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Abbreviations:
NT: no-till; plt: plants; RELARC: Russell E. Larson Agricultural Research Center; V5-V7: vegetative growth stages for corn; WAP: weeks after planting

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Agronomic and economic tradeoffs between alternative cover crop and organic soybean sequences

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Abstract

Organic grain producers are interested in reducing tillage to conserve soil and decrease labor and fuel costs. We examined agronomic and economic tradeoffs associated with alternative strategies for reducing tillage frequency and intensity in a cover crop–soybean (*Glycine max* L. Merr.) sequence within a corn (*Zea mays* L.)–soybean–spelt (*Triticum spelta* L.) organic cropping system experiment in Pennsylvania. Tillage-based soybean production preceded by a cover crop mixture of annual ryegrass (*Lolium perenne L. ssp. multiflorum*), orchardgrass (*Dactylis glomerata* L.) and forage radish (*Raphanus sativus* L.) interseeded into corn grain (*Z. mays* L.) was compared with reduced-tillage soybean production preceded by roller-crimped cereal rye (*Secale cereale* L.) that was sown after corn silage. Total aboveground weed biomass did not differ between soybean production strategies. Each strategy, however, was characterized by high inter-annual variability in weed abundance. Tillage-based soybean production marginally increased grain yield by 0.28 Mg ha^{-1} compared with reduced-tillage soybean. A path model of soybean yield indicated that soybean stand establishment and weed biomass were primary drivers of yield, but soybean production strategy had a measurable effect on yields due to factors other than within-season weed–crop competition. Cumulative tillage frequency and intensity were quantified for each cover crop—sequence using the Soil Tillage Intensity Rating (STIR) index. The reduced-tillage soybean sequence resulted in 50% less soil disturbance compared to tillage-based soybean sequence across study years. Finally, enterprise budget comparisons showed that the reduced-tillage soybean sequence resulted in lower input costs than the tillage-based soybean sequence but was approximately \$114 ha^{-1} less profitable because of lower average yields.

Sustainable intensification of organic agriculture is critically important in the USA given the increasing demand for domestic sources of organic feed grains. Organic grain production has historically relied on frequent and intensive tillage to prepare seedbeds, incorporate nutrient amendments and regulate pest cycles, but reduced-tillage practices could prevent soil erosion, improve soil quality and enhance the long-term sustainability of organic cropping systems (Carr, 2017). Reducing the intensity and frequency of tillage within organic rotations can also lead to additional economic and environmental benefits, including decreased labor demand, fuel inputs and greenhouse gas emissions (Mirsky *et al*., 2012). However, recent studies suggest that reducing tillage intensity via the use of chisel-plowing can increase weed incidence by 50% compared to inversion-tillage (Cooper *et al*., 2016) and can produce tradeoffs between physical, biotic and chemical soil properties (Peigné *et al*., 2018). Understanding how reduced-tillage practices influence tradeoffs among agronomic, economic and environmental goals would benefit organic grain production systems.

Integration of reduced-tillage practices in organic systems may require greater utilization of cover crops and other cultural practices to provide pest- and nutrient-regulation services previously delivered by tillage-based tactics. Development of reduced-tillage practices for organic soybean (*Glycine max* L. Merr.) production has primarily focused on no-till planting soybean into a weed-suppressive cereal rye (*Secale cereale* L.) mulch that is terminated using a roller-crimper (Mirsky *et al*., 2012; Reberg-Horton *et al*., 2012; Wallace *et al*., 2017). High interannual yield variability has been observed and attributed to reduced soybean stands that result from cover crop residue interference at planting and dry soil conditions before planting in some years (Crowley *et al*., 2018). High interannual variability in weed abundance has also been observed and attributed to interactions between the efficacy of weed control tactics, weather conditions and weed seedbank abundance and composition (Nord *et al*., 2012).

Evaluation of organic, no-till soybean production within the context of a rotation has identified some additional agronomic challenges. Cereal rye establishment following late fall grain crop harvest can limit cover crop performance due to cold weather and frost, resulting in reduced spring growth, potential nutrient loss and increased potential for early season weed competition (Mirsky *et al.*, 2009). Many farmers in the northern Mid-Atlantic cannot successfully establish fall cover crops after corn (*Zea mays* L.) grain harvest due to the limited growing season window, which reduces the likelihood of producing cereal rye biomass levels in the spring sufficient for organic, no-till soybean production (Mirsky *et al.*, 2009; Keene *et al.*, 2017).

Interseeding cover crops into a standing corn crop early in the growing season (i.e., relay intercropping; Brooker *et al.*, 2014) is becoming a viable alternative to post-harvest cover crop establishment. In northern latitudes, interseeding cover crops into standing corn gives the option to harvest grain corn without compromising the ability to establish a cover crop before winter (Curran *et al.*, 2018; Noland *et al.*, 2018; Youngerman *et al.*, 2018). Interseeded cover crops can produce agronomic benefits such as reduced soil nitrate leaching potential (Noland *et al.*, 2018). However, the most well-adapted cover crop grass species for interseeding, annual ryegrass (*Lolium perenne L. ssp. multiflorum*), does not produce spring biomass levels of 5000–9000 kg ha^{-1} which has been identified as a sufficient amount for weed suppression in no-till, organic soybean production (Mirsky *et al.*, 2012; Caswell *et al.*, 2019). Additionally, no-till termination of annual ryegrass in organic production systems is problematic (Clark, 2007; Curran *et al.*, 2014). Consequently, interseeding in a corn–soybean transition permits the no-till establishment of cover crops but necessitates the use of tillage in the spring to terminate cover crops and control weeds. In comparison, use of high-residue, cereal rye mulch necessitates fall tillage to control emerged weeds and prepare and level a seedbed for cover crop seeding, but permits the no-till establishment of the cash crop.

