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Cereal rye residue management tactics influence interrow and intrarow weed recruitment dynamics in field corn when planting green

Research Article

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Abstract

Delaying cover crop termination until cash crop planting (i.e., planting green) is an emerging no-till practice. Improved management recommendations are needed for optimizing weed suppression benefits while minimizing other pest, fertility, and crop management risks when planting green in corn production systems. In a 2-yr field experiment, we evaluated the interaction between cereal rye residue management tactics (standing residue, roll-crimping, roll-crimping with row cleaners) and herbicide programs (1-pass preemergence [PRE], 2-pass postemergence [POST]) when planting green on weed recruitment spatial patterns and corn performance compared to standard termination (14 d preplant [DPP]) and ryelage harvest (14 DPP) practices. In a 2-yr on-farm experiment, we evaluated corn performance in response to the same residue management tactics. Cereal rye biomass production varied significantly across years in on-station experiments, with average (4.9 Mg ha^{-1}) and anomalous (9.9 Mg ha^{-1}) levels observed in 2020 and 2021, respectively. In 2020, planting green with an integrated roll-crimper/row cleaner system resulted in greater intrarow weed density compared with planting green into standing cereal rye. Interrow weed density was lower when roll-crimping was employed compared to early termination (14 DPP). Planting green into standing cereal rye resulted in greater mean corn height (V5 stage) compared to other treatments, but corn population and yield did not differ. In 2021, few differences in weed recruitment patterns were observed, but corn population and yield were significantly lower in planting green treatments compared to early termination. In both years, late-season weed biomass was lower in two-pass POST programs compared to one-pass PRE programs. On-farm trials showed that planting green into standing residue increases corn height and can reduce corn populations, which may lead to reduce yields. Our results suggest that management recommendations for optimizing herbicide application timing should consider intrarow and interrow weed recruitment dynamics associated with residue management tactics needed to optimize corn performance.

Introduction

Cereal rye is a widely used cover crop in Northeast U.S. grain production systems (CTIC 2020) due to its winter-hardiness and consistent establishment rate when sown in short fall growing season windows (Mirsky et al. 2009). Currently, there is growing interest in delaying cereal rye termination until a cash crop is planted (i.e., planting green; Reed et al. 2019) to increase the ecosystem services provisioned by cereal rye (Blanco-Canqui et al. 2015) and to manage planting conditions in wet springs, which may increasingly occur with climate change (Kaye and Quemada 2017). The concept of planting green represents a change in long-held management recommendations for cereal rye termination before corn is planted (Duiker and Curran 2005) and requires a reevaluation of pest and fertility management recommendations to optimize the benefits and minimize the risks associated with this management practice.

Planting green is a viable integrated weed management tactic because increased biomass gains from delaying termination are likely to increase weed suppression (Mohler 1996; Teasdale 1996). Recent field studies have demonstrated the potential for increased weed suppression with the use of planting green tactics in conventional no-till systems, but they have also suggested the need for integrating those tactics with herbicide-based tactics to achieve weed management goals (Ficks et al. 2022a, 2023; Grint et al. 2022). However, reducing herbicide inputs when planting green could offset other pest, fertility, and crop management factors that sometimes lead to reduced yield and economic returns in cereal rye–corn crop sequences. Agronomic tradeoffs related to delaying cereal rye termination prior to corn production include increased nitrogen immobilization (Patel et al. 2019; Quinn et al. 2023), reduced soil-water availability (Raimbault et al. 1990), increased incidence of seedling disease (Acharya et al. 2022), reduced

Figure 1. (**A**) Integrated roll-crimper and double-disk row-cleaning system mounted on planter toolbar (ZRX; Dawn Equipment, Sycamore, IL), which is designed to (**B**) part standing cover crop residue away from intrarow zone and roll-crimp toward interrow zone in a one-pass plant and roll-crimp operation.

stand establishment due to residue interference (Champagne et al. 2021), and increased potential for interference via allelopathy (Koehler-Cole et al. 2020).

Residue management tactics designed to overcome stand establishment issues, such as use of row-cleaners, can produce spatial variability in weed recruitment due to sowing-related soil disturbance that creates safe sites for weed germination (Caldwell and Mohler 2001; Gallandt 2006; Mortensen et al. 1995). Organic no-till corn studies have highlighted the need to strike a balance between maximizing cover crop biomass production to suppress weeds while managing cover crop surface mulch with roll-crimpers and other tools to reduce negative impacts on corn development, such as inadequate seed placement, suboptimal soil temperatures for seedling emergence, and seedling etiolation in response to the light-quality environment in the intrarow zone (Mischler et al. 2010; Teasdale et al. 2012).

Residue management tools designed specifically for high-residue cover cropping systems are becoming commercially available. For example, planter-mounted integrated roller-crimper systems are designed to run in combination with double-disk row cleaners, which parts standing residue away from the intrarow zone just prior to roll-crimping. This residue management system leaves soil exposed over the intrarow zone while forming a surface-mulch in the interrow zone (Figure 1). Recent research in organic no-till systems has shown spatial variability in weed recruitment when this integrated roll-crimper system is employed, where weed density and biomass is significantly greater in the intrarow zone due to row-cleaning disturbance compared to the interrow zone, where surface mulch is created from the roll-crimping process (Champagne et al. 2019, 2021).

