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Trade-Offs in Cereal Rye Management Strategies Prior to Organically Managed Soybean

K. A. Crowley,* H. M. Van Es, M. I. Gómez, and M. R. Ryan

ABSTRACT

Three cereal rye (*Secale cereale* L.) management strategies for organic soybean [*Glycine max* (L.) Merr.] production were compared in terms of their agronomic, soil health, and economic benefits. In central New York in 2014–2015 and again in 2015–2016, we compared (i) a "No-cover" control treatment, in which bare soil was plowed prior to planting soybean, (ii) a "Plow-down" treatment with cereal rye plowed at jointing stage prior to planting soybean, (iii) a "Ryelage" treatment with cereal rye harvested for forage and plowed prior to planting soybean, and (iv) a "Roll-down" treatment with cereal rye roller-crimped prior to no-till planting soybean. Water infiltration and soil respiration were greater in the Roll-down treatment compared with the No-cover treatment; however, weed biomass in soybean was greatest in the Roll-down treatment. Soybean yield did not differ between treatments in 2015, but yields were lower in the Roll-down treatment in 2016, which was likely due to dry conditions in May and June. Practices used in the Roll-down system required the least amount of labor, but harvesting cereal rye for ryelage and then using tillage before growing organic soybean maximized profitability. Our results show soil health improvement, labor reductions, and enhanced profitability from growing cereal rye before organic soybean. However, no single cover crop management strategy provided all of these benefits. More research is needed to better understand the effects of precipitation at different times, and how management can be improved to overcome trade-offs between strategies.

Core Ideas

- A field experiment was conducted to compare cereal rye management strategies.
- Roller-crimping cereal rye reduced labor requirements and increased soil health.
- Harvesting cereal rye for ryelage maximized profitability.
- Spring moisture affects soybean yield in roller-crimped systems.

Weed management in organic systems is labor-intensive, and weeds often contribute to lower yields. Traditionally, organic agriculture has relied on soil tillage and cultivation for weed control. However, tillage is fuel- and labor-intensive, and excessive tillage leads to soil compaction and destruction of soil structure. No-till has been promoted as an alternative that reduces fuel and labor expenses associated with tillage, preserves soil structure, reduces compaction, and improves overall soil health. However, no-till management, especially continuous no-till, can be challenging in organic systems where synthetic herbicides are prohibited.

Soil health has been defined as, "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" (USDA-NRCS, 2017), and improving soil health is a founding principle in organic agriculture. Traditionally, soil chemical and physical properties have dominated the dialogue around soil health and soil quality but increasingly, the critical role of soil biology is being recognized (Lehman et al., 2015). All three components are essential to the functioning of the soil ecosystem. The chemical health of the soil is determined by the availability of micro- and macronutrients, pH, cation exchange capacity, the salinity/sodicity of the soil, and the presence of heavy metals (Moebius-Clune et al., 2016). Physical soil health is based on soil structure, which influences how much water can infiltrate, how much moisture is retained, the amount of microbial activity, and the stability of soil aggregates. Soil biological health involves the activity of soil biota, which play key roles in nutrient cycling, preservation of soil structure and fertility, control of erosion, mitigation of floods and droughts, and control of pests and pathogens, among other functions (Lehman et al., 2015).

Cover crops are a potential solution for both managing weeds and improving soil health in organic production. Cover crops seeded in the fall can out-compete weeds both in the fall and in the spring before planting, and have the potential to decrease weed–crop competition by reducing weed abundance and seed rain, producing phytotoxic chemicals, immobilizing nutrients, producing smothering residues, and changing soil structure and quality (Hodgdon et al., 2016). Cover crop benefits to soil health include reducing erosion, runoff, and nitrate leaching; increasing soil water infiltration and storage; enhancing microbial populations and habitat for beneficial insects; and reducing root disease

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K.A. Crowley, H.M. Van Es, M.R. Ryan, Section of Soil and Crop Sciences, Cornell Univ., Ithaca, NY; M.I. Gómez, Charles H. Dyson School of Applied Economics and Management, Cornell Univ., Ithaca, NY. Received 20 Oct. 2017. Accepted 4 Mar. 2018. *Corresponding author (kac328@cornell.edu).

Abbreviations: PMN, potentially mineralizable nitrogen; POXC, permanganate-oxidizable carbon.

and plant–parasitic nematodes (Kaspar et al., 2001; Magdoff, 2001; Reicosky and Forcella, 1998). Cover crops can also sequester C in soils (Kong et al., 2005; Kuo et al., 1997; Poeplau and Don, 2015). For example, McDaniel et al. (2014) conducted a meta-analysis on the effects of cover crops using over 122 studies and found that crop rotations that include cover crops had 8.5% more total C than those without cover crops.

Cereal rye (*Secale cereale* L.) has been shown to be an exceptional cover crop because it can be planted later in the fall than other cover crops, reduces soil erosion, scavenges N, produces a large amount of biomass, and is highly weed-suppressive. Cereal rye, originally brought to the northeastern United States by English and Dutch settlers, is a cool season, annual grass that can grow 0.9 to 1.8 m tall (Casey, 2012). It has flat leaf blades and an awned, spike-like inflorescence. Cereal rye has been shown to improve soil biological and physical health. It can increase soil organic matter (Villamil et al., 2006; Lal et al.,1979), particulate organic matter (Surapur, 2014), total organic C (Liu et al., 2005), soil microbial biomass (Mendes et al., 1999), soil aggregation (Liu et al., 2005; Sainju et al., 2003), and aggregate stability (Steele et al., 2012). By reducing plant-available N, cereal rye can be used to suppress weeds, which is particularly relevant in legume crops that fix their own N and grow well in low soil N conditions (Wells et al., 2013).

In addition to being used as a cover crop, cereal rye can be harvested as grain for foods, alcoholic beverages, and livestock feed. It can also be included in pastureland and cut for hay (Casey, 2012). Interest among dairy farmers in using winter cereals as a double crop has increased in recent years in the northeastern United States due to extreme weather in 2012 and 2013 that impacted corn (*Zea mays* L.) silage and hay yields (Ketterings et al., 2015). In addition, interest among organic dairy farmers has increased due to the expense of organic feed (Jemison et al., 2012). Although double cropping with small grains such as cereal rye and soybean [*Glycine max* (L.) Merr.] is common in the southern United States, the shorter growing season in central New York and other northern regions prevents farmers from harvesting grain from cereal rye and then planting soybean. However, cereal rye can be harvested as haylage, or "ryelage," months before grain, allowing farmers in central New York to plant full-season soybean.

Cereal rye in conventional systems is typically killed in the spring with an herbicide, but organic systems have traditionally relied on tillage or mowing for termination. These termination strategies are not ideal, as tilling can have negative effects on soil health, and mowing requires energy-intensive equipment (Ashford and Reeves, 2003). In addition, mowing leaves the cover crop in small pieces that decompose rapidly and may result in less weed suppression than if the cover crop remained intact (Creamer and Dabney, 2002). A relatively new strategy for cover crop termination that leaves the cover crop intact and allows for season-long weed control without tillage is roller-crimping. The roller-crimper was first developed in South America (Derpsch et al., 1991, as cited in Mirsky et al., 2013), and popularized by the Rodale Institute in Kutztown, PA. It terminates cover crops by rolling them down with a large steel cylinder, providing a thick layer of persistent mulch that can suppress weeds. Roller-crimping requires 10-fold less energy than a rotary mower (Ashford and Reeves, 2003), and is much faster and therefore less expensive and labor-intensive than mowing.