Tillage-based organic weed control is labor-intensive, time-sensitive and constrained by soil conditions and weather. Precipitation patterns have been shown to have strong indirect effects on weed abundance in organic grain systems due to direct impacts on crop competitiveness and the efficacy of weed control tactics (Teasdale *et al.*, 2018). Organic farmers have few rescue options in the event that weed control tactics fail due to untimely precipitation events. The effectiveness of these tillage-based weed control tactics is highly dependent on soil moisture conditions and weed growth stage at the time of cultivation (Peigné *et al.*, 2007). When a farmer is unable to successfully cultivate in a timely manner due to weather conditions, subsequent cultivation events will likely be less efficacious due to continued growth and development of the emerged weed community.

One of the proposed benefits of utilizing cover crop mulch in no-till organic crop production for within-season weed suppression is the elimination of frequent cultivation practiced in tillage-based production. However, inter-annual variability in fall and spring environmental conditions (growing degree days, cumulative precipitation) significantly influence cereal rye biomass production (Mirsky *et al.*, 2009), which is positively correlated with weed suppression when biomass levels reach and exceed 5000 kg ha^{-1} (Mohler and Teasdale, 1993; Nord *et al.*, 2012; Keene *et al.*, 2017). To ensure adequate weed control, integration of other cultural and mechanical weed control tactics in addition to using cover crop mulch is sometimes necessary (Mirsky *et al.*, 2013). Utilizing high soybean planting rates (>650,000 seed ha^{-1}) for wide-row (76 cm) soybean management has been shown to hasten canopy closure, decrease weed abundance and increase soybean yield in organically-managed, no-till planted soybean (Liebert and Ryan, 2017). High-residue, inter-row cultivation has also been shown to decrease weed abundance when employed as a supplemental weed control tactic in no-till soybean, and recent experiments suggest that weed control efficacy is optimized by utilizing high-residue cultivation twice, approximately 4 and 5 weeks after planting (Keene and Curran, 2016; Liebert *et al.*, 2017).

In this study, we evaluate the differences in weed suppression, soybean yield and net profitability between alternative cover crop/soybean sequences in three consecutive years in an organic corn–soybean–spelt (*Triticum spelta* L.) rotation in Pennsylvania, including (i) drill-interseeding a cover crop mixture into corn followed by full-tillage organic soybean production (NT/Cc—T/Sb) and (ii) post-harvest seeding cereal rye into a tilled seedbed followed by reduced-tillage soybean production (T/Cr—NT/Sb). We hypothesized that: (1) full- and reduced-till soybean production methods would produce similar weed control levels; (2) soybean yield would not differ between tillage-based and reduced-tillage soybean management; and (3) reduced-tillage soybean production would produce greater net returns due to lower inputs compared to full-tillage soybean production.

Materials and methods

Site description and experimental design

A cropping systems experiment was conducted on certified organic land at the Pennsylvania State University Russell E. Larson Agricultural Research Center (RELARC) near Rock Springs, Pennsylvania (40°43′N, 77°56′W) from 2014 to 2017. The transition to organic production at the experimental site was initiated in 2010, at which time an annual grain crop rotation was implemented. The soil at the site was comprised of Hagerstown silt loam soil (fine, mixed, semiactive, mesic Typic Hapludalfs), with some Opequon-Hagerstown soil (clayey, mixed, active, mesic Lithic Hapludalfs). The site has an average annual high/low temperature of 25/5.1°C, with annual rainfall averaging 1006 mm.

The cropping systems experiment followed a 3-yr rotation of corn–soybean–spelt using a full entry design with cover crops preceding corn and soybean. Four cropping system treatments were imposed using a randomized complete block, split-plot design with four replications. Main plots were the cash crop entry (18 × 96 m) and split-plots (9 × 48 m) were the cropping system treatments, which included alternative cover cropping and tillage practices. In this paper, we report on cover crop/soybean performance metrics within cropping system treatments beginning with cover crop establishment preceding soybean. Two alternative cover crop–soybean sequences were evaluated. The reduced-tillage soybean sequence (T/Cr–NT/Sb) was imposed in two cropping system treatments and the full-tillage soybean sequence (NT/Cc–T/Sb) was evaluated in the other two cropping system treatments. Consequently, data are pooled across plots receiving the same cover crop–soybean treatment sequences ($n = 8$).

Experimental cropping sequences and field operations

In order to provide a comprehensive assessment of cover crop–soybean sequence effects on tillage intensity and frequency, we utilized the Soil Tillage Intensity Rating (STIR) to determine the severity of each field operation on the soil (USDA ARS, 2016). The STIR index is calculated using RUSLE2 (USDA ARS, 2016); factors that contribute to the index include type of field operation, equipment speed, equipment depth and percent of soil area being disturbed. Each field operation occurrence was recorded every year, and the disturbance intensity was calculated by multiplying the number of occurrences for each field operation by that operation's respective STIR index value.