This study was designed to evaluate the interaction between alternative residue management tactics and herbicide program approaches on weed control and no-till corn performance when planting green. Alternative residue management tactics for planting green were compared to standard termination practices (14 d preplant [DPP]), where cereal rye was either left on the surface as a cover crop or harvested for forage to simulate double-crop forage systems (Binder et al. 2020; Ketterings et al. 2015; West et al. 2020) in on-station experiments. A replicated on-farm strip trial was also completed to evaluate a subset of residue management tactics on corn performance. We hypothesized that 1) roll-crimping in combination with row-cleaning would increase corn performance relative to alternative planting green tactics but lead to greater intrarow weed recruitment in the absence of preemergence (PRE) residual herbicides; and 2) integrating postemergence (POST) herbicide programs with planting green tactics would reduce weed escapes in comparison to PRE herbicide programs when integrated with planting green tactics.

Materials and Methods

On-Station Experiment

A field experiment was conducted at the Pennsylvania State University Russell E. Larson Agricultural Research Center near Rock Springs, PA (40.11833°N, 76.427500°W) in 2019 to 2020 and replicated in a different field in 2020 to 2021. Experiments focused on a fall-sown cereal rye to no-till corn sequence and were initiated in fields following no-till corn silage production. The experiment was designed as a two-factor randomized complete block imposed in a split-plot treatment structure with four replicates. Main plots were 3 by 18 m and split plots were 3 by 9 m.

The main plot factor included five cereal rye treatments that coupled alternative termination timing and residue management tactics (Table 1). Treatments included cereal termination 14 DPP, which was timed to the phenological stage that optimizes forage quantity and quality (Zadoks stage 50 to 53; Thelen and Leep 2002), or 1 d after corn-planting (1 DAP), which reflects current management recommendations for negotiating cover crop biomass accumulation and crop production tradeoffs using planting green tactics (Reed et al. 2019).

Cereal rye terminated at 14 DPP was either 1) harvested for forage 1 d prior to chemical termination or 2) left standing at corn planting, with minimal row-cleaning employed at planting to simulate standard no-till practices. Cereal rye terminated 1 DAP was either 3) left standing with no additional residue management tactics employed, 4) roll-crimped using a front-mounted roll-crimper (I&J Manufacturing LLC, Gordonville PA) in a one-pass planting operation, or 5) roll-crimped using an integrated roll-crimper system equipped with double-disk row cleaners (ZRX; Dawn Equipment, Sycamore, IL).

Alternative weed control programs were imposed in split-plots with two treatment levels, including S-metolachlor (1.67 kg ai ha^{-1}) + mesotrione (0.19 kg ai ha^{-1}) + atrazine (1.12 kg ai ha^{-1}) + glyphosate (1.26 kg ae ha^{-1}) applied as a 1) PRE program 1 DAP or as a 2) POST program prior to 30-cm corn height and near the V3 corn growth stage. Glyphosate (1.26 kg ae ha^{-1}) + ammonium sulfate (2.5% v/v) was applied to terminate cereal rye for 14 DPP

Table 1. Cereal rye termination timing and residue management tactics employed.[a]

	Termination timing[b]		Residue management[c]		
Cereal rye treatments	Zadoks stage	Corn planting	Forage harvest	Roll crimper	Row cleaner
14 DPP (harvested)	50–53	14 DPP	Yes	None	Double disk
14 DPP (standing)	50–53	14 DPP	No	None	Double disk
1 DAP (standing)	60	1 DAP	No	None	None
1 DAP (rolled)	60	1 DAP	No	Yes	None
1 DAP (rolled + RC)	60	1 DAP	No	Yes	Double-disk

[a] Abbreviations: DAP, days after planting; DPP, days preplant; RC,.

[b] Cereal rye termination timing is based on the Zadoks growth stage relative to corn planting.

[c] Residue management tactics were employed either before or after forage harvest, or when corn was planted.

and 1 DAP treatments, and at corn planting as a preplant burndown treatment in POST split-plots. Consequently, PRE and POST treatments represent a two- and three-pass system in the 14 DPP treatments and a one- and two-pass system in the 1 DAP treatments.

Field Operations

Soils in experimental fields were sampled each fall at the block level and amended with phosphorus, potassium, and lime based on soil fertility test recommendations prior to cereal rye establishment. In the second year, noninversion tillage was completed with a high-speed disk using a shallow working depth (5 cm) to remove potential soil variation produced by silage-harvest wheel traffic. Cereal rye ('Aroostook') was established with a no-till drill (Great Plains, Salina, KS) on October 1 each year using a 100 kg ha^{-1} seeding rate and a 2-cm seeding depth. This seeding date was targeted to simulate cover cropping windows after corn silage production or earlier-harvested grain corn that can be achieved with use of shorter-day hybrids or harvesting at high moisture in some production regions within the Northeast. A 97-d relative maturity corn hybrid (DKC47-54RIB; Dekalb, Dekalb, IL) was planted using a John Deere 1720 MaxEmerge no-till planter (Deere & Company, Moline, IL) at a rate of 82,000 seeds ha^{-1} and a 5-cm seeding depth in 76-cm-wide rows. Urea ammonium nitrogen (UAN; 30-0-0) was banded beside the row and calibrated to deliver 39.2 kg N ha^{-1}. Starter fertilizer (10-34-0) was applied in-furrow at planting and calibrated to deliver 5.6 kg N ha^{-1}.