The roller-crimper is the key to a system that has been referred to as cover crop-based, organic rotational no-till (Mirsky et al., 2012). In this system, cash crops are no-till planted into cover crops terminated with a roller-crimper. It is called "rotational" no-till because tillage is used prior to seeding the cover crop for long-term suppression of perennial weeds (Mirsky et al., 2012). Organic rotational no-till systems have been shown to reduce fuel and labor requirements by 27 and 31%, respectively, compared with traditional organic management (Mirsky et al., 2012; Ryan, 2010). In addition, rolled cover crop mulches provide very effective in-season weed suppression. Cereal rye is especially effective as a rolled mulch: it can suppress weeds by weakening germination cues (via reducing light and temperature fluctuations), interfering physically with weed emergence, immobilizing N (resulting from the high C/N ratio of the residue), and releasing allelopathic metabolites that cause phytotoxin inhibition (Mirsky et al., 2013). Despite these advantages, planting cereal rye before soybean does have potential risks, such as increasing pest problems (Stinner and House, 1990) and depleting soil moisture at the beginning of the growing season (Liebl et al., 1992; Wagner-Riddle et al., 1994), which can adversely affect soybean germination and yield (Liebl et al., 1992; Wells et al., 2016). Rolled cereal rye can also impede seed placement (Clark et al., 2017; Wagner-Riddle et al., 1994).

The aim of this experiment was to assess cereal rye management strategies prior to organic soybean for their impact on soil health, weed suppression, crop yield, and profitability. The treatments included:

1. No-cover (no cereal rye was seeded)
2. Plow-down (cereal rye was moldboard plowed at jointing stage)
3. Ryelage (cereal rye was harvested for fodder at boot stage and stubble was moldboard plowed before planting soybean)
4. Roll-down (cereal rye was roller-crimped)

We hypothesized that, compared with a no cover crop control, integrating a cereal rye cover crop prior to soybean would improve soil health, maintain weed suppression and soybean yield, and/or improve profitability to varying degrees, depending on management strategy.

MATERIALS AND METHODS

Experimental Design and Field Operations

This experiment was conducted in 2015 and 2016 at two locations at Musgrave Research Farm near Aurora, NY (42.73°N, 76.65°W). The soil type at the 2015 site was 77% Lima silt loam, (fine-loamy Oxyaquic Hapludalf) with 0 to 3% slopes, and 22% Honeoye silt loam (fine-loamy Glossic Hapludalf) with 2 to 8% slopes (Soil Survey Staff, 2016). The previous crop at the 2015 site was grain corn. The soil type at the 2016 site was 58% Lima silt loam with 3 to 8% slopes, 25% Honeoye silt loam with 2 to 8% slopes, and 17% Lima silt loam with 0 to 3% slopes (Soil Survey Staff, 2016). The previous crop at the 2016 site was soybean, although it was planted late (30 July), mowed, and moldboard plowed in September before it had reached a height of 15 cm. Based on routine soil sampling and analyses before the start of the experiment, we consider that the soils at the two field sites were similar, with pH ranging from 7.4 to 7.5 and organic matter

Table 1. Schedule of field operations in 2014–2015.

Field operation	Year	Date	Equipment
Moldboard plowed entire field	2014	24 Sept.	Kverneland 125 4-bottom plow
Tandem disked entire field		25 Sept.	John Deere 637
Cultimulched entire field		29 Sept.	John Deere 950
Drill-seeded cereal rye in Ryelage, Plow-down, and Roll-down treatments		7 Oct.	John Deere 1590 no-till drill, 3-m width
Plow-down treatment moldboard plowed at Zadoks 37	2015	7 May	Kverneland Model A 3-bottom plow
Ryelage treatment harvested at Zadoks 53-57		15 May	John Deere 972 Forage Chopper
No-cover and Ryelage treatments moldboard plowed		22 May	Kverneland Model A 3-bottom plow
All tilled plots disked and cultipacked		4 June	John Deere 637
Roll-down treatment roller-crimped at Zadoks 71		4 June	I&J MFG Roller-crimper, 3-m width
Planted soybean		4 June	John Deere 7200 Conservation Tillage Planter, 4-row
Soybean cultivation in all plots except Roll-down		20 June	Belly-mount, 2-row unit
Soybean cultivation in all plots except Roll-down		25 June	John Deere 825 4-row cultivator
Soybean cultivation in all plots except Roll-down		6 July	John Deere 825 4-row cultivator
Soybean cultivation in all plots except Roll-down		13 July	John Deere 825 4-row cultivator
Soybean cultivation in all plots except Roll-down		17 July	John Deere 825 4-row cultivator
High-residue cultivation in Roll-down treatment		27 July	John Deere 825 High Residue Cultivator
Interseeded hairy vetch into soybean		28 July	InterSeeder 4-row drill interseeder
Harvested soybean		12 Oct.	Almaco SP20 2-row combine

Table 2. Schedule of field operations in 2015–2016.

Field operation	Year	Date	Equipment
Moldboard plowed entire field	2015	9 Sept.	Kverneland 5-bottom plow
Tandem disked entire field		9 Sept.	John Deere 4320 and John Deere disc
Cultimulched entire field		18 Sept.	John Deere 950
Drill-seeded cereal rye in Ryelage, Plow-down, and Roll-down treatments		18 Sept.	John Deere 1530 no-till drill, 3-m width
Plow-down and No-cover treatments moldboard plowed at Zadoks 43-45	2016	22 Apr.	Kverneland Model A 3-bottom plow
Ryelage treatment harvested at Zadoks 52-55		4 May	John Deere 972 Forage Chopper
Ryelage treatment moldboard plowed		17 May	Kverneland Model A 3-bottom plow
All tilled plots disked and cultipacked		23 May	John Deere 637
Roll-down treatment roller-crimped at Zadoks 65-67		26 May	I&J MFG Roller-crimper, 3-m width
Planted soybean		31 May	John Deere 1750 maxEmerge XP Planter, 6-row
Tine-weeded all tilled plots		24 June	RabeWerk Tine Weeder with 85 degree bent tines
Irrigation		7–8 July	
Soybean cultivation in all plots except Roll-down		13 July	John Deere 825 4-row cultivator
Soybean cultivation in all plots except Roll-down		28 July	John Deere 825 4-row cultivator
Interseeded hairy vetch into soybean		28 July	InterSeeder 4-row drill interseeder
Harvested soybean		19 Oct.	Harvested by hand

ranging from 2.7 to 2.8%. Conventional corn and soybean were grown at both field sites previously, but in 2015 these fields started the transition to organic certification and no materials that are prohibited in certified organic production were used during the experiment. The experiment was arranged in a spatially balanced, randomized complete block design, with four replications (van Es et al., 2007). Treatment plots measured 9 × 21 m.

In the fall prior to each field season, organic amendments were applied to all plots to ensure adequate cereal rye growth (Tables 1 and 2). In 2014, dairy manure solids (2.0–0.4–0.7, N–P–K) were applied at 22.4 Mg ha^{-1} and in 2015 poultry manure (Kreher's 5–4–3) was applied at 1.4 Mg ha^{-1}. After fertilization and moldboard tillage, the three cover crop treatments were drill-seeded with 'Aroostook' cereal rye at 200 kg ha^{-1} in 19-cm rows (Tables 1 and 2). In the spring of each year, the Plow-down treatments were moldboard plowed at Zadoks 34–35 (Zadoks et al., 1974), and the Ryelage treatments were harvested at Zadoks 53–57 and plowed 7 to 13 d later. In 2015, the No-cover treatment was moldboard plowed at the same time as the Ryelage treatment. However, in 2016, the No-cover treatment was plowed at the same time as the Plow-down treatment, due to unwanted cereal rye growth (ranging from 73 to 912 kg ha^{-1}). The Roll-down plots were roller-crimped at Zadoks 71 in 2015 and Zadoks 65–67 in 2016 (Tables 1 and 2). Both years, the roller-crimper was front-mounted and filled with water to a total mass of 1195 kg, and cereal rye was rolled perpendicular to the direction it was drilled, which is a recommended practice for increasing ground cover and weed suppression.

