaying termination (e.g., planting green) in no-till soybean production within the Mid-Atlantic region. We hypothesized that cereal rye seeding rates would have a greater impact on winter annual weed suppression compared to summer annual weed suppression. We documented the agronomic tradeoffs between planting-green tactics and winter-fallow management, including weed control and cash crop performance.

Materials and Methods

Pennsylvania Experiment

Field experiments were conducted at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) near Rock Springs, PA (40.715000°N, 77.934167°W), and the Southeast Agricultural Research and Extension Center (SEAREC) near Landisville, PA (40.118333°N, 76.427500°W). The experiment was initiated in the 2018–2019 growing season at RELARC and in the 2019–2020 growing season at both locations for a total of three site years. Soil texture at the experimental sites were Hagerstown silt loam (RELARC) and Duffield silt loam (SEARC). Each experiment was established in the fall following a soybean crop with high infestations of horseweed (*Erigeron canadensis* L.), a multiple herbicide–resistant, winter-annual species of significant agronomic importance in Pennsylvania.

Experimental Design and Field Operations

A single-factor, randomized complete block design with four replications was used to evaluate cereal rye ('Aroostook') seeding rates (0, 51, 101, and 135 kg ha^{-1}) imposed in 3- by 9-m plots. This seeding rate gradient includes lower rates that are commonly used by growers targeting soil-health management goals and higher rates that are believed to optimize weed suppression potential within low-input systems. Cereal rye seed lots were not subsampled to quantify seed mass (i.e., seeds per kilogram), which constrains our inferences to relative comparisons of seeding rates within site-years, given the potential for variation in seed size that has been observed (Lounsberry et al. 2022).

Cereal rye was no-till drilled using 19-cm-row spacing between late September and early November depending on site-year (Table 1). Dicamba-resistant soybean was no-till planted at each location using a rate of 371,000 seeds ha^{-1} and 76-cm-row spacing at the cereal rye heading stage in mid-May (Zadoks growth scale 50 to 59; Table 1). Cereal rye was roll-crimped, and soybean was planted in a single pass using ZRX integrated rollers (Dawn Equipment, Sycamore, IL) and double-disk row-cleaners positioned in front of planter units. Glyphosate (1.26 kg ae ha^{-1}, Roundup PowerMax®; Bayer Crop Science) + dicamba (0.56 kg ae ha^{-1}, XtendiMax®; Bayer Crop Science) were then applied 1 d after planting (DAP) with a tractor-mounted sprayer using a carrier volume of 185 L ha^{-1} to terminate cereal rye and control emerged weeds. Glyphosate (1.26 kg ae ha^{-1}) + dicamba (0.56 kg ae ha^{-1}) were applied postemergence (POST) at the V4 soybean growth stage. Artificial seedbanks of large crabgrass [*Digitaria sanguinalis* (L.) Scop.], redroot pigweed (*Amaranthus retroflexus* L.), and common lambsquarters (*Chenopodium album* L.) were established in a single square-meter microplot in the middle of each plot in late fall (early December), using seeding rates of 200, 800, and 400 seeds m^{-2}, respectively, to ensure uniform summer annual weed populations.

Data Collection

Aboveground biomass of cereal rye and winter annual weeds were collected in two randomly placed 0.25-m^2 quadrats within each plot 3 d prior to soybean planting. Horseweed population density and the height of up to 40 randomly sampled horseweed plants were recorded prior to biomass sampling within quadrats. Summer annual weed densities and heights, as well as soybean stand counts, were measured within the artificial seedbank microplots 35 to 42 d after soybean planting, just prior to POST applications at the V4 growth stage. Cereal rye residue and soybean biomass were collected just prior to the POST application at the V4 growth stage within one randomly place 0.5-m^2 quadrat to characterize cereal rye residue effects on crop fitness (Williams et al. 1998). Aboveground biomass samples were separated by plant species in the laboratory, oven dried at 65 C for 7 d, and weighed. Soybean yields were evaluated by harvesting the middle two rows with a small-plot harvester and are reported at 13.5% moisture.