The no-till planter configuration included 1) a residue-slicer (Pequea Planter LLC, Gap PA) consisting of a straight-edged coulter positioned between gauge wheels and mounted in front of double-disk row openers, and 2) a closing wheel system consisting of one spiked and one smooth cast wheel. After-market residue-slicers are designed to improve residue cutting, soil penetration, and seed depth placement beyond standard no-till coulters. The combination of selected closing wheels is designed to improve slit closure in no-till systems with surface residues (Mirsky et al. 2013). Row-cleaning was employed in 14 DPP treatments using the ZRX double-disk row-cleaner without roll-crimpers engaged, which differs from most independently mounted row-cleaning units that are commercially available but was necessary given logistics of comparing roll-crimping and row-cleaning independently or in combination within the experimental design. The integrated ZRX roller-crimper and double-disk row cleaner system is designed to part residue toward the interrow space during the roll-crimping process, which exposes soil in the intrarow and reduces the likelihood of residue hair-pinning in the seed slit.

All herbicide treatments were applied using a CO_2-pressurized backpack sprayer calibrated to deliver 185 L ha^{-1} with TeeJet AIXR110015 nozzle tips (Spraying Systems, Glendale Heights, IL). Nitrogen was side-dressed at the V4 to V5 corn growth stage using a tractor-mounted sprayer with drop nozzles calibrated to deliver UAN at 156.8 kg N ha^{-1}.

Data Collection

Aboveground cereal rye biomass was collected in two randomly placed 0.25-m^2 quadrats per split-plot 1 d prior to cover crop termination. Biomass samples were oven dried at 65 C for 7 d and weighed (as kg ha^{-1}) to estimate dry-matter biomass production.

Weed density was recorded near the V3 corn growth stage in only the POST split-plot treatment to evaluate cereal rye residue management effects on weed recruitment dynamics. A single 0.5-m^2 sample was taken in the middle interrow of each plot and placed randomly within the middle-third (3 to 6 m lengthwise) of plots. Quadrats (0.5 m^2) were rectangular in shape (66 by 76 cm) and designed with a grid that separated intrarow (12.7 cm width per side) and interrow space (51 cm width) so weed recruitment could be quantified by interrow and intrarow zones. Intrarow zone width was chosen based on estimates of potential soil disturbance by double-disk row cleaners described in previous research (Champagne et al. 2019, 2021). Weed density counts were quantified by interrow and intrarow zones, and by functional group (monocot or dicot species). The same sampling procedure and quadrat was used to estimate total weed biomass production in late August each year. Weeds were harvested at ground level, sorted by functional group, and then dried at 65 C for 7 d and weighed.

Corn stand assessments were conducted at the V5 growth stage using a 5.33-m transect placed between the middle two rows of each split plot. Within each transect, corn populations were recorded, and heights were quantified by measuring from the base to the straightened top leaf. Due to field and labor constraints in 2020, corn yields were evaluated at the main plot level by harvesting the middle two rows with a small plot harvester, and moisture was corrected to 15.5%. In 2021, a sensor malfunction in the electric-drive metering system (Precision Planting, Tremont IL) prevented seed drop in two plots and within a small portion of three other plots near plot edges (1 to 3 m). The former plots ($n = 2$) were removed from all analyses and the latter plots ($n = 3$) were subjected to a data correction for corn stand and yield data using plant population maps generated by the monitor system (20/20 Precision Planting, Tremont IL) prior to analysis.

On-Farm Strip Trial

An on-farm strip trial was completed in 2020 and 2021 growing seasons within separate fields on a cooperating no-till grain farm located near New Paris, PA (40.107948°N, 78.643975°W). Soils were a Morrision channery sandy loam (fine-loamy, mixed, active, mesic Ultic Hapludalfs). Cereal rye (variety VNS) was sown at 50 kg ha^{-1} following winter wheat production in mid-September in 2019 and 2020. In 2020, cereal rye establishment was suboptimal, and wheat (VNS; *Triticum aestivum* L.) was overseeded in mid-November at 84 kg ha^{-1} to ensure adequate cover in spring. Four cover crop residue management treatments were imposed in field length strips (180 m in 2020 and 120 m in 2021) using a randomized complete block design with four replications. Treatments included 14 DPP cover crop termination followed by planting into standing residue with light row-cleaning compared to three planting green (1 DAP) treatments: 1) standing residue, with no additional residue management tactics employed; 2) roll-crimped residue with no row cleaning; or 3) roll-crimped residue using a ZRX integrated roll-crimper system equipped with double-disk row cleaners. Plot width was 6.1 m (8 rows) with the middle 3.05 m (4 rows) used for all measurements including yield. Field corn (P1077AM; Pioneer, Johnston, IA) was planted at 83,500 seeds ha^{-1} on May 15, 2020, and May 21, 2021. In 2020, treatments were imposed using the same planter and tools described for on-station experiments. In 2021, a similar planter (John Deere 1750 4-row equipped with finger meters and ZRX mounted roller-crimper system) was used. Selection of cover crop burndown products and herbicide program were left to the discretion of the cooperator. Due to comprehensive residual programs and uniformly low weed pressure, data collection was limited to corn performance metrics, including mean height, height variation (i.e., coefficient of variation), population, ear:plant ratio, and grain yield. Corn population was assessed at the V5 growth stage in 2020 and V4 growth stage in 2021 using three representative 9-m transects per strip. Within these transects, the height of the first 20 corn plants was quantified by measuring from the base to the straightened top leaf. The number of corn ears was recorded within three representative 9-m transects just prior to harvest. Grain yield was estimated with use of the cooperators combine yield monitor and adjusted for moisture.