All plots except the Roll-down plots were disked and cultimulched before soybean planting (Tables 1 and 2). In 2015, soybean was planted directly after the tilled plots were disked and cultimulched and the Roll-down plots were rolled (Tables 1 and 2). In 2016, however, soybean was planted 8 d after disking and cultimulching and 5 d after rolling, due to dry conditions. 'Viking 2299' (maturity group 2.2) and 'Viking 2399' (maturity group 2.3) soybean was planted in 2015 and 2016, respectively, into all treatments in 76-cm rows at a target rate of 625,000 seeds ha^{-1}. In 2015, this rate was achieved, but in

2016, a different planter was used, which resulted in a slightly higher planting rate (767,000 seeds ha^{-1}). Soybean seed was inoculated with *Bradyrhizobium japonicum* prior to planting. Previous research concluded that similarly high soybean planting rates are essential for optimizing soybean yield and profitability in cover crop-based, organic rotational no-till soybean (Ryan et al., 2011; Liebert and Ryan, 2017).

Plots were irrigated with a small amount of water in 2016 due to extremely dry conditions. On 7 and 8 July, soaker hoses were used to apply 568 L of water to the middle 7.6 m of all 12 rows in each plot. This was equivalent to a 0.64-cm rainfall in all plots. To ensure that irrigation was even across all treatments and all plots, the rate of water released from each soaker hose was measured and confirmed to be equal. The 12 hoses were then placed in each plot and allowed to run for an interval of time calculated based on the targeted 0.64-cm rainfall.

In 2015, the three tilled treatments were cultivated five times in June and July, and the Roll-down treatment was cultivated with a high-residue cultivator in late July (Tables 1 and 2). In 2016, all tilled plots were tine-weeded in late June and cultivated twice in July (Tables 1 and 2). There was no high-residue cultivation in the Roll-down treatment in 2016, as limited weed growth in the dry conditions made it unnecessary. In both years, hairy vetch (*Vicia villosa* Roth) was interseeded at 34 kg ha^{-1} in late July (Tables 1 and 2) into the three cover-crop treatments with a high-clearance drill interseeder (InterSeeder Technologies, Woodward, PA). Three rows of hairy vetch were seeded 20 cm apart between each 76-cm soybean row. Originally, we intended to continue the experiment with the same treatment structure by establishing hairy vetch and rotating to corn after soybean. However, hairy vetch biomass accumulation was determined to be inadequate for successful corn in the Roll-down treatment in the spring of 2016, and thus the experiment was terminated after hairy vetch biomass sampling. To maintain management consistency between years, hairy vetch was also interseeded into soybean in 2016 to match the interseeding that was done in 2015.

Data Collection

Weather data were collected at a meteorological station at the research site (Northeast Regional Climate Center, 2017). Air temperature data were summarized by taking the mean of daily temperature averages in each growing season (1 June–31 September for soybean, and 1 October–31 May for cereal rye). Precipitation data were summarized by monthly accumulated precipitation, as well as by total accumulation over the course of the soybean growing season (1 May–20 October). Air temperature and precipitation data were compared with a 30-yr (1981– 2010) average calculated by the National Climate Data Center (Northeast Regional Climate Center, 2017).

Soil was sampled on 5 Aug. 2015 and 8 Aug. 2016. From each 9 × 21 m plot, four 15-cm-diameter cores were taken to a 15-cm depth for aggregate stability testing. Sixteen and 20 2.5-cm-diameter cores per plot were taken in 2015 and 2016, respectively, to a depth of 15 cm, for potentially mineralizable nitrogen (PMN), permanganate-oxidizable carbon (POXC), and soil respiration testing. Cores taken within each plot were mixed thoroughly. Approximately 40 g of soil material from each plot was sieved to 2 mm, ~32 g of which was used for in-field PMN preparations (described below). The remaining sieved soil material was weighed, dried at 60°C for 3 d, and weighed again to calculate the moisture content for PMN analysis. Unsieved soil material was stored in a cooler until transferred to double paper bags for air drying. Additional soil samples were taken in 2016 on 24 May, 31 May, 7 June, and 15 June for nitrate and ammonium analysis. Sampling for this analysis consisted of 10 2.5-cm-diameter cores per plot, taken to a 15-cm depth.

Soil respiration, POXC, and aggregate stability testing was conducted on air-dried soil according to Zibilske (1994), Weil et al. (2003), and the standard operating procedures for the Cornell Comprehensive Assessment of Soil Health (Schindelbeck et al., 2016). Potentially mineralizable N was measured using the anaerobic incubation method developed by Drinkwater et al. (1996). Nitrate and ammonium extracts were taken from soil samples dried at 50°C overnight according to Griffin et al. (2009), and extracts were analyzed for nitrate and ammonium with an autoanalyzer (BRAN+LUEBBE, method G-109-94 and G-145–95, BRAN+LUEBBE, Norderstedt, Germany), and EPA methods 353.2 and 350.1, respectively (USEPA, 1983). Cornell Sprinkle Infiltrometers (Ogden et al., 1997) were used successfully in the field on 10 Aug. 2015 and 19–20 July (split over 2 d) and 15 Aug. 2016 to measure infiltration. The target simulated rainfall rate in 2015 was 15 cm h^{-1}, although the actual rate ranged from 11 to 20 cm h^{-1}. Due to dry conditions, the 2016 target simulated rainfall rate was 24 cm h^{-1} (actual rate ranged from 10 to 39 cm h^{-1}). Sorptivity was calculated as follows, according to Kutílek (1980):

$$S = (2T_{ro})^{0.5} \times r$$

where S = sorptivity, T_{ro} = time to runoff, and r = rainfall rate.

Cereal rye biomass was measured in each plot by clipping cereal rye in one 0.5 m^2 quadrat prior to termination: 7 May and 22 April for the Plow-down treatment, 15 May and 4 May for the Ryelage treatment, and 4 June and 26 May for the Roll-down treatment in 2015 and 2016, respectively. Cereal rye in the Plow-down and Roll-down treatments was clipped at the soil surface, and cereal rye in the Ryelage treatment was clipped at 10 cm above the surface, to simulate a forage harvester. Plant material was placed in paper bags, dried at 65°C for 1 to 2 mo, and then weighed. Soybean stand density and weed biomass were measured on 3 Sept. 2015 and 6 Sept. 2016 in 0.5-m^2 quadrats at two locations per plot. Common ragweed (*Ambrosia artemisiifolia* L.) was weighed separately from other weeds due to its previously reported prevalence in cover crop based, organic no-till soybean systems in the northeast (Liebert and Ryan, 2017; Mirsky et al., 2013; Nord et al., 2012). This prevalence is due to common ragweed's early emergence; the roller-crimper does not control emerged seedlings (Mirsky et al., 2013). Weeds were dried in paper bags for at least 72 h at 65°C and weighed. Hairy vetch seedlings were still very small at the time of weed biomass sampling and thus hairy vetch biomass was not sampled. In 2015, soybean from four 15.2-m rows in the middle of each plot was harvested on 12 October, with a two-row plot combine (Almaco SP20, Nevada, IA). In 2016, due to increased growth of the interseeded hairy vetch compared with 2015, it was not feasible to use a combine for harvest, so soybean harvest was instead done by hand with electric clippers on 19 October. Four 2.7-m rows were harvested per plot, and soybean was threshed with the same combine used in 2015 (Almaco SP20, Nevada, IA). Weight and moisture of harvested soybean were recorded. For both years, soybean yield was adjusted to 13% moisture. In the spring following soybean harvest, hairy vetch biomass was sampled on 2 and 12 June in 2016 and 2017, respectively, using the same method described above for cereal rye biomass sampling.