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Table 2. Effect of cereal rye seeding rate on cereal rye biomass at termination (Zadoks growth scale 50 to 59), winter annual weed density just prior to soybean planting, summer annual weed density 35 to 42 d after planting, and soybean yield in Pennsylvania site-years ($n = 3$).[a,b]

Cereal rye seeding rate	Cereal rye biomass	Winter annual weed biomass	Summer annual weed density	Soybean yield
kg ha^{-1}			plant m^{-2}	kg ha^{-1}
0	—	701 (211) A	54 (29) a	2,900 (800)
51	3,600 (400)	102 (31) B	26 (14) b	3,100 (800)
101	4,100 (400)	53 (16) B	23 (13) b	2,900 (800)
135	3,700 (400)	80 (24) B	24 (13) b	2,900 (800)
ANOVA		P-value		
Seeding rate	ns	***	**	ns

[a]Abbrevations: ANOVA, analysis of variance; ns, nonsignificant.
[b]Cereal rye biomass, log-transformed winter annual weed biomass, and soybean yield are fit using linear mixed effects models and winter annual weed biomass presented as back-transformed means. Summer annual weed density data are fit using generalized linear mixed effects models and a negative binomial distribution, where the significance of model terms is based on likelihood ratio tests (Wald chi-quared) and population-level estimates are presented as back-transformed means. Significance of model terms shown as: **$P < 0.01$, ***$P < 0.001$. Seeding rate treatments containing the same letter are not significantly different ($P > 0.05$). Means (SE) are averaged over site-years.

Delaware Experiment

A field experiment was initiated at the University of Delaware's Research and Education Center (UDREC) near Georgetown, DE (38.635278°N, 75.459722°W) in 2018–2019 and repeated during the 2019–2020 growing season. Soil texture at the sites was a Hammonton loamy sand. Endemic winter and summer annual weed populations were used to evaluate treatment effects. The most abundant winter annual weed species included mouse-ear chickweed [*Cerastium fontanum Baumg.* ssp. *Vulgare* (Hartm.)], Johnny jump-up violet (*Viola bicolor* Pursh), cutleaf evening-primrose (*Oenothera laciniata* Hill), and annual knawel (*Scleranthus annuus* L.). Endemic summer annual weed species included pigweeds (*Amaranthus* spp.), morningglory (*Ipomoea* spp.), and common ragweed (*Ambrosia artemisiifolia* L.) in 2019; and Palmer amaranth (*Amaranthus palmeri* S. Watson), annual morningglory (*Ipomoea* spp.), and annual grasses in 2020.

Experimental Design and Field Operations

A two-factor, randomized complete block design with four replications was used to evaluate the interaction between nitrogen fertility level and the same cereal rye ('Aroostook') seeding rates as the Pennsylvania experiments (0, 51, 101, and 135 kg ha^{-1}). Plot size was 3 by 9 m. The nitrogen fertility treatment factor was added to the experimental design due to frequently observed nitrogen resource limitation in Delaware's coarser textured soils. The nitrogen fertility treatment included 34 kg N ha^{-1} applied at spring green up (Feekes scale 3 to 4) and nontreated control (0 kg N ha^{-1}).

Cereal rye was no-till drilled in 19-cm-row spacing in October following field corn harvest (Table 1). Field operations were aligned with the Pennsylvania experiment, including soybean planting rate, soybean row spacing, and herbicide management programs (Table 1). The primary difference among field operations between locations was that cereal rye was not roll-crimped at planting, and row-cleaners were not used at the Delaware location, which reflects current management practices in this region, where earlier cash crop planting dates often result in less phenologically advanced cereal rye at the time of termination or planting.

Data Collection and Analysis

Aboveground cereal rye was collected in a randomly placed 0.25-m^2 quadrat within each plot 3 d prior to soybean planting. At the same timing, winter annual weed density was recorded within the randomly placed 0.25-m^2 quadrat. Summer annual weed density was collected each year and biomass was collected in 2018–2019 at 35 to 42 DAP, just prior to POST applications, using one representative and randomly placed 0.25-m^2 quadrat per plot. Aboveground biomass samples were separated by plant species, oven dried at 65 C for 7 d, and weighed. Soybean yields were evaluated using a two-row small-plot harvester and are reported at 13.5% moisture.

