Weed Science 2017 65:426–439
© Weed Science Society of America, 2017

Rolled Mixtures of Barley and Cereal Rye for Weed Suppression in Cover Crop–based Organic No-Till Planted Soybean

Jeffrey A. Liebert, Antonio DiTommaso, and Matthew R. Ryan*

Maximizing cereal rye biomass has been recommended for weed suppression in cover crop–based organic no-till planted soybean; however, achieving high biomass can be challenging, and thick mulch can interfere with soybean seed placement. An experiment was conducted from 2012 to 2014 in New York to test whether mixing barley and cereal rye would (1) increase weed suppression via enhanced shading prior to termination and (2) provide acceptable weed suppression at lower cover crop biomass levels compared with cereal rye alone. This experiment was also designed to assess high-residue cultivation as a supplemental weed management tool. Barley and cereal rye were seeded in a replacement series, and a split-block design with four replications was used with management treatments as main plots and cover crop seeding ratio treatments (barley:cereal rye, 0:100, 50:50, and 100:0) as subplots. Management treatments included high-residue cultivation and standard no-till management without high-residue cultivation. Despite wider leaves in barley, mixing the species did not increase shading, and cereal rye dominated cover crop biomass in the 50:50 mixtures in 2013 and 2014, representing 82 and 93% of the biomass, respectively. Across all treatments, average weed biomass (primarily common ragweed, giant foxtail, and yellow foxtail) in late summer ranged from 0.5 to 1.1 Mg ha^{-1} in 2013 and 0.6 to 1.3 Mg ha^{-1} in 2014, and weed biomass tended to decrease as the proportion of cereal rye, and thus total cover crop biomass, increased. However, soybean population also decreased by 29,100 plants ha^{-1} for every 1 Mg ha^{-1} increase in cover crop biomass in 2013 ($P = 0.05$). There was no relationship between cover crop biomass and soybean population in 2014 ($P = 0.35$). Soybean yield under no-till management averaged 2.9 Mg ha^{-1} in 2013 and 2.6 Mg ha^{-1} in 2014 and was not affected by cover crop ratio or management treatment. Partial correlation analyses demonstrated that shading from cover crops prior to termination explained more variation in weed biomass than cover crop biomass. Our results indicate that cover crop management practices that enhance shading at slightly lower cover crop biomass levels might reduce the challenges associated with excessive biomass production without sacrificing weed suppression in organic no-till planted soybean.

Nomenclature: common ragweed, *Ambrosia artemisiifolia* L.; giant foxtail, *Setaria faberi* Herrm.; yellow foxtail, *Setaria pumila* (Poir.) Roemer & J. A. Schultes; barley, *Hordeum vulgare* L.; cereal rye, *Secale cereale* L.; soybean, *Glycine max* (L.) Merr.

Key words: Cover crops; organic rotational no-till; roller-crimper; reduced-tillage; mulch.

Challenges with current weed management practices have prompted farmers, agronomists, and agroecologists to explore alternative approaches that reduce environmental degradation and nontarget effects. For example, soil tillage and interrow cultivation, which are common weed management practices in organic cropping systems, can increase soil erosion (Lal 1991; Logan et al. 1991; Pimentel et al. 1995) and greenhouse gas emissions (Lal 2004; Paustian et al. 2000; Reicosky 1997). On the other hand, synthetic herbicides used in conventional management can alter plant communities in adjacent noncrop areas, reduce habitat quality, and depress biodiversity (Boutin et al. 2014; Pleasants and Oberhauser 2013; Relyea 2005). Increasing problems with herbicide-resistant weeds have also stimulated interest in practices that can be used to reduce selection pressure and the development of resistant populations (Beckie 2006; Mortensen et al. 2012; Norsworthy et al. 2012). In addition to these management considerations, concerns about food security have prompted agriculturists to identify and design cropping systems that provide supporting and regulating ecosystem services in addition to simply provisioning agricultural products (Foley et al. 2005). Cover crops are a viable solution to many of the problems with current weed management practices, and long-term cover crop–based systems can increase soil nitrogen and carbon (McDaniel et al. 2014; Poeplau and Don 2015) while providing

---

DOI: 10.1017/wsc.2016.23

* First, second, and third authors: Graduate Student, Professor, and Assistant Professor, Soil and Crop Sciences Section, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. Corresponding author's E-mail: jal485@cornell.edu

many other important ecosystem services (Schipanski et al. 2014).

In conventional no-till cropping systems, nonselective, postemergence herbicides are commonly used to terminate cover crops prior to planting a cash crop (Ashford and Reeves 2003; Weston 1990). As synthetic herbicides are not permitted in organic production, growers must instead rely on physical methods for cover crop management. Mowing can be successfully used for cover crop termination (Creamer and Dabney 2002; Wilkins and Bellinder 1996), but only certain types of mowers are compatible with organic no-till systems. For instance, both rotary and flail mowers can unevenly distribute cover crop residue, resulting in poor weed suppression in areas where the mulch layer is thin or absent (Teasdale and Mohler 2000). Mowing prior to anthesis (Zadoks 60) can also stimulate some cover crops to regrow, which increases competition with the cash crop for available light, moisture, and nutrients (Raper et al. 2004; Westgate et al. 2005). Additionally, rotary and flail mowing increases the surface area of cover crop residue, thereby accelerating decomposition and diminishing the persistence of the mulch and its ability to physically suppress weeds later in the season (Creamer and Dabney 2002).

