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Abbreviations:
IJRC: I & J roller-crimper; DRC: Dawn ZRX roller-crimper; MT: mowing & tedding; PC: plowing & cultivation

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Cover crop management strategies affect weeds and profitability of organic no-till soybean

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Abstract

Cover crop residue retention on the soil surface can suppress weeds and improve organic no-till soybean (*Glycine max*) yield and profitability compared to a tilled system. Appropriate cereal rye (*Secale cereale*) fall planting date and termination methods in the spring are critical to achieve these benefits. A plot-scale agronomic experiment was carried out from September 2018 to October 2021 in Kutztown, PA, USA to demonstrate the influence of cereal rye planting date (September or October) and mechanical termination method [no-till (I & J roller-crimper, Dawn ZRX roller, and mow-ted) and tilled (plow-cultivate)] on cover crop regrowth density, weed biomass, soybean yield, and economic returns. In one out of three years, the September rye planting accumulated more cover crop biomass than the October planting, but the regrowth of the rye after roller-crimping was greater with this planting date. Cover crop planting date had no effect on total weed biomass and demonstrated varying effects on soybean grain yield and economic returns. The Dawn ZRX roller outperformed the I & J roller-crimper in effectively terminating cover crops, while the I & J roller-crimper demonstrated more uniform weed suppression and led to greater soybean yields over a span of three years. Organic no-till strategies eliminated the need for tillage and reduced variable costs by 14% over plow-cultivated plots, and generated ~19% greater net revenue across the study period (no-till *vs* tillage = US \$845 *vs* US \$711 ha^{-1}). Terminating cereal rye with roller-crimping technology can be a positive investment in an organic soybean production system.

Introduction

Organic growers in the northeastern USA typically terminate cover crops by mechanical incorporation. Efforts have been made to advance organic rotational no-till management practices in row crop production systems using a roller-crimper that reduces soil inversion and preserves the benefits of cover crops (Mirsky et al., 2012). Cover crop-based organic rotational no-till, which was developed as an alternative to conventional no-till methods, utilizes a non-chemical strategy to convert standing cover crops into a weed-suppressing mulch (Moyer, 2020). Ideally, mechanical termination with a roller-crimper will create cover crop residue mulches that persist throughout the cash crop growing season. Studies on cover crop species and surface mulch rates have shown that over 8 Mg ha^{-1} dry biomass with >10 cm mulch thickness can effectively suppress weeds (Creamer et al., 1996; Teasdale and Mohler, 2000; Mirsky et al., 2013). In addition to weed suppression, cover crops can improve soil health and subsequent cash crop yield (Cottney et al., 2022; Toom et al., 2021). Given the numerous benefits of cover crops, careful consideration should be given to their establishment in the fall and termination methods in the spring to maximize biomass and weed suppression (Mirsky et al., 2011).

Cover crop management tactics in rotational no-till soybeans have resulted in contrasting outcomes when compared to their conventionally tilled counterparts (Bernstein et al., 2011; Delate, Cwach, and Chase, 2012; Smith et al., 2011). Many factors correlate with success in the organic no-till system, including favorable weather and integration of tactics that address cover crop establishment and method of termination.

In several regions across the USA, including the mid-Atlantic, cereal rye is the most preferred winter cover crop (National Cover Crop Survey, 2020). It has many beneficial attributes including the ability to withstand sub-zero winter temperatures, produce ample biomass, and form a dense root system to scavenge soil nutrients (Mirsky et al., 2013; White and Weil, 2010). The crop has a high C:N ratio (>30:1), slow decomposition rate (Dhakal et al., 2020; Singh et al., 2020), and a wide planting window in the fall (Mirsky et al., 2011). Cereal rye is also known for its ability to deplete the weed seedbank by physically attenuating emergence, releasing phytotoxic chemicals, immobilizing nutrients, and changing germination cues (Hodgdon et al., 2016; Mirsky et al., 2013). Mirsky et al. (2011), Duiker and Curran (2005), and Teasdale et al. (2004) evaluated rye for its weed-suppressive potential by manipulating planting dates in the fall or termination dates in the spring. Early planting and late spring termination of cereal rye reportedly increased weed suppression (Mirsky et al., 2011; Teasdale et al., 2004). In the mid-Atlantic region, the planting date for cereal rye is primarily determined by the established crop rotation. For example, longer-season maize (*Zea mays*) hybrids and soybean cultivars can advance the rye seeding to later in the fall, which may affect rye cumulative growing degree days and biomass production. In the northeastern USA, cereal rye is typically sown from midsummer to late fall. Although much work has been conducted to quantify the effect of planting/termination time and methods of termination alone on cereal rye production (Crowley et al., 2018; Mirsky et al., 2011), less is known about the combined effects of planting date and termination methods on cereal rye and subsequent cash crop yield in organic no-till systems.

Previous studies determined the appropriate growth stage for roller-crimping cereal rye for no-till soybean planting was at anthesis to ensure adequate termination and reduce rye regrowth (Ashford and Reeves, 2003; Mirsky et al., 2011; Moyer, 2020). Cereal rye should be terminated within a few days of anthesis to avoid potential exhaustion of soil moisture from the surface (Wagner-Riddle, Gillespie, and Swanton, 1994); to ensure cover crop desiccation; and to uniformly cover the surface for improved in-season weed suppression (Creamer and Dabney, 2002). A front-mounted roller-crimper paired with a back-mounted planter allows for the mechanical termination of cereal rye while simultaneously planting soybean in a single pass. Some front-mounted roller-crimpers control down pressure with hydraulic systems. Previous research on the performance of these roller-crimpers is restricted to weed emergence studies and not weed infestation in soybean and the relation to cover crop regrowth after termination.

An increasing number of organic growers are interested in adopting reduced-tillage practices that integrate both the weed-suppressing and soil-conserving features of conventional no-tillage systems and the soil-building and economic benefits of organic practices (Mirsky et al., 2013). No-till organic systems are known to reduce fuel and labor requirements by 27 and 31%, respectively, compared to tillage-dependent organic systems (Mirsky et al., 2012; Ryan 2010). Crowley et al. (2018) reported 25 and 43% less variable costs and labor required for the rolled-crimped cereal rye, respectively, when compared to the moldboard plowed system in New York, USA.

There are several other organic cover crop termination strategies in the mid-Atlantic region in addition to roller-crimping. Using a rotary or flail mower for mechanical termination is easily adopted by farmers because many already possess the necessary equipment (Moore, Gillespie, and Swanton, 1994); however, this method may result in a cover crop mulch that decomposes rapidly, creating an open soil surface where weeds emerge, resulting in high weed pressure during the cash crop season (Crowley et al., 2018; Rosario-Lebron et al., 2019). In contrast, a sickle-type mower (e.g., haybine or discbine) leaves the cover crop intact after termination. While various mechanical tools have been tested for their ability to terminate cover crops, there is a lack of information that compares these tools in achieving agronomic and economic outcomes in organic rotational no-till systems.