Statistical Analysis

Data were analyzed with R software (version 3.6.1; R Core Team 2021). Cereal rye biomass (in megagrams per hectare [Mg ha^{-1}]) was analyzed by averaging samples across split-plots and by termination timing (14 DPP, 1 DAP), and then fitting termination timing ($n = 2$), year, and their interaction as a fixed effect and block as a random effect using the *lme* function in the NMLE package (Pinheiro et al. 2019). Interrow, intrarow, and total weed density data were analyzed independently by fitting generalized linear mixed effect models with a Poisson distribution (log link function) and observation-level random effects using the *glmer* function in the LME4 package (Bates et al. 2015). These models were fit using cereal rye residue management treatment ($n = 5$), year, and their interaction as fixed effects and block as a random effect. Significance of fixed effects in weed density models was evaluated using log-likelihood ratio tests (Wald χ) to compare full versus reduced models using the *anova* function. Corn population (plants ha^{-1}), height (cm), ear:plant ratio, variation in height (coefficient of variation; CV), and yield (kg ha^{-1}) were analyzed at the main plot level by fitting cereal rye residue management treatment, year, and their interaction as fixed effects and block as a random effect using the *lme* function. Corn stand assessment data were averaged across split-plots (on-station) or subsamples (on-farm) prior to analyses. Weed biomass was modeled by interrow and intrarow zones, and as a total by summing interow and intrarow zones within each quadrat. Weed biomass models were fit by year using cereal rye residue management ($n = 5$), herbicide program ($n = 2$), and their interaction as fixed effects. Block and cereal residue management nested within block were fit as random effects. Prior to analyses, weed biomass was log-transformed to address assumptions of normality, and due to the presence of heteroskedasticity, the *varIdent* function within NLME was used to group variances by herbicide treatment (Zuur et al. 2009). 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.

Table 2. Cumulative GDD_{4C} during cereal rye growth period and mean aboveground biomass at termination among experimental years and termination timing.[a]

Cereal rye termination by year	Sowing date	Termination date	Oct-Dec GDD_{4C}[b]	Total GDD_{4C}	Biomass (Mg ha^{-1})[b]
2019–2020					
14 DPP	October 1	April 28	272	492	1.8 (0.1)
1 DAP		May 14		571	4.9 (0.3)
2020–2021					
14 DPP	October 1	April 28	337	573	7.4 (0.7)
1 DAP		May 13		691	9.9 (1.2)

[a] Abbreviations: DAP, days after planting; DPP, days preplant; GDD, growing degree days at 4.4 C base temperature.

[b] Aboveground biomass at termination among experimental years and termination timing are presented as mean ± SE.

Results and Discussion

On-Station Experiment

Aboveground cereal rye biomass differed between experimental years ($F_{1,9} = 33$; $P < 0.001$) and termination timing ($F_{1,9} = 13$; $P < 0.01$). Delaying cereal rye termination from 14 DPP to 1 DAP resulted in greater biomass production, ranging from a 33% increase in 2021 to a 270% increase in 2020 (Table 2). The magnitude of change between termination timings is a function of total biomass production differences across years. Total biomass production ranged from 7.4 to 9.9 Mg ha^{-1} across termination timings in 2021, which was significantly greater at both termination timings than levels observed the previous year (1.8 to 4.9 Mg ha^{-1}).

Phenological development of cereal rye was similar across years, resulting in nearly identical dates for imposing termination treatments. Greater growing degree day accumulation was observed in the autumn of the 2020–2021 season (Table 2), which may contribute to differences in biomass production. Cumulative precipitation during the cereal rye growing season (October 1 to May 1) was also higher in 2021 (72 cm) than 2020 (49 cm), which may also contribute to biomass differences.

Based on our experience, cereal rye biomass production in 2019–2020 is more representative of cereal rye performance for the targeted growing season window in the Northeast region, whereas production in the 2020–2021 season was anomalous but may approximate biomass potential for the Northeast region based on future climate change scenarios (Grocholski et al. 2023).

Weed Control Outcomes

The effect of cereal rye residue management tactics on weed density at the V3 growth stage varied among years in intrarow

Table 3. Main effect of herbicide program within experimental year on intrarow, interrow, and total weed biomass in mid-August.[a–d]

Herbicide treatment by year	Intrarow weed biomass	Interrow weed biomass	Total weed biomass
2020		——— kg ha^{-1} ———	
PRE (one-pass)	2.60 (1.3)	21.3 (7.5)	26.5 (12.1)
POST (two-pass)	0.50 (0.3)	0.80 (0.3)	1.40 (0.6)
F-value; $P < 0.05$	17; $P < 0.001$	77; $P < 0.001$	56; $P < 0.001$
2021			
PRE (one-pass)	5.20 (3.5)	39.9 (18.4)	73.8 (32.4)
POST (two-pass)	0.25 (0.2)	0.25 (0.1)	0.50 (0.2)
F-value; $P < 0.05$	11; $P < 0.01$	60; $P < 0.001$	71; $P < 0.001$

[a] Abbreviations: POST, postemergence; PRE, preemergence.

[b] Data are presented as means (± SE) averaged across cover crop treatments due to no observed cover crop or herbicide by cover crop interactions ($P > 0.05$).

[c] PRE herbicides were applied May 21, 2020, and May 13, 2021. POST herbicides were applied June 17, 2020, and June 16, 2021.

[d] The herbicide protocol for both treatments included S-metolachlor (1.67 kg ai ha^{-1}) + mesotrione (0.19 kg ai ha^{-1}) + atrazine (1.12 kg ai ha^{-1}) + glyphosate (1.26 kg ae ha^{-1}).