Statistical Analyses

Analysis of variance was conducted to test for differences in cereal rye biomass, weed response variables, and soybean performance metrics using R software (R Core Team 2019). Cereal rye seeding rates were modeled as a discrete, categorical response variable due to the lack of treatment levels necessary for regression models. Models of Pennsylvania data were fit using cereal rye seeding rate as a fixed effect, and models of Delaware data were fit using cereal rye seeding rate, fertility, and their interaction as fixed effects. Site-year and block nested in site-year were fit as random effects. Horseweed and summer annual weed densities (plants per square meter) were analyzed with generalized linear mixed effect models and a negative binomial distribution in the LME4 package (Bates et al. 2015). All other metrics were modeled using linear mixed-effect models in the NLME package (Pinheiro et al. 2019). Weed biomass data (kilograms per hectare) were log transformed to achieve normality, and the seeding rate control (0 kg ha^{-1}) was excluded from analysis of cereal rye biomass models. Due to low horseweed densities at SEARC, including in nontreated controls, horseweed population data were analyzed only for RELARC site-years ($n = 2$) for the Pennsylvania experiment. Pairwise comparisons of the least-square means were obtained using the EMMEANS package (Lenth 2019) and back-transformed means (standard errors) are presented in the Results for generalized linear mixed effect models and log-transformed data.

Results and Discussion

Pennsylvania

Our results did not support the hypothesis that increasing cereal rye seeding rates would decrease winter annual weed populations at the time of preplant burndown applications or summer annual weed populations at the time of POST applications. Notably, increasing cereal rye seeding rates had no effect ($P = 0.27$) on cereal rye biomass when averaged across site-years, which suggests that seeding rate is not a driver of cereal rye biomass potential across the range of planting dates (late September to early November) and growing conditions (414 to 694 GDD) observed in these experiments (Table 2). Averaged across site-years, cereal rye biomass production ranged from 3,600 to 4,000 kg ha^{-1} across seeding rates when terminated at the late-heading stage.

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Table 3. Effect of cereal rye seeding rate on soybean population, soybean biomass, and cereal rye surface residue biomass 35 to 42 d after soybean planting within Pennsylvania site-years ($n = 3$).[a,b]

Cereal rye seeding rate	Soybean population	Soybean biomass	Cereal rye surface residue
kg ha^{-1}	1,000 plants ha^{-1}	kg ha^{-1}	
0	212 (17)	689 (117) a	—
51	205 (17)	567 (117) ab	2,700 (900)
101	202 (17)	480 (117) b	3,200 (1,000)
135	201 (17)	447 (117) b	2,900 (900)
ANOVA		P-value	
Seeding rate	ns	***	ns

[a]Abbrevations: ANOVA, analysis of variance; ns, nonsignificant.
[b]Data were fit using the linear mixed effects models. Significance of model terms are shown as ***P < 0.001. Seeding rate treatments containing the same letter are not significantly different (P > 0.05). Means (SE) are averaged over site-years.

Table 4. Effects of cereal rye seeding rate, nitrogen fertility, and their interaction on cereal rye biomass termination 1 DAP (Zadoks growth scale 50 to 59), winter annual weed density just prior to planting, summer-annual weed density 35 to 42 DAP, and soybean yield at Delaware site-years ($n = 2$). Means (SE) are presented at the cereal rye seeding rate main effect level and are averaged over fertility levels and site-years.[a,b]

Cereal rye seeding rate	Cereal rye biomass	Winter annual weed density	Summer annual weed density	Soybean yield
kg ha^{-1}		plant m^{-2}		kg ha^{-1}
0	—	39 (7) a	45 (16) a	2,100 (400)
51	2,100 (200)	22 (4) b	23 (9) b	2,500 (400)
101	2,500 (200)	20 (4) b	5 (9) b	2,600 (400)
135	2,400 (200)	16 (3) b	24 (9) b	2,400 (400)
ANOVA		P-value		
S	ns	***	**	ns
F	*	ns	*	ns
S × F	ns	ns	ns	ns

[a]Abbrevations: ANOVA, analysis of variance; F, fertility; ns, nonsignificant; S, seeding rate.
[b]Cereal rye biomass and soybean yield are fit using linear mixed effects models. Weed density data are fit using generalized linear mixed effects models and a negative binomial distribution, where the significance of model terms is based on likelihood ratio tests (Wald chi-squared) and population-level estimates are presented as back-transformed means. Significance of model terms shown as *P < 0.05, **P < 0.01, ***P < 0.001. Seeding rate treatments containing the same letter are not significantly different (P > 0.05).