Our aim in this research was to assess cereal rye management strategies prior to planting organic soybeans for their impact on cover crop termination, weed suppression, crop yield, and net revenue. Two planting dates of cereal rye, along with three no-till termination methods, were compared with the standard plow and cultivate method used for organic soybean production. We hypothesized that an early fall cereal rye planting date would result in greater rye biomass, which in turn would increase in-season weed suppression potential, soybean yield, and farm profitability under reduced-tillage management systems when compared to the plow-cultivate system that incorporates the cover crop residue with tillage.

Materials and methods

Experimental site and design

An experiment was conducted at Rodale Institute Research Farm, Kutztown, PA, USA (40°33′ N, 75°43′ W) over three site years: 2018/2019 (site-year 1), 2019/2020 (site-year 2), and 2020/2021 (site-year 3). The experiment was conducted each year in adjacent fields managed within the same crop rotation [maize—oat (*Avena sativa*)—soybean—wheat (*Triticum aestivum*)]. Although in close proximity, soil types differed between years. The soil type in Year 1 was Berks Channery Silt Loam (loamy-skeletal, mixed, active, mesic Typic Dystrudepts), and in Years 2 and 3 was Clarksburg Silt Loam (fine-loamy, mixed, superactive, mesic Oxyaquic Fragiudalfs) with 3 to 8% slopes (USDA-NRCS, 2019). The previous crop in Year 1 was oat and Years 2 and 3 were oat + red clover (*Trifolium pratense*).

The study site has a sub-humid temperate climate, with a long-term (1981–2021) average annual precipitation and mean annual temperature of 1231 mm and 10.8°C, respectively (Fig. 1). Approximately 50% of annual precipitation occurs from May through September. Annual precipitation values were 1609, 1381, and 1237 mm for Years 1, 2, and 3, respectively. The mean annual temperature for Years 1, 2, and 3 were 11.2, 11.9 and 11.8°C, respectively (Fig. 1). Weather data were taken from the PRISM Climate Group database (https://prism.oregonstate.edu/).

The experiment was laid out in a split-plot design with four replications arranged in a randomized complete block. The main plots (24 m × 24 m) were two cereal rye cover crop planting dates: (i) September 15 (early planting date) and (ii) October 15 (late planting date). Main plots were separated by 3-m buffer strips. The subplots (24 m × 6 m) were four mechanical termination treatments: plow and cultivate (PC), roller-crimping using the I & J roller-crimper (IJRC), roller-crimping using the Dawn ZRX roller-crimper (DRC), and mow and ted (MT).

Field operations

Prior to cereal rye planting in the fall of each year, a moldboard plow was used for primary tillage, followed by a disk and packer to prepare the seedbed for planting. For each planting date treatment each year, uncertified cereal rye seeds (Albert Lea Seed, MN, USA) were direct-seeded in all plots at 188 kg ha^{-1} (Mirsky et al., 2009) using a drill (John Deere 450 drill, Deere and Co., Moline, IL, USA) with 19-cm row spacing.

In the spring of each year, cereal rye was mechanically terminated at Zadoks 65 stage at anthesis (Zadoks, Chang, and Konzak, 1974). Rye in the PC treatment was mowed with a flail mower to allow for effective plowing, then moldboard

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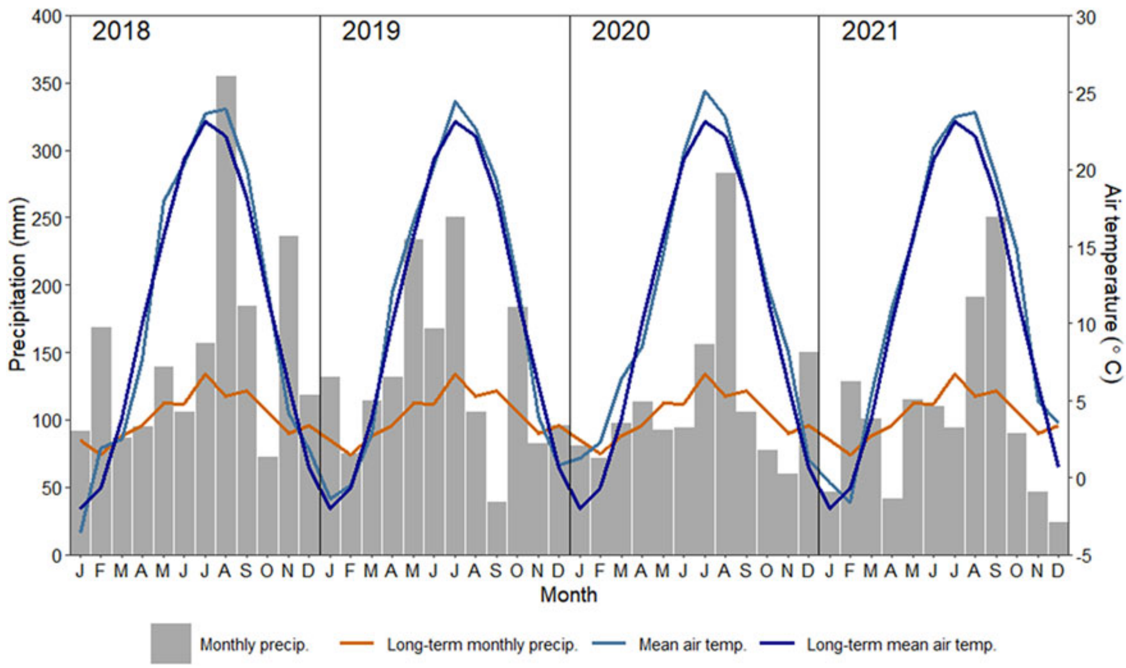

Figure 1. Total monthly precipitation and monthly mean air temperature values from 2018–2021, and long-term (40 years) average monthly values for the experiment location in Kutztown, PA, USA.

plowed, disked, and packed, prior to soybean planting (Fig. 2a). In this treatment, interrow cultivators were used to manage weeds in soybean. The type and dates of interrow cultivation for each site-year are given in Table 1. The MT treatment involved cutting and windrowing using a haybine mower conditioner (New Holland Agriculture, PA, USA) (Fig. 2b) with a 4.3-m swath, followed by tedding with a two-rotor G2LP tedder (Enorossi Co., Calzolaro, Italy) to spread the cut rye stalks evenly across the plot.

The two roller-crimping termination treatments had different characteristics. The DRC (Fig. 2c) (Dawn Equipment Co., Sycamore, IL, USA) had multiple rollers, to correspond with number of planting rows, where each roller moved independently on a parallel linkage and was operated using a hydraulic pressure control system. The IJRC (I & J manufacturing, Gap, PA, USA) used in this study was 3.1–m wide and consisted of a steel cylinder with blunt metal blades welded to the outside in a chevron pattern (Fig. 1d). The IJRC weighed about 950 kg and was front mounted on a tractor. Each year, soybeans were planted with a Monosem NG Plus vacuum precision planter. Both implements were driven through the field at approximately 7 km h^{-1}. In these treatments, cereal rye roller-crimping and soybean planting occurred in the direction cereal rye was planted and at the same time, achieving a one-pass cover-crop-based no-till system.