(Wald $\chi^2 = 35.1$; $P < 0.001$; Figure 2A) and interrow (Wald $\chi^2 = 36.4$; $P < 0.001$; Figure 2B) zones, and by total density (Wald $\chi^2 = 33.7$; $P < 0.001$; Figure 2C). Weed recruitment dynamics were not further analyzed by functional group because grass species were dominant in 2020 and broadleaf species were dominant in 2021. The three most common grass species were giant foxtail (*Setaria faberi* Herrm.), large crabgrass [*Digitaria sanguinalis* (L.) Scop.], and yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.]. The three most common broadleaf species were common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and Pennsylvania smartweed [*Persicaria pensylvanica* (L.) H. M Gomez]. Given the difference in cereal rye performance between years, treatment effects on weed recruitment dynamics are best described within year.

In the first year, which represents average cereal rye biomass production for the region, planting green with use of the integrated roll-crimper/row-cleaner system resulted in greater intrarow weed density compared with planting green into standing cereal rye. Interrow weed density was lower in planting green treatments using roll-crimping tactics compared to early-termination (14 DPP) treatments, but it did not statistically differ from planting green into standing cereal rye. Weed recruitment patterns highlight a potential tradeoff between intrarow and interrow weed suppression potential that results from alternative residue management tactics (Figure 2 A and B), but total weed density did not statistically differ among treatments in 2020 (Figure 2C).

In the second year, which represents above-average cereal rye biomass production for the Northeast region, planting green with use of roll-crimping tactics resulted in lower intrarow weed density than early-termination treatments (14 DPP) but it did not differ from that of planting green into standing cereal rye. The forage-harvest (14 DPP) treatment resulted in greater intrarow, interrow, and total weed density than other treatments. No differences in interrow or total weed density were observed among planting green (1 DAP) treatments.

In both years, a herbicide program effect was observed in analysis of intrarow, interrow, and total weed biomass evaluated in late August (Table 3). Cereal rye residue management tactics did not affect ($P < 0.05$) weed biomass nor vary within herbicide program (Table 3). The one-pass PRE program resulted in greater intrarow, interrow, and total weed biomass compared to the two-pass POST program when averaged across cover crop residue management treatments. However, mean biomass levels were generally low across treatments, ranging from <1 to 74 kg ha^{-1}.

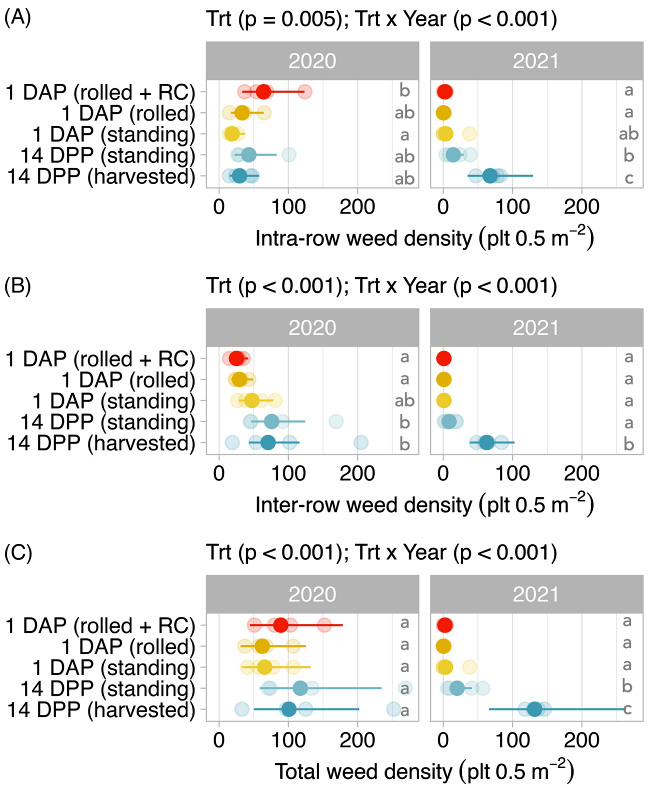

Figure 2. Effect of cover crop treatment, which includes cereal rye termination timing and residue management tactic, on (A) intrarow weed density, (B) interrow weed density, and (C) total weed density prior to postemergence (POST) application at the V3 corn growth stage in POST treatments by corn production year (2020, 2021) in on-station experiments. Data are back-transformed geometric means (circles) and SEs (lines). Observations by replicate are shown in shaded circles. Within year by cover crop treatment combinations, treatments with the same letter are not significantly different ($P > 0.05$); absence of letters indicate no treatment differences within year. Cereal rye termination timing was 14 d preplant(DPP) or 1 d after planting (DAP). Residue management strategies include cereal rye harvested for forage (ryelage), no residue management tools employed at planting (standing), roll-crimped at planting using front-mounted, full width roll-crimper (roll), and roll-crimped at planting using an integrated roll-crimper with row-cleaners (rolled + roll-cleaner).

Corn Stand Assessment and Yield

The effect of cereal rye management tactics on corn populations at the V5 growth stage varied by experimental year ($P = 0.004$; Table 4). Stand establishment was uniformly high among treatments in 2019–2020. In the subsequent year, planting green treatments (1 DAP) resulted in lower populations than the 14 DPP ryelage harvest treatment, ranging from 19% to 20%. No differences were observed between 14 DPP and 1 DAP treatments where cereal rye residue was left standing.