Treatment effects were observed in analysis of winter annual weed biomass (P < 0.001; Table 2) and horseweed density (P < 0.001; Figure 1) at the time of burndown herbicide applications (1 DAP). However, these effects were limited to differences between cereal rye sown at each rate compared with the nontreated control, whereas no differences were detected among seeding rates (Table 2; Figure 1). Averaged across site-years, winter annual weed biomass and horseweed density were lower in cereal rye seeding rate treatments compared with those of the control at the time of preplant burndown applications. No differences were observed (P > 0.05) among seeding rate treatments, including the no-cover-crop control, in analysis of the proportion of horseweed individuals over 10 cm in height at the time of burndown herbicide applications within RELARC locations. Previous experiments have shown a reduction in horseweed rosette diameter within cereal rye stands relative to a fallow control (Bunchek et al. 2020; Wallace et al. 2019). In our experiment, cereal rye termination and burndown applications within fallow control plots occurred near initiation of the horseweed bolting phase, which likely contributes to absence of cover crop treatment effects on height-based thresholds (>10 cm).

Treatment effects were also observed in an analysis of summer annual weed density (P < 0.01; Table 2) at the time of POST applications (35 to 42 DAP). Each cereal rye seeding rate resulted in lower summer annual weed density, ranging from a 51% to 57% reduction compared with the control, but no differences among seeding rates were observed. Averaged across cereal rye treatments (0 to 135 kg ha^{-1}), less than 1% of summer annual weeds were taller than 10 cm at 35 to 42 DAP (data not shown). Additional metrics were collected 35 to 42 DAP to further characterize crop-weed interactions. Treatment effects were not observed in an analysis of soybean stand (plants per hectare) or biomass of cereal rye surface residues (P > 0.05; Table 3). We observed a significant treatment effect on soybean biomass (P < 0.001), for which 101 and 135 kg ha^{-1} rates resulted in lower soybean biomass compared with the control. However, no seeding rate effect was observed in an analysis of soybean yields.

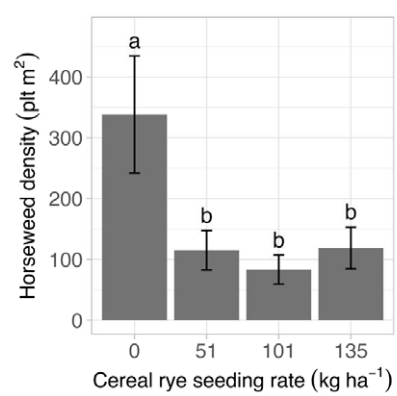

Figure 1. Effect of cereal rye seeding rates on mean horseweed density (plants per square meter) just prior to termination (Zadoks growth scale 50 to 59) at Rock Springs, PA, site-years ($n = 2$). Data are fit using a negative binomial distribution, where significance of model terms are based on likelihood ratio tests (Wald chi-square) and population-level estimates are presented as back-transformed means (SE) averaged across site-years. Seeding rate treatments containing the same letter are not significantly different (P > 0.05).

Delaware

Cereal rye biomass was not affected by seeding rate (P = 0.23) at the time of preplant burndown applications (Table 4). Averaged

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across years, cereal rye biomass was 19% greater ($P < 0.05$) following spring nitrogen applications (2,500 kg ha^{-1}) compared with the control (2,100 kg ha^{-1}). Significant interactions between seeding rate and fertility treatment were not observed in analysis of weed density (Table 4). However, seeding rate treatment effects were observed in analysis of winter annual weed density at preplant burndown and summer annual weed density at POST application timings ($P < 0.01$; Table 4). Weed density was lower in each seeding rate compared to the control, but no differences were observed among seeding rates. Averaged across nitrogen fertility treatments, winter annual weed density was 42% to 59% lower when assessed 1 DAP and summer annual weed density was 45% to 48% lower 35 to 42 DAP compared with the control. Summer annual weed density was lower ($P < 0.05$) in spring-applied nitrogen (34 kg N ha^{-1}) compared with the control when averaged across seeding rate treatments. There was no significant treatment effect on the proportion of summer annuals over 10 cm in height and total summer annual weed biomass 35 to 42 DAP. Summer annual weed density was analyzed by species in 2020–2021 due to an even distribution across the experimental location. In analysis by species, no treatment effects were observed ($P > 0.05$). Finally, no treatment effects on soybean yield were observed (Table 4).