An economic analysis was conducted to quantify the difference in variable costs, return over variable costs, and labor requirements between each treatment. Variable costs included cereal rye seed (cv. Aroostook, Ernst Conservation Seeds Inc.), soybean seed (cv. Viking 2299, Lakeview Organics), and custom rates for field operations. Soybean seed costs in the economic analysis were based on the cost of Viking 2299 at 625,000 seeds ha^{-1}. There were several differences between actual field operations and those included in the economic analysis. First, tillage prior to cover crop seeding in the fall was excluded from the No-cover treatment, as this more accurately represents standard practices when a cereal rye cover crop is not seeded. Second, although the Ryelage treatment was harvested with a forage chopper, the cost of harvesting the cereal rye in the economic analysis was based on the costs of mowing, raking, and baling. Third, the cost of roller-harrowing was substituted for tine-weeding, as values for tine weeding were not available from the same source.

Custom rates for most field operations, with the exception of roller-crimping and high-residue cultivation, came from a single source (Pike, 2016). These rates include the cost of hiring machinery with fuel and operator, and exclude the cost of seed, fertilizer, and other materials. The cost of roller-crimping was estimated at \$9.88 ha^{-1}, based on expert opinion (A. Frankenfield, personal communication, 2016), and a separate source was used for the cost of high-residue cultivation (\$31.27 ha^{-1}), which took place once in the Roll-down treatment in 2015 (Stein, 2016). Income sources consisted of soybean and ryelage farm gate sales, which were calculated based on the yield of soybean and ryelage from the experimental plots. Soybean (organic feed-grade) was valued at the 2015 national average of \$0.87 kg^{-1} (\$23.75 bu^{-1}) (USDA-AMS, 2016). Ryelage value was determined with the PennState Extension Feed Value Calculator (PennState Extension, 2016), based on forage quality data from ryelage samples that we collected at the time of harvest and that were analyzed by Dairyland Laboratories Inc. (Arcadia, WI). The value of the ryelage in our plots ranged from \$56.29 to \$57.71 Mg^{-1}. The above-stated costs and the revenue sources were used to calculate return above variable costs for each treatment. Labor required for each treatment were also calculated. Labor hours for most operations, with the exception of baling and high-residue cultivation, came from a single source (Stein, 2016). Labor hours for baling (Lazarus, 2016) and high-residue cultivation (Stein, 2009) were from separate sources.

Statistical Analysis

Mixed model analysis of variance (ANOVA) was completed in R version 3.2.2 (R Core Team, 2015) to test treatment effects in soil, agronomic, and economic data. Treatment, year, and their interaction were included as fixed effects, and block was included as a random effect. A random block × year interaction was included if it explained any of the variance in the model. If there was a significant ($P < 0.05$) treatment × year interaction, the interaction was included in the model, and treatment means were compared within year using Tukey's pairwise comparison. If there was a significant treatment effect but no significant interaction effect, the interaction was excluded from the model and treatment means were pooled over years and compared with Tukey's pairwise comparison. If variances were considerably different between the two years, data from each year was analyzed separately. Soil nitrate, weed biomass, and soybean density data were log-transformed for analysis, and back-transformed means are presented. Significant differences are shown in tables and figures with letters, and similar letters indicate no significant difference ($P > 0.05$).

RESULTS AND DISCUSSION

Weather Conditions

Weather during the two experimental years differed dramatically. Differences in spring precipitation, especially for the month of soybean planting, illustrate that the optimum cereal rye management practice might depend on weather conditions. In 2015, accumulated precipitation in May and June was 14.1 and 20.3 cm, respectively—nearly double the 30-yr (1981–2010) average of 8.0 and 9.6 cm. In 2016, accumulated precipitation for the same two months was only 6.3 and 2.8 cm. In July, accumulation in 2015 was slightly lower than the 30-yr average, at 7.1 cm compared with 8.9 cm, but in 2016, July accumulation was still far below normal, at 4.8 cm. Overall, accumulated precipitation throughout the soybean growing season was much higher than normal in 2015, and much lower than normal in 2016 (Fig. 1). Soybean was irrigated in July of 2016, as described above.

Temperatures during the cereal rye growing season (1 October - 31 May) were lower than normal in 2015 and higher than normal in 2016 (2.1°C and 4.8°C compared to 3.8°C, respectively). Temperatures during the soybean growing season (1 June–31 September) were comparable to the average in both years (19.3 and 20°C in 2015 and 2016, respectively, compared with the average of 19.7°C).

Soil Indicators

Soil Respiration

Soil respiration is a measurement of the CO_2 evolved from soil during a set duration of time and is a useful indicator of the overall biological activity of the soil (Moebius-Clune et al., 2016). In this experiment, both treatment and year affected soil respiration. Soil respiration values were greater in 2015 (1.31 mg CO^2 g^{-1} wk^{-1}) than 2016 (0.79 mg CO^2 g^{-1} wk^{-1}), most likely because of the greater precipitation in 2015, which likely stimulated soil microorganisms. No treatment × year interaction was observed, so treatment means were analyzed pooled over years (Table 3). The Roll-down treatment had higher respiration than the No-cover treatment. This difference is quite interesting given that cereal rye was only grown for one season.

A positive relationship was observed between the duration of cereal rye growth and the amount of CO_2 evolved. This is congruent with other studies that have reported the effects of cover cropping on soil respiration. Hurisso et al. (2016) found

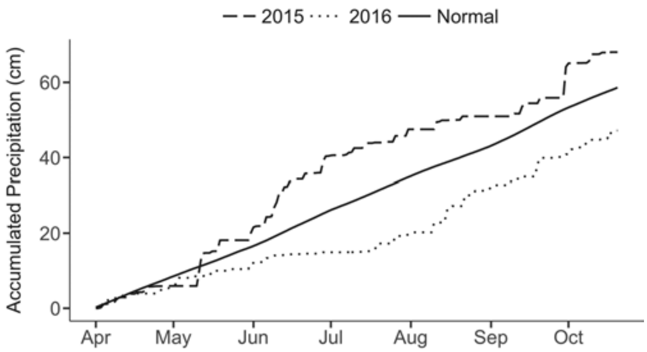


Fig. 1. Accumulated precipitation for 2015 and 2016, compared with the 30-yr (1981– 2010) climate average, calculated by the National Climate Data Center (Northeast Regional Climate Center, 2017).

that C mineralization (i.e., soil respiration) is associated with practices that encourage organic matter mineralization, such as the addition of cover crops, and Fernandez et al. (2016) found that, at one of three sites, there was twice as much soil respiration in plots with cereal rye than in a no-cover crop control. It is possible that the lack of tillage during the growing season in the Roll-down treatment could also explain the higher soil respiration. Although Hurisso et al. (2016) argue that tillage leads to enhanced C mineralization (i.e., respiration), other studies have found higher C mineralization in no-till compared with conventional-till systems (Perez-Brandán et al., 2012; Vargas Gil et al., 2009). Perez-Brandán et al. (2012) reason that the increased respiration in the no-till systems is likely due to the accumulation of residue that creates a more temperature- and moisture-moderating environment that is more conducive to microbial activity (Perez-Brandán et al., 2012). These factors may be another reason for the higher respiration in the Roll-down treatment.

Permanganate-Oxidizable Carbon (POXC)

Permanganate-oxidizable C measures the pool of labile organic C and has been shown to be more sensitive to changes in management than total organic C (Weil et al., 2003). In addition, POXC is often correlated with other soil quality indicators, including substrate-induced and basal respiration, aggregate stability, and microbial biomass (Weil et al., 2003). Here, POXC did not differ between treatments or between years, and there was no treatment × year interaction. Permanganate-oxidizable C levels were low across the board, scoring only 30 to 35 out of 100 on the Cornell Soil Health scale (Moebius-Clune et al., 2016).