The full-tillage soybean sequence (NT/Cc–T/Sb) was preceded by corn grown for grain and utilized a cover crop mixture that was interseeded at the V5 corn growth stage. The mixture consisted of annual ryegrass 'KB Supreme', orchardgrass (*Dactylis glomerata* L.) 'Potomac' and forage radish (*Raphanus sativus* L.) 'Tillage' with three rows drilled on 19-cm spacing at 11, 11 and 3.4 kg ha^{-1}, respectively, to a depth of 0.63–1.2 cm. This mixture was interseeded to allow cover crop establishment prior to corn grain harvest and was designed to increase N retention in manure-based, organic dairy systems (Finney *et al.*, 2016). Field corn was harvested for grain in late October to early November and the overwintering cover crop mixture was terminated in the spring prior to soybean planting in late May using inversion (moldboard) tillage (Table 1). Secondary tillage was conducted to create a seedbed and soybean was planted on 76-cm row-spacing at 444,600 plt ha^{-1} using a four-row planter (John Deere 7200). Terminating the cover crop via inversion tillage facilitated earlier soybean planting except when wet spring conditions hindered field operations and delayed planting into June (Table 2). After soybean planting, blind cultivation with a spring tine-harrow or a rotary hoe was used to control in-row weeds and a hoeing cultivator was used to control inter-row weeds (Table 1). Cultivation was employed as an adaptive management practice, so the number of cultivation passes differed each year due to differences in environmental conditions and weed severity.

The reduced-tillage soybean sequence (T/Cr–NT/Sb) was preceded by corn grown for silage. Following corn silage harvest in late September to early October, primary and secondary tillage was used to prepare a seedbed (Table 1) and cereal rye ('Aroostook') was no-till drill-seeded (Great Plains 1005NT) on 19-cm row spacing at 134 kg ha^{-1}. Cereal rye was terminated with a roller-crimper the following spring at full anthesis (Zadoks 69), with termination timing ranging from last week of May to first week of June. Based on previous experience (Keene *et al.*, 2017), we employed a double-roll strategy to improve termination efficacy by rolling at anthesis with a 3-m roller-crimper (Kornecki *et al.*, 2006) front-mounted to a tractor and 5–7 days later at soybean planting using a roll-crimping system (ZRX roller-crimper and row cleaners; Dawn Equipment, Sycamore, IL, USA) that was integrated into a four-row no-till planter (John Deere 7200). Soybean were no-till planted on 76-cm row spacing at 555,750 plt ha^{-1}. We used higher seeding rates for no-till planting because previous research has shown that: (1) reduced stand establishment can occur when no-till planting into high-residue, cover crop mulch (Snyder *et al.*, 2016; Keene *et al.*, 2017), and (2) increasing soybean planting rates can be an effective cultural weed management practice due to enhanced weed–crop competition via earlier crop canopy closure (Ryan *et al.*, 2011; Liebert and Ryan, 2017). The double-disk row cleaners on ZRX systems are designed to remove residue from the soybean row to improve seed-to-soil contact and soybean stand establishment. However, the amount of soil and cover crop mulch disturbance that resulted from the use of these row cleaners varied across years and was a function, in part, to soil moisture conditions at the time of planting. High-residue, inter-row cultivation (John Deere 886; Moline, IL, USA) was employed adaptively based on in-season weed competition each year (Table 1). The high-residue cultivator has a single 50-cm wide sweep between each soybean row that runs 2-cm below the soil surface to sever the roots of established weeds, while minimizing residue disturbance. When utilized, high residue cultivation occurred twice about a week apart starting at 4 weeks after soybean planting.

Data collection

Aboveground cover crop biomass was sampled between late October and early November in each year using six randomly placed 0.25 m^2 quadrats in each split-plot. Cover crop biomass was sampled again just prior to cover crop termination using nine randomly placed 0.25 m^2 quadrats per split-plot. Biomass was clipped at the ground level and sorted by species in the laboratory. All plant material was dried for at least 5 days at 65° C and then weighed in the laboratory. Biomass data were averaged across subsamples prior to statistical analyses.

Late season weed biomass was sampled in mid-August using nine randomly placed 0.5 m^2 quadrats per split-plot. Each quadrat was positioned between crop rows in the middle of a planter pass. Quadrats (66 by 76 cm) were constructed to sample the area between crop rows (76 cm) and included a grid to partition inter-row weeds from in-row weeds. The in-row weed grid space included the outside 12.7 cm width on each side, which corresponds to the zone which is not (or less) disturbed by high-residue or hoeing cultivation. The inter-row weed grid space included the inside 51 cm width of the quadrat, which corresponded to the zone targeted by inter-row cultivation. In each quadrat, weeds were collected separately by their location (in-row and inter-row). Weeds were clipped at ground level, separated by species and dried for at least 5 days at 65°C before weighing. Biomass was averaged across subsamples and by location (in-row and inter-row) before statistical analyses. Soybean populations were assessed 6 weeks after planting (WAP) after last cultivation by counting the number of plants in 5.3 m of the row at three random locations within each of the three yield rows per split-plot. Soybean yield data were collected by machine harvesting six rows (middle two rows of each planter pass) from each split-plot using a small plot combine and grain yield was adjusted to 13% moisture.

An enterprise budget analysis was conducted to examine variable costs and net profits between alternative cover crop–soybean sequences. Enterprise budget analysis can be used to estimate an operation's revenue and expenses based on certain practices and is frequently utilized to draw comparisons among alternative management practices. Budgets were calculated for each cropping system using the Mississippi State Budget Generator v6.0 (Laughlin and Spurlock, 2008). Tractor and other implement sizes were based on commercial farm operations in the Mid-Atlantic. Production costs were based on the previous year's input prices. A 6% interest rate for opportunity cost was factored in starting from the date of input use until harvest. Net returns ($ ha^{-1}) were calculated for each system by multiplying mean soybean yields by the expected market price for organic soybean and subtracting total production costs.