Management Implications

Our results indicate that increasing cereal rye seeding rates has limited potential to enhance suppression of winter and summer annual weed species when planting green in a no-till soybean production system within the Mid-Atlantic region. The lack of weed suppression differences among seeding rates may be attributed, in part, to the lack of an observed cereal rye biomass response among seeding rates. Similarly, Reed and Karsten (2022) showed no biomass response to increasing cereal rye seeding rates from 34 to 134 kg ha^{-1} when evaluating delayed termination (i.e., planting green) effects on soybean performance in Pennsylvania. Yet, a positive relationship between crop sowing density and weed suppression is well-described in the literature for small grain cash crops (Mohler 2001) and remains an important component of multi-tactic weed control in low-input systems (McCollough and Melander 2022). Perhaps one reason for the lack of seeding rate response in cover crop research is that sowing cereal rye after late-harvested crops in the fall, coupled with use of burndown herbicide applications prior to sowing, reduces the likelihood of significant winter annual weed emergence flushes that occur at or shortly after cover crop sowing. In such a scenario, weed suppression benefits that result from higher seeding densities during the crop establishment phase may be negligible in the fall and cereal rye tillering capacity at lower seeding rates may diminish the effect of in-row crop competition from higher seeding densities by spring when weed-crop competition resumes (Brennan and Boyd 2012; Håkansson 2003).

Soil inorganic nitrogen pools mediate the relationship between fall sowing date (fall GDDs) and total cereal rye biomass production (Mirsky et al. 2017). Sedghi and Weil (2022) report that fall sowing dates that are typical for Maryland when following late-harvested grain crops (i.e., October) will likely result in greater nitrogen leaching because of insufficient cereal rye growth necessary to immobilize NO_3-N through the soil profile. The marginal cereal rye biomass response to spring nitrogen applications in our Delaware experiments may be attributed to the combination of lack of soil nitrogen at planting due to leaching potential in coarse soils and insufficient fall GDDs needed for cereal rye growth to optimize nitrogen uptake in early spring.

These results show that meaningful levels of weed suppression can be achieved across cereal rye seeding rates that producers employ based on other agronomic or economic considerations. Terminating cereal rye at the heading stage resulted in an 89% reduction in winter annual weed biomass across our Pennsylvania site-years and a 50% reduction in winter annual weed density at the Delaware location when averaged across seeding rates. Haramoto (2019) also found 63% to 98% suppression of winter annual weed biomass using 34 and 112 kg ha^{-1} cereal rye seeding rates, respectively, compared to that of a fallow control. At our Pennsylvania site, suppression of horseweed population densities did not differ among cereal rye seeding rates but did reduce densities by 70% compared to the fallow treatment, which is similar to horseweed suppression levels of previous field experiments (Bunchek et al. 2020; Wallace et al. 2019) that used high seeding rates (135 kg ha^{-1}), as well horseweed suppression levels observed in other studies focused on integrating cereal rye and herbicide-based tactics (Essman et al. 2020; Schramski et al. 2021).

We also observed meaningful levels of summer annual weed suppression at moderate levels of cereal biomass production among cereal rye seeding rates. At our Pennsylvania locations, terminating cereal rye at the heading stage resulted in an average of 3,600 to 4,000 kg ha^{-1} biomass across site-years and reduced summer annual weed densities by 55% compared to fallow treatments. At the Delaware location, cereal rye biomass production ranged from 2.0 to 2.5 Mg ha^{-1} across site-years and reduced summer annual weed densities by 47%. Bish et al. (2021) found a limited effect of cereal rye seeding rate (56 to 123 kg ha^{-1}) on reductions in waterhemp (*Amaranthus tuberculatus*) density 4 WAP, but a 70% to 88% reduction across seeding rates compared to a fallow control when initial waterhemp densities were less than 700 plants m^{-2}.