Each year and in each treatment, 8 rows of certified organic soybeans were planted at 76-cm row spacing at a seeding rate of 519,000 seeds ha^{-1}. Seeding depth for all treatments was maintained between 2.5 and 4 cm. Hydraulic pressure in DRC was calibrated to the desired seeding depth. In Year 1, the soybean variety was Blue River 2A12 of maturity group 2.4 (Mourtzinis and Conley, 2017) (Albert Lea Seed, Albert Lea, MN, USA) and in Years 2 and 3, Blue River 22DC6 of maturity group 2.2 (Albert Lea Seed, MN, USA) was planted. Soybean planting dates for each termination treatment are provided in Table 1 along with dates for other field activities in chronological order.

Data collection

Cover crop biomass and regrowth

Aboveground rye biomass was determined immediately prior to termination by hand-clipping three representative 0.25 m^2 quadrats per replicate block. The height of rye plants was measured from soil surface to the top of the spike, excluding awns, at 15 representative locations in each block. Biomass samples were placed in a forced-air oven for 96 h at 48°C and dried to a constant weight. The cover crop biomass samples were ground to pass through a 1-mm mesh screen in a Wiley mill (Model 4, Laboratory Mill, Thomas Scientific, Chadds Ford, PA, USA). Ground samples were analyzed for total C and N concentration using a Flash EA 1112 CN Automatic Elemental Analyzer (Thermo Finnigan, Milan, Italy).

Cereal rye plants that regrew (i.e., plants that survived mechanical termination and returned to their upright growth habit) were counted once a week for three consecutive weeks following the termination event. The number of erect rye tillers within a 0.25–m^2 quadrat was determined at three random locations in each plot. A tiller was considered ‘regrowth’ if it remained green, did not have a visibly broken stem, and stood at least at a 20–degree angle from the ground at the time of the assessment.

Soybean stand density, biomass, and yield

Soybean establishment was assessed by measuring stand density in each growing season at the V2-V3 growth stage. The number of soybean plants was counted in two of the eight rows in the center of each plot along a 5.3 m transect. At physiological maturity (R7), whole soybean plants were harvested from a 1.86 m^2 area in the center of each plot. Samples were stored in 47.8°C forced air dryers for two weeks. Each sample was weighed and then hand threshed using a 1.3–cm screen sieve and a winnower. The grain was weighed to determine yield, which was adjusted to 13% moisture, to obtain standard yield. The rest of the plant

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Figure 2. Cover crop termination method. (a) Cultivated field for soybean planting, (b) mowing cereal rye cover crop using haybine mower, (c) roller-crimping cereal rye cover crop using Dawn ZRX roller and Monosem planter, and (d) front-mounted I & J roller-crimper terminating cereal rye cover crop and rear-mounted Monosem vacuum planter in Kutztown, PA, USA.

materials were weighed to determine dry aboveground biomass yield.

Weed biomass

Weed samples were taken in mid-August during the pod-filling (R4–R6) stage from four 0.25–m^2 quadrats in each plot. Two quadrats were centered over a single crop row; the other two were centered between crop rows. The samples from two quadrats for each row position were composited later for statistical analysis. Individual species were categorized into broadleaf and grass then put in separate paper bags. Total weed biomass was determined by averaging within-row and between-row measurements. Samples were dried in forced air dryers at 47.8°C to a constant weight and then weighed to determine biomass.

Economic analysis

Enterprise budgets were constructed for all treatments every year. Production costs included the cost of input (seed), field operations (tillage, planting, cultivation, harvesting, hauling, roller-crimping, etc.), labor, and cash rent equivalent of land. Production costs were estimated using field activity records, published literature (Chase, 2020; Chase et al., 2019), and vendor prices. Seed costs used in the analysis were based on actual prices from Albert Lea Seed (Albert Lea, MN). Seed costs for soybeans were \$1.84 kg^{-1} for each year. The cost of cereal rye seeds was \$0.68, \$0.75 and \$0.75 kg^{-1} for Years 1, 2, and 3, respectively. Cash rental rates for non-irrigated cropland for the study area were obtained from USDA NASS (2022), and were \$284, \$257 and \$346 ha^{-1} for Years 1, 2, and 3, respectively.

Operational costs for all field activities were derived from Plastina (2018, 2019, 2020, 2021). The annual operating cost for field activities included fixed (depreciation, housing, interest, and insurance) and variable costs (fuel, oil, and maintenance). The cost for roller-crimping was estimated at either \$6.4 or \$6.7 ha^{-1}, based on the fixed cost of using a field cultivator reported by Plastina (2019, 2020, 2021). Hourly labor requirements for field operations were obtained from Hanna (2016).

Soybean market prices were based on nationwide feed-grade soybean prices reported by the Mercaris™ market survey (Mercaris, Silver Springs, MD, USA). With the assumption of immediate sale of soybean after harvest, the market price was computed based on soybean prices for two weeks after harvest each year. Organic soybeans were valued at \$0.71, \$0.71 and \$1.16 kg^{-1} for Years 1, 2, and 3, respectively (MERCARIS, 2023). Net revenue (in \$ ha^{-1}) for each treatment was calculated for each year by multiplying mean soybean yield by the market price for organic soybean and subtracting total production costs.

Statistical analyses

All data were analyzed using *R*-Studio (version 4.2.0) (Posit, Boston, MA, USA). The R-program utilized ‘dplyr’ and ‘readr’ within core ‘tidyverse’ package for data manipulation and

Table 1. Timeline for field activities for cover crop-based organic soybean production from 2018 to 2021 in Kutztown, PA, USA

	Date of operation		
Field activities	Year 1	Year 2	Year 3
Cereal rye management			
Tillage using MB plow	9/14/2018	9/3/2019	9/11/2020
Tandem disked entire field	9/14/2018	9/12/2019	9/15/2020
Packed entire field	9/14/2018	9/16/2019	9/15/2020
Drill-seeded cereal rye in early PD plots	9/17/2018	9/16/2019	9/15/2020
Tine weeding cereal rye in early PD plots	–	9/19/2019	9/21/2020
Tine weeding cereal rye in early PD plots	–	9/30/2019	9/28/2020
Drill-seeded cereal rye in late PD plots	10/17/2018	10/15/2019	10/15/2020
Tine weeding cereal rye in late PD plots	–	10/18/2019	10/20/2020
Tine weeding cereal rye in late PD plots	–	11/6/2019	11/3/2020
Soybean management			
Flail-mowed rye and MB-plowed PC plots	5/24/2019	5/21/2020	5/27/2021
Tandem disked and packed PC plots	6/4/2019	5/26/2020	5/28/2021
Planted soybeans in PC plots	6/4/2019	6/1/2020	6/1/2021
Mowed and tedded rye in MT plots	5/18/2019	6/2/2020	5/28/2021
Planted soybeans in MT plots	6/4/2019	6/2/2020	5/28/2021
Rolled-crimped rye and planted soybeans in IJRC plots	6/3/2019	6/1/2020	5/28/2021
Rolled-crimped rye and planted soybeans in DRC plots	6/5/2019	6/2/2020	6/8/2021
Tine weeding in PC plots	6/17/2019	6/4/2020	6/3/2021
Tine weeding in PC plots	6/27/2019	6/8/2020	–
Tine weeding in PC plots	–	6/16/2020	–
S-Tine cultivation soybeans in PC plots	–	6/26/2020	6/16/2021
S-Tine cultivation in PC plots	–	7/14/2020	7/6/2021
Buffalo cultivation in PC plots	7/22/2019	–	7/15/2021
Harvested soybeans	9/24/2019	10/15/2020	10/13/2021

MB, Moldborad plow; PD, cereal rye planting date; PC, plow and cultivate; MT, mow and ted; IJRC, I & J roller-crimper; DRC, Dawn ZXR roller-crimper.