Statistical analysis

Linear mixed effects (LME) models were fit to investigate the main effects of cover crop–soybean sequences for each response variable of interest, including: (1) aboveground cover crop biomass (kg ha^{-1}) in the fall and spring; (2) total, in-row and

Table 1. Type and number of field operations each year for alternative cover crop–soybean sequences (NT/Cc–T/Sb, T/Cr–NT/Sb)

Type of field operation	Soil disturbance	NT/Cc–T/Sb			T/Cr–NT/Sb		
Tillage events	STIR index[a]	2015	2016	2017	2015	2016	2017
		---------No. of field operations---------					
Moldboard plow	29	1	1	1	1	1	1
Tandem disk	18	1	1	1	1	1	0
S-tine	11	1	1	4	1	1	1
Cultipack	19	1	1	2	1	1	1
Cultivation events							
Spring tine-harrow	11	0	2	2	–	–	–
Rotary hoe	11	0	0	3	–	–	–
Hoeing cultivator	20	3	4	2	–	–	–
High-residue cultivator	16	–	–	–	2	0	2
Frequency of disturbance[b]		7	10	15	6	4	5
Intensity of disturbance[c]		137	179	224	109	77	91

Each field operation is listed with its respective soil disturbance index. Total frequency and intensity of soil disturbance are calculated for each year, in each crop rotation sequence.

[a] Soil Tillage Intensity Rating (STIR) is derived from RUSLE2 (USDA ARS, 2016). Lower values indicate less soil disturbance. Factors used to determine STIR index values include tillage type, equipment speed, depth of operation and % of soil area disturbed.

[b] Total number of disturbance-based field operations each year.

[c] Calculated by summing STIR values across field operations each year.

Table 2. Date of field operations for alternative cover crop–soybean sequences (NT/Cc–T/Sb, T/Cr–NT/Sb) by soybean production year

Field operation	NT/Cc–T/Sb			T/Cr–NT/Sb		
	2015	2016	2017	2015	2016	2017
	-----------------Date-----------------					
Cover crop seeding	18 Jul	08 Jul	29 Jun	03 Oct	25 Sept	12 Oct
Corn harvest	30 Oct	05 Nov	20 Oct	26 Sept	17 Sept	16 Sept
Spring cover crop termination	14 May	10 May	09 May	01 Jun	20 May	30 May
Soybean planting	04 Jun	19 May	05 Jun	07 Jun	27 May	05 Jun

between-row late-season weed biomass (kg ha^{-1}); (3) soybean population expressed as a proportion of total planted; and (4) soybean yield (Mg. ha^{-1}). Weed biomass response variables did not meet assumptions of normality and mean-variance stabilization was achieved using a natural log transformation. To account for differences among years, a random-effects structure was fitted with block nested within a year (year/block). For each LME model, we calculated the marginal and conditional coefficient of determination (R^2_m and R^2_c, respectively) to describe the proportion of the variance in the response associated with fixed effects only (R^2_m) and random plus fixed-effect components (R^2_c) of the model using the package 'MuMIn' (Nakagawa and Schielzeth, 2013). All LME models were fit with restricted maximum likelihood estimations (REML; Pinheiro *et al*., 2017) using the package 'nlme' (Pinheiro *et al*., 2017) in R.3.2.5 (R Core Team, 2018).

We used piecewise structural equation modeling (Lefcheck, 2016) to assess direct and indirect effects of the alternative cover crop–soybean sequences on soybean yields. The multilevel path model was constructed from three LME models with year as a random effect: (1) soybean population (% of planted) distributed by cropping sequence treatment; (2) weed abundance (kg ha^{-1}) distributed by cropping sequence treatment and soybean population; and (3) soybean yield (Mg. ha^{-1}) distributed by soybean population, weed abundance and cropping sequence treatment. The inclusion and directionality of variables were based on *a priori* hypotheses generated from previous research. We expected that variation in soybean yield could be explained by within-season vegetation (weed–crop) dynamics, and thus, differences in cropping sequence treatment effects on soybean yield would be mediated through effects on soybean population and weed abundance. Preliminary analysis of component models showed significant main effect terms but no significant interactions. Therefore, a reduced model that included only the additive effects was used in the final SEM. The fit of our path model was subjected to a test of directed separation using Fisher's *C* statistic in the piecewiseSEM package (Lefcheck, 2016), which identifies significant relationships among unconnected variables using a significance threshold of $\alpha = 0.05$. Standardized regression coefficients and *P*-values were obtained for paths to determine the significance and directionality of the predictor on response variables. Standardized coefficients enable direct comparisons among paths by expressing relationships between variables as the change in standard deviation units (Grace and Bollen, 2005). Marginal and conditional coefficients of determination were calculated for each component model and the error terms associated with each component model were calculated as $\sqrt{1-R_{\mathrm{m}}^2}$. Finally, semi-partial R^2 values (sr^2) were calculated for each predictor of soybean yields using the 'r2glmm' package (Jaeger, 2016). The semi-partial R^2 statistic reports the proportion of the response variance explained by a given predictor variable that cannot be explained by any other predictor variable in the model (Grace and Bollen, 2005).

Results and discussion

Performance of alternative cover cropping strategies

Interseeding a mixture of annual ryegrass + orchardgrass + forage radish in grain corn prior to tillage-based soybean production resulted in an average 417 kg ha^{-1} ($F_{1,35} = 33.7$, $P < 0.001$) total aboveground cover crop biomass production in late-fall compared to 115 kg ha^{-1} of the post-harvest establishment of cereal rye prior to no-till planted soybean. Examination of variance components showed that the cover cropping strategy contributed 26% of the total variation observed in aboveground cover crop biomass in late-fall, whereas the temporal (year) and spatial (block) factors contributed 36% of the total observed variation (Fig. 1a). Mean interseeded cover crop biomass ranged from approximately 100 to 750 kg ha^{-1} across experimental years. Similar levels of fall biomass and interannual variability of interseeded cover crops has been observed in recent on-farm trials across the Mid-Atlantic region (Curran *et al.*, 2018). Mean cereal rye biomass production ranged from approximately 25 to 250 kg ha^{-1} in late fall across years. Variation in cereal rye biomass between years can be attributed, in part, to cereal rye seeding dates, which ranged from September 25 to October 12 (Table 2) across experimental years and reflects the interannual variability that results from differences in corn silage maturity and the execution of primary and secondary tillage in variable fall weather conditions prior to cover crop seeding.