The low POXC can be explained by the history of tillage in both sites, as POXC has been shown to be correlated with management practices that build soil organic matter (Hurisso et al., 2016), and tillage typically stimulates decomposition of organic matter. Hurisso et al. (2016) noted that tilled fields, and even fields that have recently been converted to no-till (as in our Roll-down treatment) have a higher correlation with mineralizable C (i.e., soil respiration) than POXC, which is supported by the fact that we saw differences in soil respiration but not in POXC. The lack of differentiation of POXC between treatments could also be due to the short duration of the treatments imposed. Research by Idowu et al. (2009) indicated that POXC might not be a good indicator for measuring short-term changes in management. In short-term experiments, different management practices are more likely to cause a difference in soil respiration than in POXC, because C mineralization can be influenced in one season, whereas building soil organic matter takes longer.

Potentially Mineralizable Nitrogen (PMN)

Potentially mineralizable N tests how much N is mineralized during an incubation period and is an indicator of both microbial activity (immobilization–mineralization) and labile organic N (Drinkwater et al., 1996). Soils with higher levels of organic matter have more organic N that can be mineralized. However, organic matter also can lead to N immobilization. The balance between immobilization and mineralization is regulated by the C/N ratio of the organic matter. When the C/N ratio is high, there is net immobilization, but as the C/N ratio decreases and microorganisms die off, there is net mineralization.

In this experiment, there was a treatment × year interaction effect on PMN, so PMN data were analyzed separately by year (Table 3). No differences among treatments were observed in 2015. However, in 2016, the mean PMN for the Plow-down treatment was almost double the means of the No-cover and Ryelage treatments. The Roll-down treatment was intermediate and not different from the three other treatments. In addition to the fact that the experiment was conducted in different fields, and different amendments were applied, the greater differentiation between treatments in 2016 could be due to differences in weather between years. In 2015, the greater precipitation most likely caused mineralization to happen earlier in the season. By the time samples were taken in August, much of the organic N at the 2015 site had probably already been mineralized. In 2016, however, the lack of precipitation could have slowed mineralization, so that at the time of sampling in August, more organic N was still available for mineralization compared with 2015.

The fact that PMN was higher in the Plow-down treatment compared with the No-cover and Ryelage treatments in 2016 indicates that there was either more organic matter or higher N-content organic matter in that treatment. Although the Plow-down treatment did have the highest amount of cereal rye aboveground biomass incorporated, the roots did not have as much time to develop in that treatment as they did in the Ryelage and Roll-down treatments. Thus, it is not clear if there was more organic matter in that treatment. In terms of N-content, since the biomass in the Plow-down treatment was incorporated earliest, it had the lowest C/N ratio, meaning a higher potential for mineralization. However, this mineralization was probably slowed by lack of moisture, as mentioned above. Assuming mineralization was slowed equally in the Plow-down and Ryelage treatments, it could be argued that the higher PMN in the Plow-down treatment resulted from the delayed mineralization of the higher-N-content biomass.

Nitrate

To better understand the effect of the treatments on soil N levels, soil samples were collected in the spring during the second year of the experiment and analyzed for soil nitrate. In spring of 2016, soil nitrate levels were affected by a treatment × date interaction, so sampling dates were analyzed separately. The No-cover treatment had higher soil nitrate levels than all three of the cover crop treatments for all four sampling dates (Fig. 2). In addition, nitrate levels became more differentiated between

Table 3. *P* values and treatment means for soil health, agronomic, and economic measurements are presented. When an interaction was not significant, it was removed from the model and data were re-analyzed without the interaction. Treatment means are presented with SE immediately to the right, in parentheses, followed by letters that compare treatment means. Similar letters indicate no significant difference ($P > 0.05$). When means are presented by year, letters are lowercase for 2015 and uppercase for 2016.

Measurement	Treatment	Year	Treatment × Year	Year	No cover	Plow down	Ryelage	Roll down
	P values				Treatment means			
Respiration, mg CO_2 g^{-1} wk^{-1}	0.027	<0.001		2015, 2016	0.949 (0.101) b	1.065 (0.070) ab	1.030 (0.111) ab	1.164 (0.145) a
POXC†, mg kg^{-1}	0.767	0.893		2015, 2016	429 (78)	447 (22)	434 (24)	455 (20)
PMN†, μg N g^{-1} wk^{-1}	0.052	0.05	0.042	2015	4.76 (0.29) a	3.81 (1.02) a	3.57 (0.72) a	4.93 (0.95) a
				2016	3.76 (0.83) B	7.66 (1.13) A	4.02 (0.69) B	6.17 (0.65) AB
Aggregate stability, %	0.737	0.045		2015, 2016	43.8 (4.1)	45.9 (4.2)	43.3 (3.8)	46.1 (5.1)
Sorptivity, mm $min^{-0.05}$	0.053	0.002‡			9.5 (1.4) b	11.5 (2.1) ab	13.1 (1.6) ab	16.9 (3.5) a
Cereal rye biomass, kg ha^{-1}	<0.001	<0.001		2015, 2016	NA	1426 (280) b	1978 (198) b	5123 (472) a
Weed biomass, kg ha^{-1}§	0.003	0.987		2015, 2016	21.3 b	14.3 b	18.6 b	356.8 a
Soybean density, 10,000 plants ha^{-1}§	<0.001	<0.001	<0.001	2015	48.2 a	47.6 a	48.1 a	47.6 a
				2016	73.4 A	74.2 A	56.6 B	41.4 C
Soybean yield, kg ha^{-1}¶	0.020			2015	2731 (168) ab	3053 (90) a	3022 (81) ab	2637 (66) b
	0.030			2016	2294 (150) A	1947 (282) AB	2203 (236) AB	1302 (302) B
Return over variable costs, US$ ha^{-1}¶	0.002			2015	1780 (147) b	1773 (79) b	2343 (43) a	1655 (58) b
	0.002			2016	1490 (131) AB	899 (246) BC	1954 (162) A	519 (264) C

† POXC = permanganate-oxidizable carbon; PMN = potentially mineralizable nitrogen.

‡ For sorptivity, the effect measured was date, not year, as sorptivity was measured over three dates.

§ Weed biomass and soybean density were log-transformed for analysis, so means presented here are back-transformed, and there are no standard errors presented.

¶ For soybean yield and return over variable costs, years were analyzed in separate models due to unequal variances (see standard errors). Soybean yield was adjusted to 13% moisture.

treatments over time. On 24 May, the Plow-down treatment had higher nitrate levels than the other two treatments. At this point, the cereal rye in the Plow-down plots had been tilled in a month prior (on 22 April), and the cereal rye stubble in the Ryelage treatment had been tilled in a week prior (on 17 May). On 31 May, there was no difference in nitrate levels between the Plow-down and Ryelage treatments, but they both had levels higher than the Roll-down treatment. On 7 June, nitrate levels in all four treatments differed from one another, with No-cover having the highest level, Plow-down coming in second, Ryelage third, and Roll-down fourth. This distribution of nitrate levels between treatments remained the same on 15 June.

Consistently higher nitrate levels in the No-cover treatment can be explained by the lack of cereal rye taking up N in the spring. The increasing levels of nitrate over time in the No-cover treatment is most likely the result of the mineralization and nitrification of soil organic matter. In the Ryelage and Plow-down treatments, slower rates of SOM mineralization and nitrification could indicate immobilization caused by the decomposition of cereal rye. This immobilization seems to be playing an even larger role in the Roll-down treatment, probably due to the greater amount of biomass and higher C/N ratio of that biomass. Immobilization from crimped cereal rye has also been noted by Clark et al. (2017), and by Wells et al. (2013, 2017). Interestingly, Wells et al. (2013) suggest that the reduction in plant-available N caused by cereal rye has potential for regulating weeds, with minor reduction in soybean yield.