'agricolae' for statistical analysis. The 'ggplot2' package was used for data visualization. The 'sp.plot()' function was used to compute ANOVA and 'LSD.test()' to separate the treatment means at $\alpha = 0.05$ significance level (https://rdrr.io/cran/agricolae/src/R/sp.plot.R). Rye planting date, cover crop termination methods, and their interactions were set as fixed effects, whereas replicate blocks and year of data collection were treated as random effects. Weed data were log-transformed based on Shapiro–Wilk and Kolmogorov–Smirnov normality tests. The non-orthogonal contrast between plow-cultivate (tillage) and no-tillage treatments (IJRC, DRC, and MT) was performed using 'contrast.pcvsnt()' function. Three-way interaction with planting date × termination method × year was analyzed for rye biomass, weed biomass, soybean density, dry matter yield, grain yield, total cost, and net revenue, whereas two-way interaction between planting date and termination method was analyzed within the week for rye regrowth. Year was set as a fixed effect for the interaction analysis. Relationships between rye regrowth and cover crop biomass for IJRC and DRC in each planting date were analyzed using linear [lm()] and nonlinear [nls()] regression functions, respectively. Also, a linear regression between weed biomass and soybean yield was used to visualize their correlation at $\alpha = 0.05$.

Results

Cover crop regrowth and biomass production

Aboveground cereal rye biomass varied over the years. Rye biomass was lower in Year 1 (5.8 Mg ha^{-1}) than Years 2 and 3, which had aboveground biomass production of 8.7 and 10.0 Mg ha^{-1}, respectively (Fig. 3a). Rye biomass was affected by year × planting date interaction (Table 2). Cereal rye planting date affected biomass production in Year 1 (September *vs* October planting date = 6.4 *vs* 5.1 Mg ha^{-1}, $P = 0.038$), but not in Years 2 or 3 [9.0 *vs* 8.4 ($P = 0.547$) and 10.3 *vs* 9.7 Mg ha^{-1} ($P = 0.803$), respectively]. Nevertheless, differences in tissue N concentration between September- and October-planted cereal rye (3-year average = 10.9 and 12.2 g N kg^{-1}, respectively) resulted in nearly equal N yield (3-year average = 93.5 and 94.3 kg N ha^{-1}, respectively) from the cover crop. The average total C concentration

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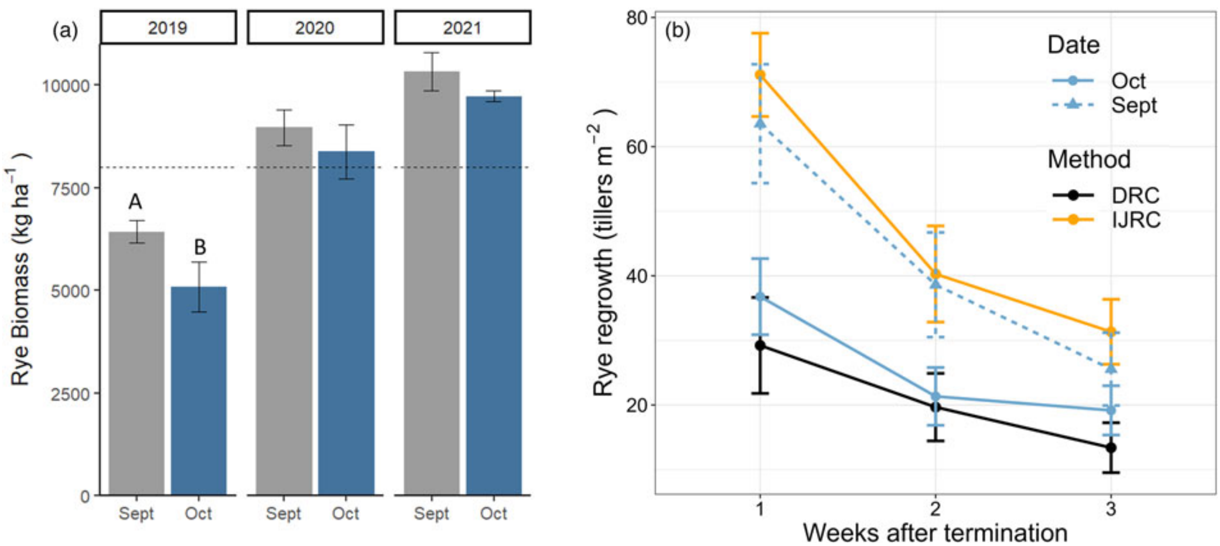

Figure 3. (a) Mean cereal rye biomass (±SEM) measured from 2019 to 2021 for September and October planting date in Kutztown, PA, USA, and (b) number of erect cereal rye tillers (±SEM) measured during three consecutive weeks after roller-crimping as affected by two cover crop planting dates and two rolling-crimping methods. Horizontal dotted line represents desired cover crop biomass for adequate weed suppression. Means followed by different uppercase letters within each year differ significantly at $\alpha = 0.05$. Data were averaged across four termination treatment methods and four replicates for pane 'a'; and three years, two planting dates, and four replicates for pane 'b'.

Table 2. *P*-values associated with the sources of variation for cereal rye regrowth (tillers m^{-2}), weed biomass (gm^{-2}), plant density (No. ha^{-1}), dry matter yield (kg ha^{-1}), seed yield (kg ha^{-1}), total cost (US \$ ha^{-1}), and net revenue (US \$ ha^{-1}) from 2019 to 2021 in Kutztown, PA, USA

Variables	Year (Y)	PD	Y × PD	M	Y × M	PD × M	Y × PD × M
Rye biomass	<0.001	0.224	0.003	–	–	–	–
Rye regrowth							
Week 1	<0.001	0.047	0.462	0.001	0.165	0.476	0.348
Week 2	0.007	0.118	0.140	0.001	0.729	0.334	0.306
Week 3	0.003	0.363	0.119	0.003	0.314	0.651	0.106
Between-row WBM							
Broadleaf	<0.001	0.731	0.681	<0.001	0.128	0.001	0.039
Grass	0.007	0.146	0.988	<0.001	0.252	0.098	0.601
Total	0.870	0.198	0.760	<0.001	0.659	0.020	0.446
Within-row WBM							
Broadleaf	<0.001	0.159	0.585	0.230	0.014	0.379	0.711
Grass	0.002	0.013	0.096	<0.001	0.539	0.289	0.968
Total	0.759	0.090	0.832	0.002	0.145	0.532	0.968
Mean WBM	0.267	0.084	0.758	0.056	0.147	0.065	0.433
Plant density	<0.001	0.699	0.598	<0.001	<0.001	0.237	<0.001
Dry matter yield	0.856	0.008	0.010	0.016	<0.001	0.461	<0.001
Seed yield	0.729	0.011	0.008	0.023	<0.001	0.480	<0.001
Total cost	<0.001	0.175	0.259	<0.001	<0.001	0.541	<0.001
Net revenue	0.032	0.020	0.005	0.004	<0.001	0.424	<0.001

PD, planting date; M, termination method; WBM, weed biomass.
Underlined *P*-values are significant.

in cereal rye tissues did not differ between planting dates (435 g C kg^{-1}).