Post-harvest establishment of cereal rye and delayed termination prior to reduced-tillage soybean production resulted in an average of 6088 kg ha^{-1} ($F_{1,35} = 255.0$, $P < 0.001$) biomass prior to termination compared to 1269 kg ha^{-1} of the interseeded mixture preceding tillage-based soybean production. This difference was not unexpected, given that cereal rye was managed for optimal biomass production preceding soybean planting, including a 10–15 days delay in spring termination. Cereal rye spring biomass production ranged from 4700 to 8200 kg ha^{-1} across experimental years (Fig. 1b) and was consistent with previous research in the Mid-Atlantic region, which has shown that 5000–9000 kg ha^{-1} of biomass can be produced depending on seeding date, soil fertility and termination date (Mirsky *et al.*, 2012; Nord *et al.*, 2012; Ryan *et al.*, 2011). Mean interseeded cover crop biomass in spring ranged from approximately 500 to 1800 kg ha^{-1} across years. Spring biomass potential of interseeded cover crops has been shown to be positively correlated with fall biomass production (Curran *et al.*, 2018), though the functional traits of cover crops (winter-kill *vs* winter hardy species) included in interseeded mixtures will influence spring biomass potential. In our experiment, forage radish, whose large taproot can aid in soil aeration and water infiltration but winter-kills, ranged from 0 to 90% of total cover crop fall biomass across years at the plot level, and averaged 52.6% of total biomass across years.

Total biomass production from fall-sown cover crops has been shown to be positively correlated to several ecosystem services, including weed suppression, prevention of nitrate leaching and aboveground biomass N (Finney *et al.*, 2016). However, we refrain from drawing inferences regarding the magnitude of ecosystem services between post-harvest and interseeding cover crop management practices because total biomass production does not likely account for other important agroecological and economic tradeoffs in the corn–soybean transition that are influenced by the frequency and intensity of tillage in the management of cover crops, such as soil erosion potential, nutrient cycling dynamics, conservation of beneficial arthropods and labor inputs.

Performance of alternative soybean production strategies

Alternative soybean production strategies did not affect soybean stand establishment ($F_{1,35} = 0.42$, $P > 0.05$; expressed as the % of total planted), total late-season weed biomass ($F_{1,35} = 1.68$, $P = 0.20$) and had a marginal effect on soybean yield ($F_{1,35} = 4.02$, $P = 0.053$) across experimental years. Large between-year variation in response variables of interest was observed in each cropping sequence (Fig. 2). Random effects, including experimental year (temporal) and block (spatial) factors, contributed 64, 36 and 40% of the total variation observed in soybean populations, total weed biomass and soybean yield, respectively.

Mean soybean yield in tillage-based soybean was 0.28 Mg. ha^{-1} greater than reduced-tillage soybean yields, which averaged 2.58 Mg. ha^{-1} across experimental years. Each soybean production strategy resulted in final soybean population stands that averaged approximately 70% of the soybean planting rate. We note, however, that planting rates differed between soybean production strategies, as outlined in the field operations methods.

Mean total weed biomass was approximately 300 and 450 kg ha^{-1} in tillage-based and reduced-tillage soybean, respectively, across experimental years and did not differ between soybean systems. However, production strategies had a significant effect on weed biomass by location. Mean between-row weed biomass did not differ ($F_{1,35} = 0.07$, $P = 0.77$) between soybean production strategies across experimental years, but mean in-row weed biomass was greater ($F_{1,35} = 17.0$, $P < 0.001$) in tillage-based compared to reduced-tillage soybean (Fig. 3). Between-year variation in in-row weed abundance can be attributed in part to environmental conditions that influence cultivation efficacy and management legacies. In 2016, a wet period following planting prevented timely blind cultivation events in full-tillage soybean, resulting in significant in-row weed abundance. In comparison, high levels of in-row weed recruitment occurred in reduced-tillage soybean in the 2017 growing season. High weed seed rain in the previous corn crop, resulting from poor weed control due to weather conditions, likely contributed to comparatively greater weed recruitment in the 2017 growing season compared to 2016.

We used a path model to parse out the effects of soybean production strategy, weed biomass and soybean populations on soybean yield. The path model allows for the assessment of our hypothesis that in-season vegetative dynamics (crop–weed interactions) are primary drivers of soybean yield differences between soybean production strategies. In the fitted path model (Fisher's $C = 1.07$; $P = 0.58$; df = 2), soybean production strategy, soybean establishment (% of total) and total weed biomass had a direct effect on soybean yield and soybean population had an additional indirect effect on soybean yield that was mediated by an effect on weed biomass (Fig. 4). The additive effects of soybean production strategy, soybean population and weed biomass explained 59% of the total observed variation in soybean yield in our experiment, whereas random effects associated with experimental year explained 27% of the total variation.