Ammonium

Ammonium levels in spring 2016 did not differ between treatments, but did differ between dates ($P < 0.01$). The two later dates, 7 and 15 June, had less ammonium (2.7 and 3.1 mg kg^{-1}, respectively) than the first date, 24 May (4.4 mg kg^{-1}). The decrease in ammonium in all treatments can be explained by increasing temperatures, which can cause both nitrification and immobilization to increase, due to increased microbial activity. For ammonium levels to have decreased while nitrate levels increased in the No-cover, Plow-down, and Ryelage treatments, nitrification must have been happening faster than mineralization. In the Roll-down treatment, the most probable explanation for decreasing ammonium is immobilization, but it could also be the result of nitrification with little to no mineralization to replenish the ammonium.

Aggregate Stability

Wet aggregate stability is a robust test of soil physical health that is related to biological and chemical processes (Idowu et al., 2009). Aggregate stability testing showed no significant differences between treatments, and no significant year or treatment × year interaction effect (Table 3). The lack of differentiation between treatments is most likely due to the short duration of the treatments. The tillage in the Plow-down and Ryelage treatments could also be masking the effect of cereal rye on aggregate stability. Aggregate stability has indeed been found to increase with incorporation of cereal rye into no-till rotations (Villamil et al., 2006; Steele et al., 2012), and with lack of tillage (Idowu et al., 2009; Al-Kaisi et al., 2014; Perez-Brandán et al., 2012) in the long term. On the other hand, one short-term study (Mochizuki et al., 2008) reported that rolling cereal rye and leaving it on the surface as mulch for just one season resulted in higher aggregate stability compared with treatments with only cereal rye stubble on the surface. More research is needed on the short-term effects of various cereal rye management strategies on aggregate stability.

Sorptivity

Water infiltration is important to drainage, moisture retention, and run-off and erosion reduction. Generally, cover crops and reduced tillage have been found to increase the rate of water infiltration (Dabney et al., 2001; Sainju and Singh, 1997; Kasper et al., 2001; Mitchell et al., 2017). This has been attributed to increased porosity, increased soil organic matter, root number, and the abundance and diversity of earthworms (Villamil et al., 2006). In this experiment, treatment and date both affected sorptivity (Table 3). No treatment × date interaction was observed, so sorptivity was pooled over all three dates for analysis. The sorptivity of the Roll-down treatment was almost double that of the No-cover treatment (Table 3). In other words, water took nearly twice as long to run off in the Roll-down system than in the No-cover treatment.

These results are supported by previous research. Findeling et al. (2003) found that even a minimum amount of mulch (~1360 kg ha^{-1}) increased sorptivity by >50%. They attributed this increase to the mulch intercepting and storing rain, pathway tortuosity and friction slowing runoff flow, and soil organic matter and microfauna activity stabilizing the soil structure. The higher sorptivity in the Roll-down treatment compared with the No-cover treatment was likely due to the cereal rye mulch on the soil surface, which acted to delay runoff in the same ways described in Findeling et al. (2003). The interception and storage of rain can also preserve the soil surface structure and decrease surface sealing. Increased infiltration in the Roll-down treatment could also be the result of macropores created by the intact cereal rye roots, which had not been destroyed by tillage.

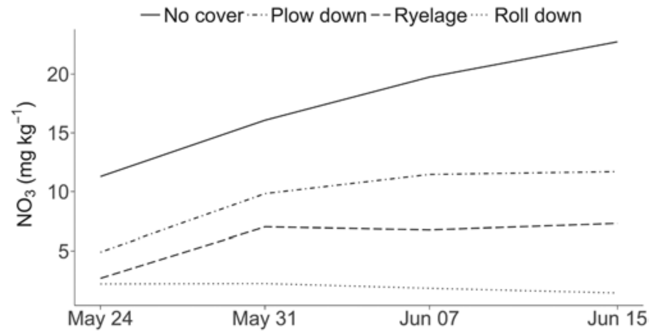
Crop and Weed Indicators

Cereal Rye Biomass

Cereal rye biomass was affected by treatment and year. There was no treatment × year interaction, so analysis was pooled over years (Table 3). It is important to remember that although the Plow-down and Roll-down treatments were cut at the surface, the Ryelage treatment was cut at 10 cm above the surface. Cereal rye biomass in the Roll-down treatment was more than double the biomass in the other two treatments due to the longer duration of growth (Table 3). The mean across treatments in 2016 (3434 kg ha^{-1}) was higher than in 2015 (2250 kg ha^{-1}).

The lower cereal rye biomass accumulation in 2015 was most likely due to the later planting date (7 Oct. 2016 compared with 18 Sept. 2016). It has been widely reported that cereal rye biomass accumulation can be maximized by early sowing (Mischler et al., 2010; Nord et al., 2012; Mirsky et al., 2011). Mirsky (2011) found that cereal rye planted on 25 August accumulated 56% more biomass compared with cereal rye planted on 15 October. Although biomass accumulation was lower in 2015, accumulation for both years was in range of what has been reported in recent years at the same research station in New York: Liebert et al. (2017) reported a mean cereal rye biomass of 5200 kg ha^{-1} in 2013 and 4500 kg ha^{-1} in 2014.

The values of cereal rye biomass accumulation seen here are substantially lower than the 8000 kg ha^{-1} that has been recommended for optimal weed suppression (Mirsky et al., 2012). Mirsky et al. (2012) reported that cereal rye biomass in the mid-Atlantic region typically does not exceed 6000 kg ha^{-1} unless seeding rate, seeding date, and soil fertility are optimized, in which case biomass levels can reach 12,000 kg ha^{-1}. These numbers are in line with what has been reported in Pennsylvania, where Mirsky et al. (2013) reported cereal rye



	May 24	May 31	Jun 07	Jun 15
NC	a	a	a	a
PD	b	b	b	b
RL	c	b	c	c
RD	c	c	d	d

Fig. 2. Soil nitrate by treatment at four dates in 2016. Similar letters within each date indicate no difference between treatments ($P > 0.05$). NC = No-cover; PD = Plow-down; RL = Ryelage; RD = Roll-down.

biomasses ranging from 5,974 to 10,608 kg ha^{-1} and Mischler et al. (2010) reported biomass ranging from 5594 to 8940 kg ha^{-1} for similar seeding and termination dates. However, southeast and central Pennsylvania have a longer growing season than central New York, and this could account for the lower values seen in experiments performed here.

Weed Biomass

Weed biomass differed by treatment, but not by year, and there was no treatment × year interaction, so analysis was pooled over years (Table 3). Weed biomass in the Roll-down treatment was considerably higher than the mean of the other treatments (Table 3). Overall weed biomass was relatively low compared with other experiments with organic soybean. For example, Ryan et al. (2009) reported that weed biomass in a long-term cropping systems experiment averaged 1360 and 1080 kg ha^{-1} in organic soybean that was managed using tillage and cultivation in the manure and legume-based systems, respectively. Low weed biomass in our experiment is likely due to previous management that effectively limited weed seed additions to the soil seed bank. Our results are congruent with other research conducted at the same site that compared organically managed soybean that was no-till planted into rolled cover crops to organically managed soybean that was planted into tilled soil. Liebert et al. (2017) reported that weed biomass in no-till planted soybean ranged from 600 to 1200 kg ha^{-1} and that weed biomass in adjacent soybean that was planted into tilled soil and managed with cultivation was only 1%, or less than the biomass in the no-till treatments. Similar to our experiment, the experiment reported in Liebert et al. (2017) was conducted in fields that were managed conventionally prior to the experiment.