The effect of cereal rye residue management tactics on mean height and height variation within a stand, quantified using coefficients of variation (%CV), differed between experimental years ($P < 0.001$; Table 4). In 2019–2020, planting green into cereal rye increased mean height compared to other treatments, and all planting green treatments increased mean corn height compared to the 14 DPP ryelage harvest treatment. No differences in corn height variation within stands were observed in 2019–2020. In

Table 4. Effect of cover crop treatment on corn population, height, variation in height, and grain yield.[a,b,c]

Cereal rye termination (residue management)[d]	Population (V5)	Height (V5)	Height (V5)	Grain yield
	1,000 plants ha^{-1}	cm	% CV	Mg ha^{-1}
2019–2020	mean (SE)			
14 DPP (ryelage)	82.7 (1.4) a	49 (1) a	10 (1) a	5.0 (0.11) a
14 DPP (standing)	83.6 (0.8) a	55 (1) ab	10 (1) a	7.1 (0.37) b
1 DAP (standing)	82.3 (0.9) a	66 (1) c	10 (1) a	7.3 (0.02) b
1 DAP (roll))	80.0 (1.5) a	58 (1) b	9 (1) a	7.6 (0.09) b
1 DAP (roll + RC)	81.4 (1.3) a	56 (1) b	8 (1) a	7.0 (0.16) b
2020–2021				
14 DPP (ryelage)	82.5 (1.2) c	60 (1) c	9 (1) a	12.6 (0.04) c
14 DPP (standing)	75.5 (1.7) bc	52 (2) b	13 (1) ab	13.3 (0.23) c
1 DAP (standing)	67.1 (2.4) ab	38 (1) a	16 (1) b	10.2 (0.34) b
1 DAP (roll))	66.5 (1.6) a	39 (1) a	16 (1) b	10.4 (0.11) b
1 DAP (roll + RC)	66.0 (2.9) a	46 (2) b	15 (1) b	8.4 (0.37) a
ANOVA (F; $P < 0.05$)[d]				
Year ($F_{1,27}$)	64; $P < 0.001$	96; $P < 0.001$	47; $P < 0.001$	36; $P < 0.001$
Cover crop ($F_{4,27}$)	8; $P < 0.001$	5; $P = 0.006$	2; $P = 0.13$	13; $P < 0.001$
Y × CC ($F_{4,27}$)	5; $P = 0.004$	46; $P < 0.001$	7; $P < 0.001$	28; $P < 0.001$

[a] Abbreviations: CC, cover crop; CV, coefficient of variation; DAP, days after planting; DPP, days preplant; RC, double-disk row-cleaner V5, corn growth stage (5 collared leaves); Y, year.

[b] Means and treatment level SEs are reported.

[c] The effect of cover crop treatment includes coupled cereal rye termination and residue management tactic, and experimental year.

[d] Residue management strategies include cereal rye harvested for forage (ryelage), no residue management tools employed at planting (standing), roll-crimped at planting using front-mounted, full width roll-crimper (roll), and roll-crimped at planting using an integrated roll-crimper with row-cleaners (roll + RC).

2020-2021, mean height trends were reversed. Mean corn height in ryelage harvest treatments was increased compared to other treatments, and both early termination (14 DPP) treatments led to increased mean height compared to planting green treatments that did not employ row cleaners. In addition, each planting green treatment led to variation in increased corn height within the stand compared to the 14 DPP ryelage treatment but they did not differ from each other.

Finally, the effects of cereal rye residue management tactics on corn grain yield also differed between experimental years ($P < 0.001$; Table 4). In the 2019–2020 season, corn grain yields were lower in the 14 DPP ryelage treatment compared to other treatments when cereal rye residues were left on the surface (14 DPP, 1 DAP), but they did not differ from each other. In the 2020–2021 season, corn grain yield was greater in 14 DPP treatments compared to planting green treatments. Within planting green treatments, use of roll-crimping with row-cleaners resulted in lower yield compared with roll-crimping or planting into standing residue without using row cleaners.

On-Farm Strip Trial

Mean cover crop biomass production was 7.9 (± 0.7) and 9.6 (± 0.8) Mg ha^{-1} in 2020 and 2021, respectively. Corn yields were limited due to drought conditions in the 2020 corn growing season, with significantly greater yields ($F_{1,21} = 125$; $P < 0.001$) observed in 2021. Cover crop residue management tactics resulted in a marginal effect ($F_{3,21} = 2.6$; $P = 0.07$) on corn grain yield (Figure 3A). Across both years, planting green into standing residue resulted in nominally lower and more variation among replicates compared to other treatments. Early termination of the cover crop resulted in nominally higher yields compared to planting green treatments.

Whereas only non-significant trends emerged from yield data, corn demographic results reveal treatment effects that may influence corn performance across a broader management by environment gradient. A significant treatment by year interaction ($F_{3,21} = 2.9$; $P = 0.05$) was observed in analysis of corn populations measured at the V5 growth stage (Figure 3B). In 2020, populations were lower when planting green (1 DAP) into standing residue compared to early termination of the cover crop. In 2021, roll-crimping with use of row cleaners resulted in similar populations to early termination and both treatments increased populations relative to planting green without row cleaning in roll-crimp and standing residue treatments. A significant treatment effect ($F_{3,21} = 2.9$; $P = 0.05$) was observed in analysis of corn ear:plant ratio (Figure 3C). Averaged across years, roll-crimping resulted in a greater ear:plant ratio (1.07 ± 0.02) than planting green into standing residues (0.96 ± 0.02), with other treatments intermediate to these extremes. This result suggests that planting into standing residues reduced the probability of reproductive success.

The effect of residue management tactics on mean corn height at the V5 corn growth also differed across years ($F_{3,21} = 9.8$; $P < 0.001$; Figure 3D). In 2020, planting green into standing residue resulted in greater mean height than other treatments. Mean corn height was also higher in planting green treatments that employed row cleaners compared to without row cleaners, as well as the early termination burndown treatment. In comparison, no differences in mean corn height were observed in 2021. Corn height variation within stands, measured using the coefficient of variation, was influenced by cover crop residue management tactic ($F_{3,21} = 20.7$; $P < 0.001$) and no interactions were observed among years ($F_{3,21} = 0.41$; $P > 0.05$; Figure 3E). Across both years, planting green into standing residue resulted in greater variation in corn height within stands than in other treatments. Planting green with use of roll-crimping and row cleaners decreased variation in corn height compared to roll-crimping without row cleaners.