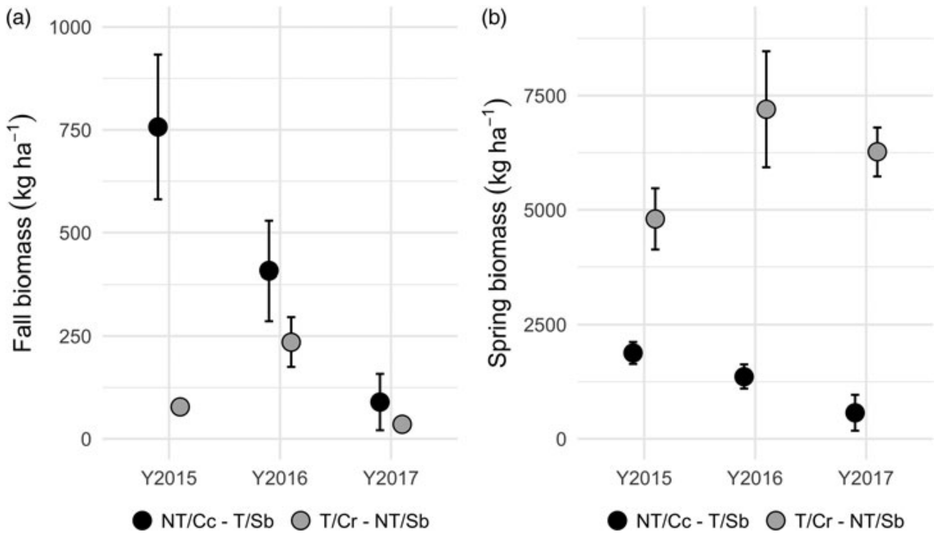

Fig. 1. Mean (a) fall and (b) spring cover crop biomass averaged across replicates ($n = 8$) within experimental years and cover crop strategy, including (1) interseeding a cover crop mixture (annual ryegrass/orchardgrass/tillage radish) into field corn (NT/Cc–T/Sb) that is terminated with primary tillage prior to soybean and (2) post-harvest seeded cereal rye that is terminated at anthesis using the roller-crimper prior to reduced-tillage soybean (T/Cr–NT/Sb). Error bars are 95% confidence intervals.

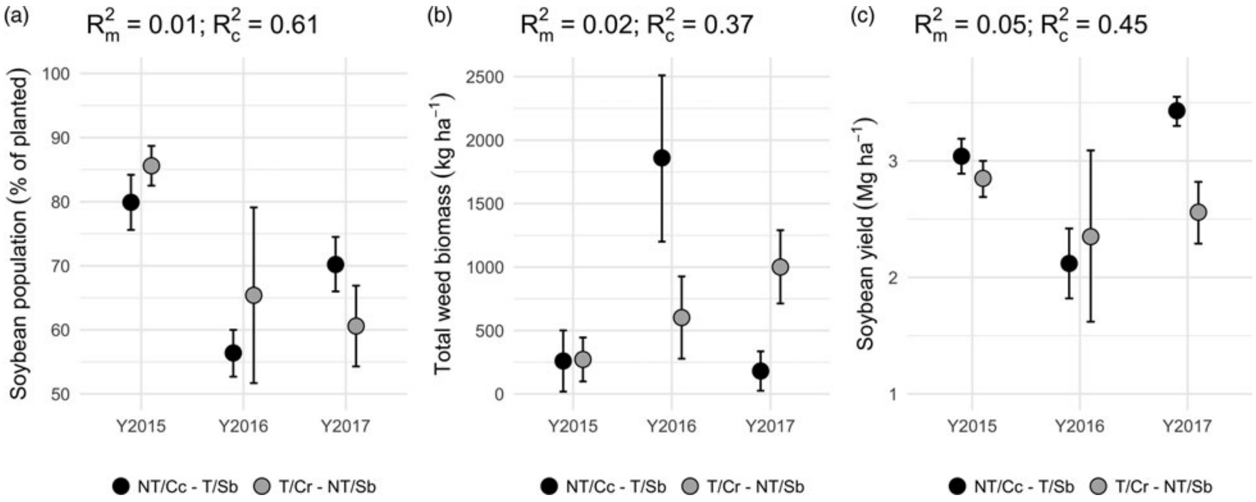

Fig. 2. Mean (a) soybean population, (b) total weed biomass and (c) soybean yield by study year and soybean production strategy, including (1) tillage-based soybean production (NT/Cc–T/Sb) that is preceded by an interseeded cover crop mixture (annual ryegrass/orchardgrass/tillage radish); and (2) reduced-tillage soybean production (T/Cr–NT/Sb) that is preceded by roll-crimped cereal rye that is terminated at anthesis. Error bars are 95% confidence intervals.

We compared semipartial R^2 values (sr^2) between each predictor variable included in the multiple regression model of soybean yield. Soybean population explained 22% of the variance in soybean yields after controlling for the effect of the other two variables, whereas weed biomass and tillage system explained 20 and 15% of the variance in soybean yields, respectively. Partial standardized coefficients for soybean population (0.47), weed biomass (−0.46) and soybean production strategy (−0.31; reduced-tillage) paths in the hypothesized diagram (Fig. 4) provide an alternative, but complementary, assessment of the relative importance of predictors of soybean yield. The partial coefficient represents the expected change in soybean yield associated with a unit change in the predictor after controlling for the covariance effect of other predictors in the model (Grace and Bollen, 2005). The indirect effect of soybean population on soybean yield as mediated by weed biomass is 0.30, which is the product of the direct effect of soybean population on weed biomass (−0.66) and weed biomass on soybean yield (−0.46). Relative to other predictor variables, soybean population had the greatest total effect (direct + indirect = 0.77) on soybean yield in our path diagram. Thus, the path model results partially support our hypothesis, as soybean population and weed biomass interactions were primary drivers of soybean yield. However, soybean production strategy had a measurable direct effect on soybean yield, rather than indirect effects mediated by effects on soybean establishment rates and weed abundance. The presence of a direct effect suggests that reduced-tillage and tillage-based organic soybean production result in different yield-regulating soil-environment (nutrient dynamics, soil temperature, soil moisture) or pest (disease, early-season insect pest) dynamics that may be influenced by in-season factors or cover crop management legacies.