In 2015, 77% of the weed biomass in the Roll-down treatment was comprised of common ragweed, whereas this species only accounted for 9% of the total weed biomass in the Roll-down treatment in 2016. Part of this difference may be explained by the fact that two different fields were used for the 2 yr of the experiment. The common ragweed biomass in 2015 was similar to what has been found in previous studies of weed biomass in organic soybean planted into rolled cereal rye. In Liebert et al. (2017), common ragweed comprised 65 and 84%

of total weed biomass in two site-years. In Nord et al. (2012), common ragweed comprised 84% of total weed biomass.

Soybean Density

Soybean density in September was affected by a treatment × year interaction, so treatment means were analyzed separately for each year. Higher overall density in 2016 was due to the higher planting rate reported in the methods section. Though soybean density was not different between treatment means in 2015, density in the Ryelage and especially the Roll-down treatments were lower in 2016 compared with the Plow-down and No-cover treatments (Table 3). The extremely low density in the Roll-down treatment in 2016 was most likely due to poor seed-to-soil contact and lack of rain after planting. Some "hair-pinning" was observed at soybean planting (i.e., the rolled cereal rye stems were pushed into the row preventing good soybean seed placement and soil contact). Normally, rain after planting will allow such soybean seeds to imbibe despite poor soil contact, but as there was no substantial rain for over a month after planting in 2016, even seeds with good soil contact might have struggled to germinate. As a result, soybean seedling growth was delayed (Crowley, 2017).

Hair-pinning has been reported in other studies. Mirsky et al. (2013) reported avoidance of hair-pinning when using a lightly fluted coulter, whereas Clark et al. (2017) had more success removing the coulters entirely, which allowed more weight to be placed on the double disk row openers. Clark et al. (2017) and Mirsky et al. (2013) observed that a spiked or spaded closing wheel was more effective than a solid closing wheel at closing the seed slit. In the experiment reported on here, two rubber press wheels were used in 2015, and one rubber press wheel was used with a curvetine (Dawn Manufacturing, Sycamore, IL) in 2016. In this experiment, it is likely that the lower density was due to the combination of less than ideal seed placement and lack of rain.

Soybean Yield

Soybean yield was affected by treatment and year. The average soybean yield across treatments in 2015 (2861 kg ha^{-1}) was 45% higher ($P < 0.05$) than the average soybean yield in 2016 (1937 kg ha^{-1}). To analyze treatment means, separate models were used for each year, as the variance was not equal between years (Table 3). Higher variance in 2016 was most likely the result of hand-harvesting the grains, as opposed to using a combine to harvest, as was done in 2015. Treatment affected soybean yield in both years. In 2015, the Roll-down treatment had lower yield than the Plow-down treatment, but the Ryelage yield did not differ from any other treatment. In 2016, the Roll-down treatment had lower yield than the No-cover treatment, and the Ryelage and Plow-down treatments did not differ from any other treatment (Table 3).

A reduction in soybean yield in rolled cereal rye has been observed elsewhere, but not as severe as what occurred in this experiment in 2016, which amounted to a 43% loss in the Roll-down treatment compared with the No-cover treatment. Davis (2010) reported a loss of at least 29% with rolled cereal rye (6000–7100 kg ha^{-1} of cereal rye biomass), but in other experiments, no reduction in yield was reported in rolled cereal rye systems (Smith et al., 2011). Given that hairy vetch was interseeded nearly 2 mo after soybean planting, it is unlikely that competition from hairy vetch reduced soybean yield. Rather, the reduction in yield in the Roll-down treatment in 2016 was most likely due to poor establishment, caused by a combination of poor seed-to-soil contact and the lack of rain after planting, as discussed previously, and to slower growth throughout most of the season (Crowley, 2017). The slowed soybean growth was most likely due to the drought. Improved soybean growth observed after irrigation in the Roll-down treatment but not in the other treatments supports the conjecture that the soybean in the Roll-down treatment was suffering from lack of moisture. The increase in growth stage immediately after irrigation in the Roll-down treatment, not seen clearly in the other treatments (Crowley, 2017), also supports this explanation.

Hairy Vetch Biomass

In spring 2016, the accumulated hairy vetch biomass in the Plow-down, Ryelage, and Roll-down treatments was 2741, 3014, and 379 kg ha^{-1}, respectively. In 2017, accumulated hairy vetch biomass in the Plow-down, Ryelage, and Roll-down treatments was 5574, 4909, and 4982 kg ha^{-1}, respectively. The greater accumulation of hairy vetch biomass in 2017 was likely due to the 2016 drought, which resulted in smaller soybean plants, later canopy closure, and thus greater resources for hairy vetch seedlings.

Economic Analysis

Variable Costs

The Ryelage treatment was by far the most costly, mainly due to the expense of baling (Table 4). The No-cover treatment was the least expensive, due to the absence of costs associated with seeding the cereal rye. The Roll-down treatment was the second-least expensive (7 and 17% higher costs compared with No-cover in 2015 and 2016, respectively), due to the absence of cultivation, except for high-residue cultivation in 2015. The Plow-down treatment was the second-most expensive (27 and 23% higher costs compared with Roll-down in 2015 and 2016, respectively), since it included both the costs associated with the cereal rye and cultivation. Although the Roll-down treatment did have higher costs than the No-cover treatment, it is interesting to note that the costs of these treatments are very close, especially in 2015, when there was considerably more tillage than in 2016. This suggests that, in a rolled cereal rye system, the reduction of costs from not cultivating has the potential to compensate for the additional cost of seeding cereal rye.

The higher cost of the Roll-down treatment compared with the No-cover treatment is similar to what was found by Delate et al. (2012), in which a system with a rolled hairy vetch and cereal rye mixture had 13% higher total costs (fixed and variable) compared with a system that was tilled with no cover crop. Our finding that the Plow-down treatment was more costly than the Roll-down treatment is supported by Bernstein et al. (2011), in which a system with tilled cereal rye had 9% greater variable costs compared with a rolled system.

Labor Required

The amount of labor required for each treatment largely follows the pattern of the treatment costs (Table 4). However, there is one exception: the labor required for the Roll-down treatment is less than the labor required for the No-cover treatment. This is because cultivation is much more time-consuming than seeding cereal rye. It is important to note that the Roll-down treatment has a considerably lower labor requirement than all

Table 4. Variable costs and labor hours per hectare associated with operations and materials by treatment. The occurrence of an operation in a treatment is marked with an "x."

Operation	Season	Operation and material† costs	Labor	Operation occurrence by treatment			
				No cover	Plow down	Ryelage	Roll down
		US$ ha^{-1}	h ha^{-1}				
2015							
Moldboard plow	Fall	$51.38	0.59		x	x	x
Disk + harrow	Fall	$46.68	0.20		x	x	x
Drill rye	Fall	$189.45	0.36		x	x	x
Mow	Spring	$38.78	0.28			x	
Rake	Spring	$23.34	0.71			x	
Bale‡	Spring	$335.59	0.90			x	
Roll/crimp rye	Spring	$9.88	0				x
Moldboard plow	Spring	$51.38	0.59	x	x	x	
Disk + harrow	Spring	$46.68	0.20	x	x	x	
Plant soybean (conventional)	Spring	$236.58	0.18	x	x	x	
Plant soybean (no-till)	Spring	$238.06	0.19				x
High residue cultivation§	Summer	$31.27	0.19				x
Interrow cultivation (×5)§	Summer	$37.79 (×5)	0.19 (×5)	x	x	x	
Combine soybean	Fall	$83.24	0.36	x	x	x	x
Total Costs				$606.83	$894.34	$1,292.05	$649.96
Total Labor				2.29	3.44	5.33	1.91
2016							
Moldboard plow	Fall	$51.38	0.59		x	x	x
Disk + cultimulch	Fall	$46.68	0.20		x	x	x
Drill rye	Fall	$189.45	0.36		x	x	x
Mow	Spring	$38.78	0.28			x	
Rake	Spring	$23.34	0.71			x	
Bale‡	Spring	$471.33	0.90			x	
Roll/crimp rye	Spring	$9.88	0				x
Moldboard plow	Spring	$51.38	0.59	x	x	x	
Disk + harrow	Spring	$46.68	0.20	x	x	x	
Plant soybean (conventional)	Spring	$236.58	0.18	x	x	x	
Plant soybean (no-till)	Spring	$238.06	0.19				x
Tine-weeding§	Spring	$21.41	0.10	x	x	x	
Interrow cultivation (×2)§	Summer	$37.79 (×2)	0.19 (×2)	x	x	x	
Combine soybean	Fall	$83.24	0.36	x	x	x	x
Total Costs				$514.87	$802.38	$1,335.83	$618.69
Total Labor				1.81	2.97	5.13	1.72

† Costs for drilling cereal rye and planting soybean include seed costs ($144.50 ha^{-1} for rye and $187.18 ha^{-1} for soybean).