Summary of Management Tradeoffs

Results from our on-station experiment indicate that the impact of residue management tactics on early-season weed recruitment

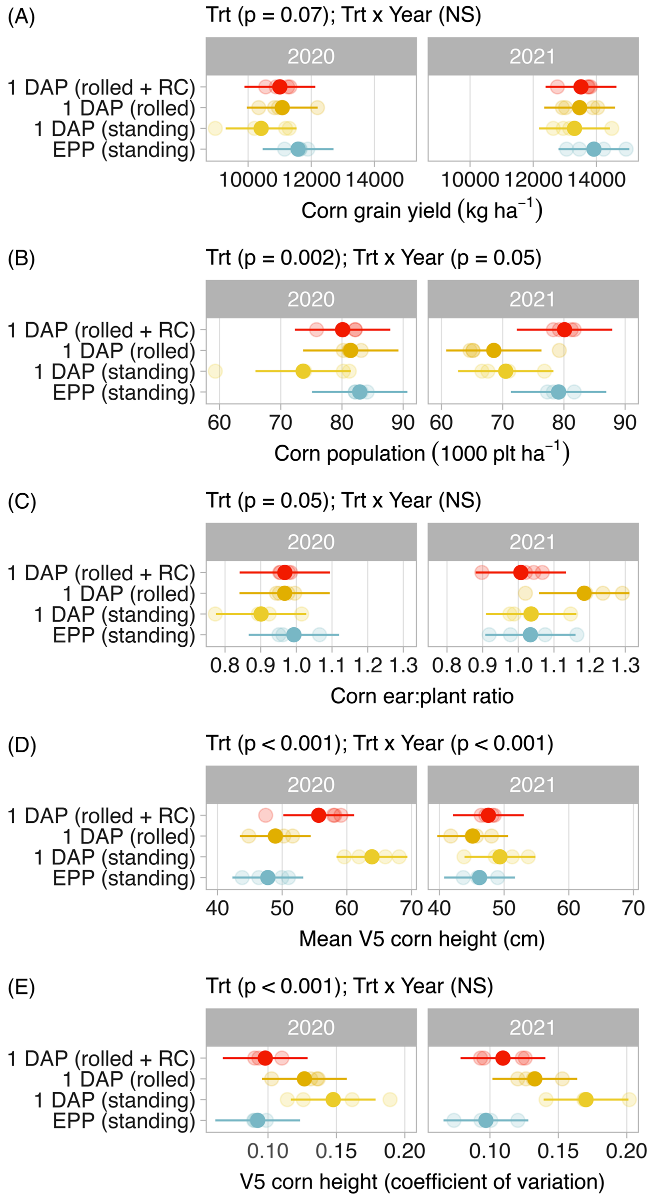

Figure 3. Effect of cover crop treatment (Trt), which includes cereal rye termination timing and residue management tactic, on corn: (A) grain yield, (B) population, (C) ear to plant ratio; (D) mean height; and (E) height coefficient of variation by corn production year (2020, 2021) in on-farm strip trials. Data are back-transformed geometric means (circles) and SEs (lines). Observations by replicate are shown in shaded circles. Cereal rye termination timing was early preplant (EPP) or 1 d after planting (DAP). Residue management strategies include no residue management tools employed at planting (standing), roll-crimped at planting using front-mounted, full width roll-crimper (roll), and roll-crimped at planting using an integrated roll-crimper with row-cleaners (rolled + RC).

dynamics and corn performance is mediated by total cereal biomass production. We observed spatial variation (intrarow vs. interrow) in weed recruitment patterns among residue management tactics but no difference in total weed recruitment in the first experimental year when cereal rye biomass production approximated theoretical thresholds (~5 Mg ha^{-1}) needed to achieve meaningful levels of weed suppression (Nichols et al. 2020). Roll-crimping and row-cleaning resulted in greater intrarow weed recruitment than planting directly into standing cereal rye, and though not statistically different, trends suggest planting directly into standing cereal rye results in greater interrow weed recruitment than roll-crimping.

Organic no-till studies have reported similar spatial variation in weed recruitment between interrow and intrarow zones when row-cleaning is employed in combination with roll-crimping (Champagne et al. 2019, 2021). Lower intrarow weed recruitment observed in standing treatments likely results from less soil disturbance compared to row-cleaning treatments, thereby maintaining indirect effects that attenuate weed germination cues, such as lower soil temperature, decreased diurnal variation in soil temperature and moisture, and lower red light (R) relative to far-red (FR) (R:FR) light conditions (Mirsky et al. 2013). In comparison, lower interrow weed recruitment in roll-crimped treatments likely results from enhancement of the same indirect effects that attenuate germination cues and potentially greater physical interference leading to resource exhaustion and greater seedling mortality during the establishment phase (Ficks et al. 2022b). Comparisons between standing and roll-crimped residue management tactics remain limited, and greater understanding of residue management (standing vs. roll-crimping) effects on postestablishment population processes across functional traits of weed species is needed.

We observed few differences in weed recruitment spatial patterns among alternative residue management tactics in our second experimental year, where significantly greater (9.9 kg ha^{-1}) rye biomass occurred in planting green treatments. Field observations suggest that differences in post-plant cereal rye architecture between roll-crimped and standing treatments was minimized because the planter toolbar left cereal rye in standing treatments lodged or oriented on the surface.