There was no year × planting date × termination method interaction on rye regrowth. Averaged across years, rye regrowth was maximum one week after roller-crimping then gradually decreased over time. Rye regrowth one week after roller-crimping (Fig. 3b) was affected by the cover crop planting dates and termination method used (Table 2). At one week after termination, the

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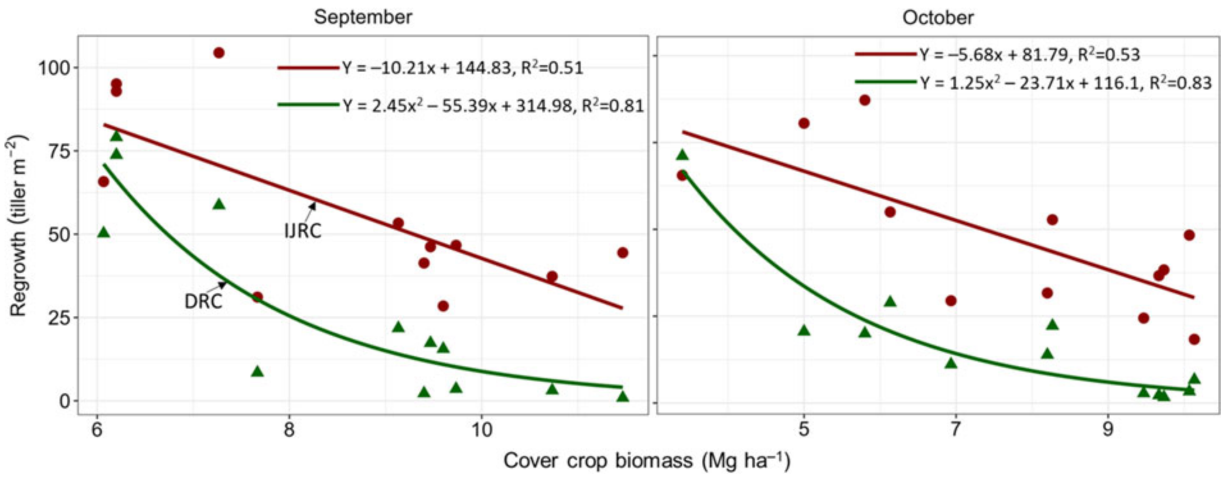

Figure 4. Relationship between cover crop biomass and cereal rye regrowth after termination with I & J roller-crimper (red line) and Dawn ZRX roller (green line) for September (left) and October (right) planting date of cereal rye in Kutztown, PA, USA during 2019–2021. Regressions are significant at $\alpha \leq 0.0001$. Data were averaged across three years and four replicate blocks.

October-planted rye was more effectively terminated by the roller-crimpers and had less regrowth than the September planted plots (Fig. 3b). Rye regrowth recorded two and three weeks after roller-crimping did not differ between fall planting dates, but was affected by the method of roller-crimping (Table 2). Rye regrowth was significantly less with the DRC for both September and October planting dates, compared to the IJRC (Fig. 3b). Rye regrowth after IJRC followed negative linear relationships with the cover crop biomass at termination for both planting dates, while the DRC followed negative non-linear relationships (Fig. 4, $P < 0.001$). The rye regrowth in DRC treatment was more dependent on the cereal rye biomass, whereas the IJRC was less dependent as visualized by greater correlation coefficients ($\sqrt{R^2}$) between cover crop biomass and rye regrowth (Fig. 4).

Weed biomass

Weed biomass was not impacted by year × planting date × termination interactions except for between-row broadleaf biomass (Table 2). Neither planting date nor termination method and their interaction affected mean weed biomass, when averaged across the years. However, differences existed in grass and broadleaf weed biomass by year for between row and within-row locations (Table 2). Cover crop planting date did not affect broadleaf and total weed biomass across years but did impact within-row grass biomass where the biomass was numerically greater in the October rye planting than in September (Fig. 5a). Averaged across the years, either total within-row and between-row weed biomass or a fraction of it was affected by termination methods (Fig. 5b). Total weed biomass emerged between crop rows was lower in the PC treatment compared to no-till treatments owing to the extremely low broadleaf weed biomass (Fig. 5b). Among no-till treatments, the IJRC was more effective in suppressing grassy weeds between crop rows than the DRC and MT, which was comparable to PC treatment (Fig. 5b). In contrast, total weed biomass measured within crops row was substantially greater at PC treatment than no-till treatments, contributed mostly by grassy weeds. The no-till treatments reduced grassy weeds within crop rows compared to PC, whereas IJRC significantly reduced the broadleaf weeds as well. Numerically, IJRC tended to suppress total weed biomass as compared to PC and other no-till treatments.

There was a termination method × planting date interaction for broadleaf and total weeds emerged between the crop rows, which was driven mostly by differences within the termination methods (Table 2). The rolling-crimping treatments (IJRC and DRC) had greater total weed biomass with the October planting date (221 and 293 g m^{-2}, respectively) than the September planting date (97 and 197 g m^{-2}, respectively), but PC and MT had total weed biomass similar between the planting dates (211 and 228 g m^{-2} for September planting and 184 and 228 g m^{-2} for October planting, respectively). This may be attributed to relatively greater cereal rye biomass produced in September-planted treatments than in October-planted treatments. However, neither rye biomass nor regrowth explained variability in weed biomass when averaged across treatments and study years ($R^2 = 0.03$ and 0.09, respectively). Overall, the IJRC among termination methods and September-planted rye treatment were associated with reduced weed pressure within and between the crop rows by effectively reducing broadleaves and grasses.

Soybean stand density, biomass, and yield

Soybean stand density was greater in 2019 (320,439 plants ha^{-1}) than in 2020 (187,620 plants ha^{-1}) and 2021 (274,235 plants ha^{-1}) ($P < 0.001$). Cover crop planting date did not affect soybean stand density in either of the three years, nor was there a planting date × termination method interaction effect within year (Table 3). Cover crop termination methods influenced stand density in each year and the effect varied over three years with cover crop planting date, which explains the year × planting date × termination methods interaction (Table 2). Soybean stand density was consistently greater in the IJRC treatment with September-planted rye, compared to the MT treatments and DRC treatment with October-planted rye in all three years, greater than the PC with October-planted rye and DRC treatments in 2020, and greater than PC with September-planted rye and DRC treatments in 2021 (Table 3). The MT and DRC treatment with October-planted rye exhibited poor crop emergence throughout the study period.