‡ Cost of baling is calculated by weight of biomass, so this value depends on the ryelage yield. The value presented here is the average cost of baling for each year. This also affects the total cost of the Ryelage treatment.

§ Operations differed between years.

other treatments. Taking an average between the two years, labor required in the Roll-down treatment represented an 11% reduction compared with the No-cover treatment, a 43% reduction compared with the Plow-down treatment, and a 65% reduction compared to the Ryelage treatment. Especially compared with the Plow-down and Ryelage treatments, this is a drastic decrease in labor, and could allow the farmer to engage in other income-generating activities, thereby making up for any lost income in a dry year. The lower labor requirements of the rolled system compared with tilled cover crop systems has been documented in previous research (Bernstein et al., 2011; Ryan, 2010).

Return over Variable Costs

Separate models were used to analyze return over variable costs, as the variance was much higher in 2016 (Table 3), due to the high variation in soybean yield that year described above. The Ryelage treatment was the most profitable treatment in 2015, and more profitable than the Plow-down and Roll-down treatments in 2016. This is mostly explained by the extra profit gained by the sale of the ryelage, as the soybean yields were not different in the Ryelage treatment compared with any other treatment in either year.

The Roll-down treatment performed well in 2015, with return over variable costs comparable to both the Plow-down and No-cover treatments. The lack of difference in profitability ($P > 0.05$) between the Roll-down and Plow-down treatments is surprising given the higher yield in the Plow-down in 2015. This could be due to the added expense in the Plow-down treatment of drilling cereal rye, which was not countered by a reduction in fuel and labor cost, as it was in the Roll-down treatment. In 2016, the low yield of the Roll-down treatment resulted in low return over variable costs, only 35 and 27% of the returns in the No-cover and

Ryelage treatments, respectively ($P < 0.05$). The lower profitability in the Roll-down treatment compared with the No-cover treatment was clearly because of the lower yield ($P < 0.05$), while the lower profit in the Roll-down compared with the Ryelage treatment was due to the lack of extra income from ryelage.

The lack of difference in returns ($P > 0.05$) between the Plow-down and Roll-down treatments in either year is contrary to the findings in Bernstein et al. (2011), where a tilled system with cereal rye was 36% more profitable than a no-till system with rolled or mowed cereal rye. In 2015, this discrepancy can be explained by the fact that the mean yield in the Roll-down treatment was only 14% below the yield in the Plow-down treatment, compared with a 32% reduction in yield in the no-till system in Bernstein et al. (2011). However, in 2016, this discrepancy is most likely due to the high standard error in our model, as the mean return for the Plow-down treatment was indeed 42% higher than the mean for the Roll-down treatment.

The higher return in the No-cover treatment compared with the Roll-down treatment in 2016 is similar to findings in Delate et al. (2012), in which a treatment that was tilled with no cover crop had higher returns than a treatment with rolled cereal rye and hairy vetch (Delate et al., 2012). This is contrary to the equal returns between those treatments in 2015, likely because the yield of the rolled system in our experiment was more comparable to the tilled, no cover system than in Delate et al. (2012).

CONCLUSIONS

We tested the effects of different cereal rye management practices before soybean in organic production on several cropping system performance indicators: soil respiration, POXC, aggregate stability, sorptivity, cereal rye biomass, weed biomass, soybean density and yield, and return over variable costs. The Roll-down treatment had some soil health benefits compared with the No-cover treatment, e.g., increasing sorptivity and soil respiration. We also noticed a trend toward higher POXC and aggregate stability when cereal rye was rolled, compared with when no cereal rye was seeded. Weed biomass was greater in the Roll-down treatment in both years compared with all other treatments, but levels were still relatively low for organic production. In 2015, although soybean yield was higher in the Plow-down treatment compared with the Roll-down treatment, the yield in the Roll-down treatment was not different from either the No-cover or the Ryelage treatment, and all treatments produced relatively high soybean yields. In 2016, however, soybean yield in the Roll-down treatment suffered considerably, mainly due to the lack of rain at the beginning and throughout most of the growing season.

The lower soybean yield in the Roll-down treatment in 2016 suggests that farmers should be aware of challenges with dry conditions over the winter and in early spring if implementing a rolled system. This conclusion is supported in Clark et al. (2017), where severe drought in 2012 led to a 28% reduction in soybean yield in an organic no-till system with rolled cereal rye compared with a tilled system with no cereal rye—a difference that was not seen in 2013, when there was sufficient moisture. Interestingly, Clark et al. (2017) reported a 75% reduction in soybean yield in their organic no-till system with rolled cereal rye compared with their tilled system with no cereal rye in 2014. Prior to soybean planting, precipitation in 2014 was markedly lower than in 2012 at their site. Although they report that nutrient limitation resulted in poor cereal rye growth and that low cereal rye biomass caused a high level of weeds and poor yields, it is likely that low precipitation in the spring of 2014 also contributed to poor performance in no-till planted soybean compared with soybean that was planted into tilled soil (Clark et al., 2017). Although this finding and the results of our own experiment show poor soybean performance in rolled systems when precipitation is low before and after planting, soybean performance was dramatically better when precipitation was adequate in 2015. Under these conditions, soybean yield in the rolled system was comparable to the tilled systems with and without cereal rye, as was observed in Smith et al. (2011) and Mischler et al. (2010). These observations suggest that irrigation in early spring, especially at time of planting, has the potential to eliminate establishment problems related to low spring rain in a rolled system.

In contrast to the Roll-down treatment, the Ryelage treatment showed no increase in weed biomass or decrease in crop yield when compared with the other treatments. In addition, the ryelage gives considerable added profit to the farmer. Although the Ryelage treatment did not show any differences in soil health in this experiment, there was a noticeable trend toward higher soil respiration, POXC, and sorptivity compared with the No-cover treatment. Future research should further explore the potential for ryelage to improve soil health. The profitability of growing and harvesting cereal rye prior to soybean shows great potential for increasing the adoption of cover crops, and if future research confirms the trend toward enhanced soil health noticed here, the adoption of this strategy could improve the sustainability of soybean cropping systems.

Overall, our results support our hypothesis that compared with the No-cover control, incorporating cereal rye into a rotation prior to soybean can improve soil health, maintain weed suppression and soybean yield, and improve profitability, but that these benefits vary depending on management strategy. No one strategy provided all of these benefits. The Roll-down treatment improved soil health and reduced labor, but weeds were more abundant and soybean yields and profitability were lower in the second year. The Ryelage treatment maintained weed suppression and soybean yield and increased profitability, but did not significantly improve soil health and required substantially more labor. Farmers should consider these benefits and drawbacks when choosing between these management strategies.

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