Our results show that tillage-based and reduced-tillage organic soybean production strategies are vulnerable to high inter-annual variability in soybean stand establishment and weed competition, though the conditions that result in yield limiting weed competition and population stands likely differ. We suggest that such conditions are highly context-specific and provide two examples based on observations of the general patterns of variation

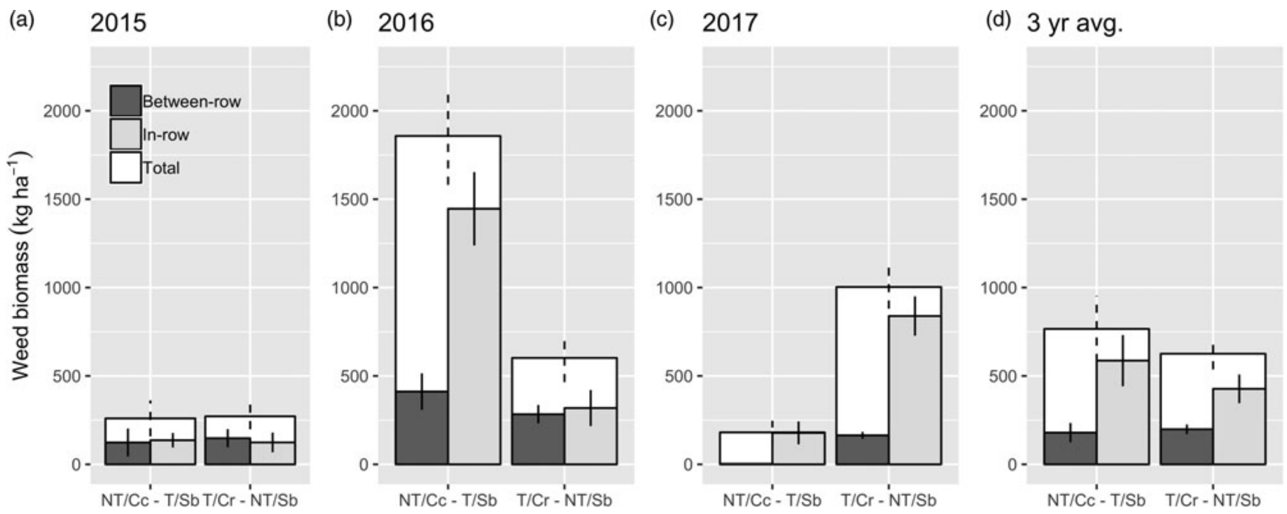

Fig. 3. Mean weed biomass (kg ha^{-1}) by study year (a–c) or averaged across years (d) and cover crop–soybean sequence, including (1) tillage-based soybean production (NT/Cc–T/Sb) that is preceded by an interseeded cover crop mixture (annual ryegrass/orchardgrass/tillage radish); and (2) reduced-tillage soybean production (T/Cr–NT/Sb) that is preceded by roll-crimped cereal rye that is terminated at anthesis. Data (mean ±SE) are presented as total weed biomass and by location (between-row, in-row).

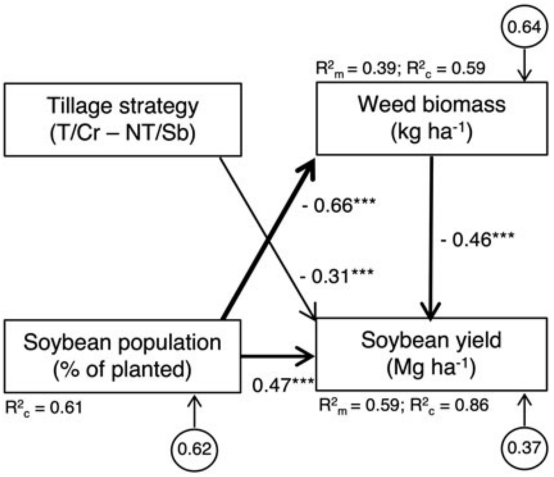

Fig. 4. Path diagram of factors influencing organic soybean yield. Arrows indicate a significant effect of one variable on another. Marginal (R^2_m) and conditional (R^2_c) coefficients of determination are reported for each component model. Path coefficients are standardized and are interpreted as the expected change in standard deviation units of y with an increase of one standard deviation unit of x. Asterisks next to path coefficients denote significance level, where ***$P < 0.001$. Error terms associated with each variable are reported in circles.

among experimental years in our study. In tillage-based soybean, low soybean yields were correlated with low soybean populations and high weed competition in the 2016 growing season. Two factors likely contributed to this result. Seedbed preparation was less uniform than other experimental years due to a comparatively shorter period between cover crop termination and soybean planting, which we speculate led to greater cover crop root biomass at the soil surface, uneven planting depth and reduced stand establishment. Secondly, in-row weed biomass was comparatively greater in the 2016 growing season compared to 2017, which we attribute to precipitation that occurred just after planting, followed by rapid germination and establishment (VE; crook stage) of the soybean crop that prevented blind cultivation at the effective weed life cycle stage (i.e., white-thread). Subsequent attempts ($n = 2$) to control in-row weeds at soybean growth stages known to tolerate blind cultivation (VC–V2 growth stage) were not effective due to the rapid establishment of weeds. Lower soybean yields were also correlated with low soybean populations in reduced-tillage soybean in the 2016 growing season. Lower stand establishment rates compared to other experimental years in the reduced-tillage system can be attributed, in part, to higher observed cereal rye biomass production (>7000 kg ha^{-1}) and the occurrence of lodging prior to roll-crimping in some areas. Weed biomass averaged approximately 600 kg ha^{-1} in 2016, but high levels of cover crop mulch likely prevented significantly higher weed biomass levels in open niche space created by reduced soybean stand establishment.