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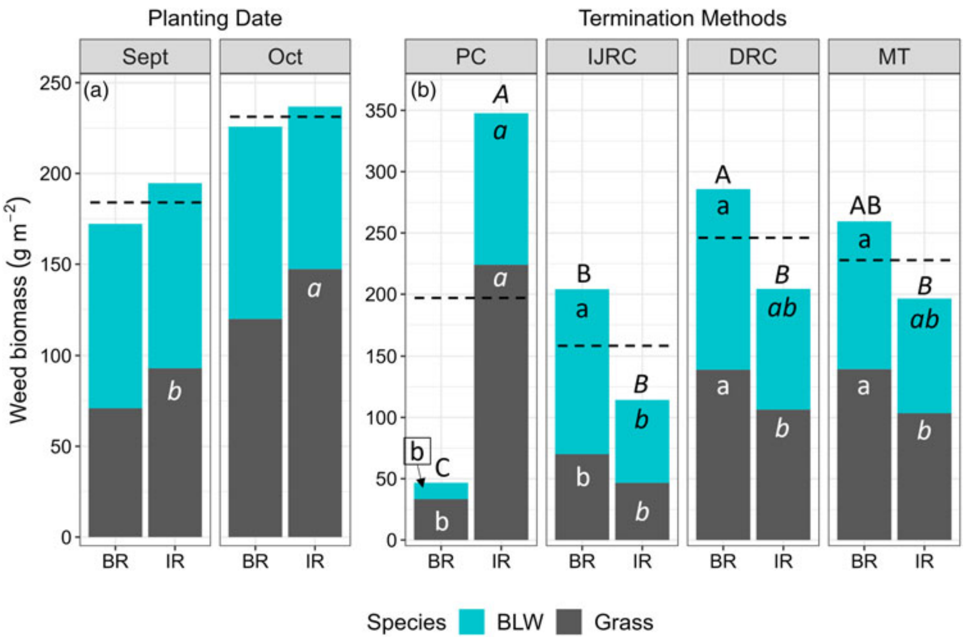

Figure 5. Broadleaf and grass biomass collected between soybean rows (BR) and on the rows (IR) from 2019 to 2021 as influenced by (a) cereal rye planting date and (b) cover crop termination methods (PC, plow-cultivate; IJRC, I&J roller crimper; DRC, Dawn roller crimper; MT, mow & ted) in Kutztown, PA, USA. Broadleaf and grass biomass means separated by common lowercase letters and total weed biomass means separated by common uppercase letters within BR and IR are not different at $\alpha = 0.05$. For IR, letters are in *italics*. Horizontal dashed lines represent the average weed biomass between BR and IR. Data were averaged across four termination methods, three years, and four replicate blocks for pane 'a'; and two planting dates, three years, and four replicate blocks for pane 'b'.

Table 3. Soybean plant density, dry matter yield, and seed yield, measured in rotation with cereal rye cover crop planted in September and October 2019, 2020, and 2021 and terminated with non-chemical strategies in Kutztown, PA, USA

		2019			2020			2021		
PD	M	Plant density (×100)	Dry matter yield*	Seed yield	Plant density (×100)	Dry matter yield	Seed yield	Plant density (×100)	Dry matter yield	Seed yield
		No. ha^{-1}	kg ha^{-1}		No. ha^{-1}	kg ha^{-1}		No. ha^{-1}	kg ha^{-1}	
Sept	PC	3709 a§	5738 a	3526 a	2325 abc	3491 c	2358 c	2848 b	3370 de	2191 de
	IJRC	3247 ab	3639 b	2086 b	2687 a	5389 ab	3529 ab	4178 a	5826 a	3682 a
	DRC	3231 ab	3506 b	2072 b	1944 cd	5833 a	3802 a	1007 c	2321 e	1424 e
	MT	2590 c	3283 b	1977 b	694 e	3942 bc	2654 bc	2558 b	4191 bcd	2317 cde
	Mean	3194	4042	2098	1912	4664	2395A‡	2648	3927	1995
Oct	PC	3492 ab	5432 a	3408 a	2080 bcd	1123 d	761 d	3637 a	3781 cde	2603 bcd
	IJRC	3418 ab	3195 b	1941 b	2529 ab	4467 abc	2961 abc	4005 a	5207 abc	3283 abc
	DRC	3002 bc	2603 b	1632 b	1625 d	3734 c	2395 c	1056 c	2684 de	1737 de
	MT	2945 bc	2369 b	1485 b	1126 e	3646 c	2391 c	2650 b	5698 ab	3438 ab
	Mean	3214	3400	1741	1840	3243	1731B	2837	4342	2339
PD × M		0.396	0.876	0.889	0.132	0.210	0.221	0.178	0.258	0.225

PD, planting date; M, termination method; PC, plow and cultivate; IJRC, I & J roller-crimping; DRC, Dawn ZRX roller-crimping; and MT, mowing and tedding.
*dry matter yield with grain. § Treatment means followed by lowercase letters, and ‡ Planting date means followed by uppercase letters within columns are significant at $\alpha = 0.05$ level. Data were averaged across four replicate blocks within each year.

In each year, cover crop planting date did not affect aboveground soybean biomass nor was there a planting date × termination method interaction within each year (Table 3). However, soybean biomass was variably affected by termination methods over the years and cover crop planting date as explained by the year × rye planting date × termination method interaction

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Table 4. Total costs and net revenue of organic soybean production as influenced by rye cover crop planting date and termination methods from 2019 to 2021 in Kutztown, PA, USA

		Total cost			Net revenue		
Planting date (PD)	Termination method (M)	2019	2020	2021	2019	2020	2021
		US \$ ha^{-1}					
Sept	PC	1041 a§	1091 a	1136 a	919 a	455 bc	1215 de
	IJRC	916 cd	903 c	964 c	450 b	942 ab	1982 ab
	DRC	921 c	908 c	964 c	436 b	1208 a	564 f
	MT	954 b	938 b	1001 b	341 b	385 c	1485 cd
	Mean	958	960	1016A‡	536	748A	1312B
Oct	PC	1044 a	1086 a	1132 a	603 b	−586 d	1662 bc
	IJRC	914 d	905 c	967 c	358 b	394 c	2103 a
	DRC	917 cd	909 c	959 c	151 c	661 b	904 e
	MT	954 b	940 b	996 b	18 d	628 b	2192 a
	Mean	957	960	1013B	282	274B	1715A
PD × M		0.390	0.619	0.151	0.895	0.237	0.303

PC, plow and cultivate; IJRC, I & J roller-crimping; DRC, Dawn ZRX roller-crimping; and MT, mowing and tedding.
§ Treatment means followed by lowercase letters, and ‡ Planting date means followed by uppercase letters within columns are significant at $\alpha = 0.05$ level.
Data were averaged across four replicate blocks within each year.

(Table 2). The PC treatment yielded the greatest soybean dry matter in 2019 (Table 3). Rolling-crimping September-planted rye (IJRC and DRC treatments) yielded more aboveground biomass than the PC and MT treatments in 2020, while IJRC and MT with October-planted rye yielded more biomass than PC and DRC in 2021 (Table 3). The IJRC treatment had greater dry matter yield than the DRC and MT treatments ($P = 0.016$) when averaged across years and planting dates. The DRC and MT treatments had inconsistent results over the three years.