In summary, our results suggest that there is no reason to increase cereal rye seeding rates for weed suppression services or decrease seeding rates for agronomic reasons (i.e., soybean population and yield) when employing planting-green tactics in no-till soybean production within the Mid-Atlantic region. Growing evidence suggests that expanding the growing season window to accumulate GDDs, including use of delayed termination tactics, is a more important driver of cereal biomass production than seeding rate (Essman et al. 2020; Feyereisen et al. 2006; Mirsky et al. 2017; Reed and Karsten 2022; Schramski et al. 2021; Vollmer et al. 2020). Most growers manage cover crop termination adaptively and do not have a singular focus on weed suppression benefits, nor target specific cover crop biomass thresholds before planting. Our results support this adaptive management approach by demonstrating positive weed suppression benefits at moderate levels of cereal rye biomass production (2 to 4 Mg ha^{-1}) when planting green within the Mid-Atlantic region.

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References

Bates D, Maechler M, Bolker B, Walker S. (2015) Fitting Linear Mixed-Effects Models using lme4. J Stat Softw 67:1–48

Bish M, Dintelmann B. Oseland E, Vaughn J, Bradley K (2021) Effects of cereal rye seeding rate on waterhemp (*Amaranthus tuberculatus*) emergence and soybean growth and yield. Weed Technol 35:1–7

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 68:1–35

Brennan EB, Boyd NS (2012) Winter cover crop seeding rate and variety affects during eight years of organic vegetable production. Agron J 104:684–698

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

Feyereisen GW, Wilson BN, Sands GR, Strock JS, Porter PM (2006) Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. Agron J 98:1416–1426

Håkansson S (2003) Competition in plant stands of short duration. Pages 81–118 *in* Håkansson S, ed. Weeds and Weed Management on Arable Land: An Ecological Approach. Uppsala, Sweden: CABI Publishing

Haramoto ER (2019) Species, seeding rate, and planting method influence cover crop services prior to soybean. Agron J 111:1068–1078

Lenth R (2019) emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.4.1. https://CRAN.R-project.org/package=emmeans. Accessed: July 1, 2021

Lounsberry NP, Warren ND, Hobbie J, Darby H, Ryan MR, Mortensen DA, Smith RG (2022) Seed size variability has implications for achieving cover cropping goals. Agric Environ Lett. 7:e20080

McCollough MR, Melander B (2022) Improving upon the interrow hoed cereal system: the effects of crop density and row spacing on intrarow weeds and crop parameters in spring barley. Weed Sci 70:341–352

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, 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, 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 (2001) Enhancing the competitive ability of crops. Pages 269–321 *in* Liebman M, Mohler CL, Staver CP, eds. Ecological Management of Agricultural Weeds. Cambridge, UK: Cambridge University Press

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

Nord EA, Curran WS, Mortensen DA, Mirsky SB, Jones BJ (2013) Integrating multiple tactics for managing weeds in high residue no-till soybean. Agron J 103:1541–1551

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. Accessed: July 1, 2021

R Core Team (2019) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/ Accessed: July 1, 2021

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

Ryan MR, Curran WS, Grantham AM, Hunsberger LK, Mirsky SB, Mortensen DA, Nord EA, Wilson DO (2011) Effects of seeding rate and poultry litter on weed suppression from a rolled cereal rye cover crop. Weed Sci 59:438–444

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

Schwinning S, Weiner J (1998) Mechanisms determining the degree of size-asymmetry in competition among plants. Oecologia 113:447–455

Sedghi N, Weil R (2022) Fall cover crop nitrogen uptake drives reductions in winter-spring leaching. J Environ Qual 51:337–351

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

Wallace JM, Williams A, Liebert JA, Ackroyd VJ, Vann RA, Curran WS, Keene CL, VanGessel MJ, Ryan MR, Mirsky SB (2017) Cover crop-based, organic rotational no-till corn and soybean production systems in the Mid-Atlantic United States. Agriculture 7:34

Weiner J, Griepentrog HW, Kristensen L (2001) Suppression of weeds by spring wheat *Triticum aestivum* increases with crop density and spatial uniformity. J Appl Ecol 83:784–790

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