Results from both on-station experiments and on-farm strip trials indicate that planting green into standing cereal rye increases corn height compared to roll-crimping treatments, and in some cases may reduce corn population and yield. Reduced light quantity and quality (R:FR) is likely the underlying mechanism that explains observed increases in corn height when planting green into standing cereal rye, which we consider here as an indicator of a seedling etiolation effect. Increased corn height in response to low R:FR light conditions created by early-season weed competition is a well-known shade avoidance response in monocot species (Page et al. 2010; Rajcan et al. 2004). Low R:FR conditions result in greater leaf area and shoot-root ratios in corn seedlings when light is the limiting factor, which may reduce acquisition of belowground resources and lead to greater susceptibility to additional forms of biotic or abiotic stress (Page et al. 2010). Our results, supported by mechanistic studies of shade avoidance, highlight the need to minimize cover crop residue effects on light quantity and quality during the corn establishment phase to mitigate impacts on crop performance.

The effect of cereal rye termination timing and residue management tactics on corn grain yields varied among years. There was a trend toward reduced yields in planting green treatments during site-years with high cereal biomass production (>8 Mg ha^{-1}). Other researchers have suggested that planting green may increase the potential for allelopathic effects on corn seedlings during the germination and establishment phase (Koehler et al. 2020) due to the known relationships between cereal rye termination and peak release of benzoxazinoids (Rice et al. 2022) and phenolic acids (Otte et al. 2020). However, it is nearly impossible to decouple short-duration allelopathic effects from competition (Mahé et al. 2022), abiotic stressors, (i.e., nitrogen immobilization), biotic stressors (i.e., seedling disease incidence), and crop management factors (i.e., seed placement) that vary across surface mass and termination timing gradients.

Our results indicate that a two-pass herbicide program approach, which included a burndown product applied at cover crop termination followed by foliar and residual products (S-metolachlor/mesotrione/atrazine/glyphosate) applied POST (V3 corn growth stage) reduces late-season weed biomass and seed rain potential compared to a one-pass program where foliar and residual products are applied PRE at the time of cover crop termination. This result is consistent across cereal rye biomass conditions (i.e., year) and residue management tactics. Two factors should be considered when drawing inferences from these results. First, though lower late season weed biomass was observed in the two-pass POST program, early season weed recruitment in the intrarow zone was greater than the one-pass PRE program in the most intensive residue management (roll-crimp, row-clean) treatment. Labor constraints prevented yield comparisons at the split-plot level in this study, but other studies of early POST practices in corn demonstrate the potential for yield loss due to early-season weed competition depending on weed size and removal timing (Myers et al. 2005; Soltani et al. 2022). Second, though late season weed biomass was greater in the one-pass PRE practice, early-season weed recruitment was negligible and observed levels of late-season weed biomass were generally low and unlikely to influence yield based on previous studies (Duiker and Curran 2005). Consequently, alternative herbicide programs used in this study reflect a choice between minimizing risk of corn yield loss due to early-season weed competition or minimizing seed rain potential due to late-season weed escapes, which will depend on traits of driver weed species. These risks may also be weighed against the fuel, labor, and herbicide input savings associated with a one-pass system.

Finally, we suggest that a spatially explicit approach for managing weeds in intrarow and interrow zones should be considered when using more aggressive residue management tactics, such as roll-crimping and row-cleaning, to optimize corn establishment. The utility of herbicide-banding in the intrarow zone in combination with other cultural control tactics in the interrow zone, such as cover crop surface mulch, has been demonstrated in previous no-till corn and soybean studies, but grower adoption remains limited (Snyder et al. 2016; Summers et al. 2021). Herbicide banding or other site-specific tactics may also overcome cover crop interference with deposition and soil-bioavailability of residual herbicides when applied at the time of cover crop termination (Whalen et al. 2020).

In conclusion, developing herbicide-based weed management recommendations for planting green systems should consider intrarow and interrow weed recruitment dynamics associated with residue management tactics needed to optimize corn performance.

Practical Implications

Improved management recommendations are needed for optimizing weed suppression benefits while minimizing other pest, fertility, and crop management risks when planting green in corn production systems. Due to equipment limitations, a range of residue management tactics are currently employed when planting green, including planting directly into standing cereal rye, roll-crimping using a front-mounted unit at planting, and employing integrated roll-crimper systems equipped with row-cleaners. This study focused on the effect of these alternative residue management tactics in combination with one-pass PRE or two-pass POST herbicide programs on intrarow and interrow weed recruitment, weed escapes, and corn performance indicators. Our results suggest that under average cereal rye biomass production levels (4.9 Mg ha^{-1}), planting directly into standing rye reduces intrarow weed recruitment, increases corn seedling etiolation, and may reduce corn yield under certain conditions. Roll-crimping with row-cleaners will likely increase in-row weeds, decrease interrow weeds, and may improve corn yield relative to planting into standing cereal rye. In higher cereal rye biomass conditions (9.9 Mg ha^{-1}), high levels of weed suppression and significant reductions in corn yield were observed across planting green residue management tactics compared to the standard termination (14 d preplant) practices. Based on our findings, we suggest that biomass threshold targets should be moderate (<5 Mg ha^{-1}) to optimize weed suppression and corn performance. We also suggest that 1) PRE programs should be prioritized if using aggressive residue management tactics (roll-crimping, row-cleaning) to reduce early-season weed competition in the intrarow zone, and 2) POST programs may be prioritized when planting green if zero-seed rain is the weed management goal.

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