While soybean grain yield did not differ between years, variation existed between cover crop planting dates and termination methods (Table 3). The yield differences between the two planting dates did not show a clear pattern. In two of the three years, yields were greater in the September cover crop planting date, but this difference was only significant in 2020. Termination method affected grain yield variably over the years and cover crop planting dates, depicted by year × rye planting date × termination method interaction (Table 2). In 2019, grain yield in the PC treatment was 48% greater than the no-till treatments, attributable to superior stand density and dry-matter biomass (Table 3). In contrast, the no-till treatments (IJRC, DRC, and MT) produced 58% more grain than the PC treatment in 2020, especially DRC with September-planted rye and IJRC regardless of the rye planting date. In 2021, IJRC produced grain more than PC and DRC treatments, while MT had inconsistent results between planting dates. Reduced yield in the DRC treatment eliminated the overall differences between the tillage and no-tillage treatments in 2021.

Economic returns

The total cost of organic soybean production varied across the years (Table 4). Greater cropland cash rental rates and fuel costs substantially increased the total cost of production in 2021, compared to previous years. Cover crop termination methods affected total costs (Table 4). As expected, the PC treatment accrued greater costs due to increased fuel use, relative to no-till treatments, in all three years. The DRC and IJRC treatments were more economical no-till strategies for cover crop termination throughout the study while the MT treatment was intermediate between PC and roller-crimping treatments.

Organic soybean net revenue varied across the years (Table 4). The revenue increase in 2021 over 2019 and 2020 reflects an increase in soybean prices from US \$19.40 to US \$31.80 per bushel (1 bushel = 27.22 kg). Net revenue differed in plots where rye was planted in September *vs* October in the latter two years (Table 4). With cover crop termination methods significantly impacting soybean grain yield, variably over the years, the PC treatment generated the highest net revenue in 2019, 1.6 times greater than the no-till strategies (US \$292 ha^{-1}), because of the highest net return from PC with September-planted rye. In the latter two years, however, September-planted rye terminated with the IJRC provided greater yields and revenue relative to the PC treatment. Soybeans in the DRC tended to generate more revenue than PC and other no-till treatments in 2020, but performed poorly in 2021 (Table 4). There was a net loss in 2020 of US \$586 ha^{-1} in the PC treatment plots where the rye was planted in October, resulting in an average net loss of US \$66 that year (Table 4). Averaged across years and cover crop planting dates, net revenue generated by the no-till termination treatments (average of DRC, IJRC, and MT) was 19% more than the PC treatment. No-till methods not only reduced the total cost of production by 14% compared to the PC treatment, but also provided competitive gross revenue, attributed to the comparable grain yield.

Discussion

Cover crop biomass and regrowth

Previous studies demonstrated the importance of maximizing cover crop biomass greater than 8 Mg ha^{-1} to achieve acceptable weed management in no-till system (Teasdale and Mohler, 2000; Ashford and Reeves, 2003; Mohler and Teasdale, 1993). One strategy to increase the biomass of winter annual cover crops is by planting in early fall (Teasdale et al., 2004; Mirsky et al., 2011). This threshold of greater than 8 Mg ha^{-1} biomass was only achieved in Years 2 and 3 of the experiment (Fig. 3a), which was greater than the average cover crop biomass of 6.77 Mg ha^{-1} ($N = 21$) recorded by USDA-ARS, Beltsville, MD, USA; Pennsylvania State University, State College, PA, USA; and Rodale Institute, Kutztown, PA, USA during 2008–2010 period in the mid-Atlantic region (Mirsky et al., 2012). Relatively poor soil fertility may have negatively affected cover crop growth in Year 1. In addition to soil differences, red clover broadcast into the preceding oat crop in the spring of 2019 and 2020 but not in 2018 may have provided additional nitrogen to the rye cover crop planted in the fall and contributed to increased rye biomass prior to planting soybeans in 2020 and 2021. The annual variation in rye biomass could also be attributed to edaphic and weather conditions driven by rainfall (Fig. 1). In 2018, September was wetter than October; the trend was reversed in 2019, potentially impacting cereal rye growth. The relatively greater amount of rye biomass produced in the September-planted treatment compared to the October planted treatment suggests that early planting of cereal rye may help achieve desirable cover crop biomass and surface residue levels in the spring for better weed suppression in no-till organic soybean.

Differences in rye regrowth between planting date treatments (Fig. 3b) may be attributed to structural properties of rye. The accumulation of lignin and thickening of cell walls in plant tissue (dry matter density) differing between two planting dates could have an impact on plant biomechanics (Shah, Reynolds, and Ramage, 2017). Less rye regrowth observed in the October planting could be attributed to an increased occurrence of softer stem tissues, which crimp more readily than lignified stem tissues. Fournier et al. (2013) reported a positive correlation between plant dry matter density and stiffness and strength of plants to tolerate mechanical stress, indicating a linkage between dry biomass quality and susceptibility of cover crops to mechanical termination (Nord et al., 2012).

Weight and engineering styles with varied flexural bending and axial loading of roller-crimpers can impact pressure exerted by blunt roller blades on the cover crop stem. A few design differences, such as the individual crimper drums of the DRC (Fig. 2), may explain differences in the rye regrowth. The presence of cereal rye tillers, following roller-crimping, has been a concern for growers, as the plants can impact the residue mulch and desiccation period (Kornecki, 2020). Desiccation delay can deplete soil moisture in the topsoil profile thereby negatively influencing soybean emergence and growth. Given that planting date affects rye regrowth, selection of appropriate equipment for termination is crucial.

Weed biomass

Broadleaf weeds, mostly *Rumex* spp., *Taraxacum officinale*, *Plantago major*, *Ambrosia artemisiifolia,* and *Convolvulus arvensis*, dominated the weed flora during early summer. Grasses, mainly giant foxtail (*Setaria faberi*) dominated the late summer flora. Total weed biomass was not affected by factors that influenced cover crop biomass (such as fall planting date) but by factors that influenced cover crop termination. Grasses within the crop rows were impacted by cereal rye planting date (Fig. 5a), attributed to the difference in cereal rye biomass produced (Fig. 3a). Mennalled et al. (2022) suggested that spring mulching affects early emergence of weeds, mostly annuals and grasses, primarily by physical interference (Teasdale and Mohler, 2000). The lack of planting date effect on broadleaf weeds may stem from the fact that perennial weeds sampled in this study, such as *Trifolium* spp. and *Calystegia sepium,* could emerge from vegetative structures with high amounts of stored resources (Mennalled et al., 2022). Broadleaf perennials such as *Taraxacum officinale* and *Asclepias syrica* were the species susceptible to mulch suppression, but the effect was not significant to have altered the community structure.