Our results also demonstrate that interannual variability in weed severity is due to in-row weed control failures (Fig. 3). In tillage-based soybean, the efficacy of in-row weed control with blind cultivation is highly-dependent on soil-moisture conditions and the weed (i.e., white-thread stage) and crop growth stage. In reduced-tillage soybean, in-row weed control is likely a function of the interaction between cereal rye biomass levels (Mirsky *et al*., 2013; Nord *et al*., 2011), soil disturbance created by the row-cleaner configuration at planting and the level of crop competition that results from stand establishment and growth rates. Synthesis of a long-term organic grain crop systems experiment in the Mid-Atlantic has shown that organic soybean production and weed control efficacy can be highly affected by environmental conditions (Teasdale and Cavigelli, 2017).

Enterprise budgets

Differences in variable costs between reduced-tillage and tillage-based soybean production were primarily driven by the frequency of primary- and secondary-tillage and cultivation events, which influence labor, fuel and maintenance costs (Table 3). Labor and fuel costs were generally comparable in 2015 and 2016 between systems, ranging from $92 to $128 per hectare. In 2017, labor and fuel costs were markedly higher in the tillage-based system, which coincided with increased weed abundance requiring additional cultivation operations (Table 1). Cover crop

Table 3. Partial budget analysis for each cover crop–soybean sequence for each growing season and averaged across years

Partial budget	2015		2016		2017		Mean (3 yr)	
	T/Cr NT/Sb	NT/Cc T/Sb	T/Cr NT/Sb	NT/Cc T/Sb	T/Cr NT/Sb	NT/Cc T/Sb	T/Cr NT/Sb	NT/Cc T/Sb
Gross returns								
Grain yield (kg ha^{-1})	2837	3027	2343	2114	2549	3413	2576	2851
Receipts ($ ha^{-1})	1872	1997	1546	1395	1682	2252	1700	1881
Variable costs ($ ha^{-1})								
Cover crop seed	86	118	86	118	86	118	86	118
Soybean seed	230	184	230	184	230	184	230	184
Labor	128	104	115	110	115	251	119	155
Fuel	107	92	109	104	64	161	93	119
Repairs/maintenance	65	62	64	60	57	123	62	82
Other[a]	47	45	2	1	2	1	17	16
Total variable costs	663	605	606	577	554	838	607	674
Net returns ($ ha^{-1})	1209	1392	940	818	1128	1414	1093	1207

Variable costs include cover crop and soybean seed cost, labor and fuel costs of field operations for establishing and managing both cover crops and soybean, and repairs and maintenance. Net returns ($ ha^{-1}) were calculated by subtracting variable costs from income obtained from soybean grain based on an average market price at $0.66 kg^{-1}.

[a] Items classified as 'other' are common across systems and include inputs such as lime and interest on capital.

seed costs were lower in the reduced-tillage system because the three species mix used in the tillage-based system was higher priced than cereal rye. However, this was offset by higher soybean seed costs in the reduced-tillage system that resulted from the use of a higher soybean seeding rate.

Reduced-tillage soybean production resulted in lower net returns compared to tillage-based soybean production in 2 of 3 yrs. Averaged across study years, reduced-tillage soybean production reduced variable costs by $181 ha^{-1} compared to tillage-based production but was $114 ha^{-1} less profitable due to lower average yields in some experimental years. Our results demonstrate that due to price premiums, moderate increases in grain yields can result in significant increases in net returns and can offset additional labor and energy costs associated with weed management. In 2017, for example, intensification of weed control operations in tillage-based soybean increased variable costs by $284 ha^{-1} compared to reduced-tillage soybean production costs, but greater yields in tillage-based soybean resulted in a $286 ha^{-1} advantage in net returns. Consequently, our enterprise budget analysis suggests that though reduced-tillage soybean production results in lower input costs, higher yields will need to be realized to remain as profitable as tillage-based soybean over the long-term. We note here that assessments of short-term profits should consider other ecosystem services. For example, the intensity of soil disturbance (STIR) associated with field operations in our reduced-tillage soybean production system was approximately 50% less than the full tillage system averaged over study years (Table 1), which suggests that measurable changes to chemical, physical and biological soil properties could result from adoption of no-till practices in organic soybean production systems over the long-term.

Summary and management implications

We evaluated agronomic and economic tradeoffs between alternative organic cover crop–soybean sequences in the northern Mid-Atlantic. Across study-years, late-summer total weed biomass did not differ between tillage-based and reduced-tillage soybean. However, high interannual variability in weed control performance was observed in both soybean production systems and high levels of weed biomass were associated with in-row weed control failures. Mean soybean yield was 0.28 Mg. ha^{-1} higher in the tillage-based system compared to the reduced-tillage system. Path analysis indicates that soybean establishment is a primary yield-limiting factor in both production systems and reduces yield directly due to stand loss and indirectly by increasing weed biomass, which was negatively correlated with yields. In reduced-tillage soybean, stand establishment in high-residue cover crops remains a significant challenge, which at present, likely reduces profit potential. Looking ahead, continued improvements in high-residue planter technology and other cultural practices will be important for improving yield stability in reduced-tillage organic soybean production. Finally, our study focused on short-term agronomic and economic performance between coupled cover crop and soybean production strategies, yet adoption of reduced-tillage soybean production is likely to positively influence several measures of environmental sustainability over the long-term.

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