Termination methods altered weed species composition within and between the crop rows (Fig. 5b), possibly due to interaction with differing weed emergence phenology and trait dispersion (Mennalled et al., 2022; Ryan et al., 2010). Differences in grass and broadleaf assembly may be explained by weed seed placement in the soil layers as well as the availability of niche opportunities such as soil moisture and nutrients as driven by the degree of soil disturbances (Hernandez Plaza, Navarrete, and Gonzalez-Andújar, 2015). Armengot et al. (2016) and Hernandez Plaza, Navarrete, and Gonzalez-Andújar (2015) indicated that reducing tillage can lower weed seed weight and increase seed output, while also increasing decay and depredation. Soil inversion and multiple weeding operations in the PC treatment may have minimized between-row weeds while boosting within-row-protected weeds, especially grasses. This was due to the fact that secondary tillage operations are limited to eliminating the flush of post-primary tillage weeds between crop rows and leaving in-row weeds untouched (Boyd, Brennan, and Fennimore, 2006).

Mowing rye (MT) led to poor crop establishment (Table 3) and severe weed pressure within rows compared to the plow-cultivate and roller-crimper treatments (Fig. 5b). Although mowing can effectively kill the cover crop, residue cover may not be uniform (Kornecki and Kichler, 2022), which leaves bare soil where weeds emerge. Abu-Dieyeh and Watson (2005) reported a significant increase in the density of *Plantago major* and *P. lanceolata* after mowing at 3-5 cm height in a turf grass system, which was also observed in our study as these species have a low growing point and are well adapted to mowing. In addition, mowed rye residue decomposes faster than the intact stem of roller-crimped residue (Collier, 2017), affecting season-long weed suppression.

Under no-till-based termination methods, most emerged weeds are likely recruited from the seedbank at the soil surface, which is dominated by many small seeds (Armengot et al., 2016; Gruber and Claupein, 2009). This may increase weed abundance if the cover crop residue on the soil surface is not of sufficient depth. Uniform surface mulch and limited rye regrowth after roller-crimping may suppress weed emergence. However, our results showed that rye regrowth explained only 9% of the variability in weed biomass. Although the DRC treatment had the lowest rye regrowth rate, it had significantly greater weed biomass between the rows, compared to the IJRC treatment. Soybean planting in the DRC treatment was delayed by a week in Year 3 (Table 1), potentially providing a competitive advantage for weeds. Other research in Iowa, USA showed a trend towards greater weed populations with DRC *vs* IJRC in organic no-till systems (Delate et al., 2023). Weed suppression achieved with roller-crimping methods was comparable to PC treatment, but inconsistent results for DRC suggest that additional research comparing roller-crimper types is needed to further elucidate factors affecting crop-weed competition in organic no-till systems.

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Crop density, biomass, yield, and economic profitability

Soybean stand density was confounded by the effect of surface residue, weed pressure, and the presence or absence of tillage. Ease of seed placement and seeding depth, along with friable soil in the PC treatment likely supported soybean emergence and establishment. Soybean density in the IJRC treatment was comparable to the PC treatment, which can be explained by the difference in within-row weed pressure (Fig. 5b). Nevertheless, only a 15% variation in soybean density was explained by total weed biomass. Delayed soybean planting in DRC in 2021 was associated with poor seedling establishment and reduced biomass and grain yield.

Soybean yield mirrored aboveground soybean biomass production ($r = 0.98$), as the grain formation in soybean is positively associated with dry matter accumulation (Monzon et al., 2021). Organic soybean yields in this study were lower than the average conventional soybean yields of 2.24 Mg ha^{-1} ($N = 22$) for the mid-Atlantic region from 2008 to 2010 (Mirsky et al., 2012), and less than the highly competitive organic soybean yield obtained by Delate et al. (2013) in Iowa at 3.2 Mg ha^{-1}. Although reduced yields may be the result of inadequate cover crop biomass to manage weed populations, we did not observe a strong relationship between weed biomass and grain yield, as the total weed biomass explained only 25% variations in grain yield, less than the observations made by Ferrero et al. (2017, $R^2 = 0.96$) and Kaur, Kaur, and Bhullar (2019, $R^2 = 0.97$). This suggests that cover crop management mediated by tillage system impacted grain yield in a variety of ways including the manipulation of weed competition and soil environment. Attributes such as diminished weed height and a lower affinity for soil nutrients can make otherwise similar weeds less competitive under reduced tillage systems compared to tilled systems (Armengot et al., 2016). This explains why even the MT treatment performed relatively better than the PC treatment in the latter two years despite having significant weed infestations.

Soybean density had no impact on dry matter and grain yield, confirming that in-season weed pressure mainly determines yield responses. Soltani et al. (2017) estimated that, on a global basis, 52.1% of soybean yield loss was caused by weed competition when not controlled. Yield response to cover crop planting date was inconsistent, although the September planting date tended to have a greater yield than the October planting date. Weed competition driven by surface residue levels, as influenced by cover crop planting date, may account for most yield differences in no-till systems. The other factors could be weather patterns, weed species composition, and existing weed seedbank (Harker and O'Donovan, 2013; Armengot et al., 2016).

Of the no-till termination treatments examined in this study, soybean yields in the IJRC treatment, at 2.2 Mg ha^{-1} (Table 3), were the most competitive. Yields in the IJRC and MT treatments showed relatively greater yield stability (Coef. Variation = 0.16 and 0.21, respectively) compared to the PC and DRC treatments (Coef. Variation = 0.27 and 0.31, respectively). Broadleaf weed infestation in the PC treatment was severe in 2020, resulting in poor yield.

Economic profitability was driven by the total cost of production, grain yield, and premium prices for organic soybeans. The net revenue from no-till cover crop management strategies in this study suggests that organic grain growers can afford to reduce tillage operations and increase profits. The IJRC was economically superior to other cover crop termination strategies because it generated a greater net revenue when averaged across the years (US \$1038 ha^{-1}) compared to the PC, DRC, and MT treatments, which might provide more confidence in adapting the technology for the transitioning organic growers (Delbridge et al., 2017). Increased fuel costs increased the production cost for PC, reducing net economic return. Although organic production may be viewed as a system with greater risks than conventional farming, this study strengthened the prospect for successful cover crop-based organic no-till soybean production, which coincides with findings by Delate et al. (2013) and Cavigelli et al. (2009).

Conclusions

Results supported our hypothesis that the choice of termination strategy is critical for weed suppression in organic no-till production in order to maximize profitability. Although this study showed an advantage from planting cereal rye in September over October for greater cover crop biomass (∼11%), rye planting date did not impact weed suppression, soybean yield, or economic returns. Roller-crimping methods influenced cover crop regrowth, with the DRC consistently outperforming the IJRC in effectively terminating the rye. Nevertheless, rye regrowth had no relationship with weed pressure or crop yield. The DRC effect was inconclusive due to confounding effects of a late soybean planting in Year 3, although the initial two years showed promising results of weed suppression and crop yield with DRC. Mowing and tedding cover crop residue was associated with within-row weed proliferation due to gaps between cut rye plants. Tillage operations for cover crop termination and between-row cultivation were found to exacerbate within-row weed proliferation. The greater weed suppression potential of IJRC resulted in increased grain yield and organic soybean profitability compared to PC and MT. The elimination of tillage in the no-till termination treatments maximized economic returns by minimizing variable costs of production over the PC treatment. We conclude that roller-crimping a cereal rye cover crop planted before late October optimizes mid-Atlantic no-till organic soybean production and provides a greater maximum net return than tilled treatments.

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Competing interests. None.

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