As an alternative to mowing, terminating cover crops with a roller-crimper is gaining popularity among organic grain farmers in North America (Mirsky et al. 2012; Raper et al. 2004). The most commonly used roller-crimper model in the United States is a steel cylinder (41 to 51 cm diameter) with blunt metal blades arranged in a chevron pattern (Mirsky et al. 2012; Raper and Simionescu 2005). When used at growth stages immediately following anthesis, cover crop termination with a roller-crimper is as effective as herbicides (Ashford and Reeves 2003; Davis 2010; Mirsky et al. 2009) and requires less energy to operate than mowing (Ashford and Reeves 2003). In contrast to rotary and flail mowing, rolling-crimping creates a unidirectional cover crop mulch layer that is oriented in the direction of travel. When growers plant a cash crop parallel to the direction of rolling-crimping, the amount of residue lodged in the furrow (i.e., hairpinning) is reduced, coulter function is improved, and seed-to-soil contact is enhanced compared with planting after rotary or flail mowing (Ashford and Reeves 2003; Kornecki et al. 2009). A sickle-bar mower does not shred plant residue, and some research has indicated that it can be a viable substitute for a roller-crimper (Bernstein et al. 2011). However, cut residue can shift under windy conditions and can be dragged through the field with planting, high-residue cultivation, and harvesting equipment.

Previous research on cover crop–based organic no-till planted soybean systems has often focused on maximizing cereal rye biomass through cultivar selection (Wells et al. 2015) or by manipulating seeding date (Nord et al. 2012; Ryan et al. 2011b), soil fertility (Ryan et al. 2011a), and termination date (Mirsky et al. 2011; Nord et al. 2012; Wayman et al. 2014). Based on work by Teasdale and Mohler (2000), a minimum threshold for cereal rye biomass of 8.0 Mg ha^{-1} at cover crop termination has been recommended for optimal weed suppression in the subsequent cash crop (Mirsky et al. 2012, 2013). However, multiple challenges can arise from such high biomass production: (1) soybean seed placement through the thick mulch can be difficult (De Bruin et al. 2005; Liebl et al. 1992; Wagner-Riddle et al. 1994); (2) soil water content can be depleted, reducing soybean germination and decreasing yield (De Bruin et al. 2005; Liebl et al. 1992; Wells et al. 2015); and (3) the amount of soybean lodging can increase (Smith et al. 2011).

Whereas excessive cover crop biomass can present many difficulties, insufficient biomass production can be equally challenging to manage. A variety of factors can result in poor cereal rye cover crop growth, including late establishment and low soil nitrogen. In these instances, a “rescue cultivation” can effectively control weeds, reducing the risk of soybean yield loss and contributions to the soil weed seedbank (Nord et al. 2011). If soybeans are no-till planted in 76-cm rows, high-residue cultivators with low-angle wide sweeps can be used to slice through the soil just below the surface, severing weed shoots from roots. Under ideal operating conditions, the soil is not inverted, and the thin shanks limit the amount of cover crop residue that is disturbed.

In this research, we quantified the effects of intercropping barley and cereal rye on weed suppression and soybean performance. Importantly, relying more on shading prior to cover crop termination than total cover crop biomass production for weed control minimizes the challenges associated with thick cover crop mulches. Barley was selected to complement the well-documented productivity of cereal rye, because it is also a winter-hardy small grain, but it is shorter in stature and has broader leaves than cereal rye. These differences in plant height and leaf morphology might increase light interception through resource partitioning.

To investigate the potential of barley and cereal rye mixtures to enhance light interception and weed suppression in cover crop–based organic no-till planted soybean, our research consisted of two primary objectives: (1) quantify the impact of cover crop mixtures of barley and cereal rye on shading, weed suppression, and soybean yield; and (2) compare the effect of high-residue cultivation (HRC) and standard no-till (SNT) on weed biomass and soybean yield. These research objectives were framed by the following hypotheses: (1) mixtures of barley and cereal rye will result in greater weed suppression than a monoculture of either cover crop, and (2) weed suppression and soybean yield will be greater in HRC than in SNT.

Materials and Methods

Site Description and Experimental Design. We conducted a field experiment from 2012 to 2014 at the Cornell University Musgrave Research Farm in Aurora, NY (42.73°N, 76.66°W). This time frame comprises data collection from two main growing seasons: year 1 (2012 to 2013) and year 2 (2013 to 2014). The dominant soil type is a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs), with partial tile drainage in both field sites. Soft red winter wheat (*Triticum aestivum* L.) was conventionally managed prior to the initiation of the experiment for years 1 and 2. Across both years, the soil pH ranged from 7.7 to 7.8, and the organic matter content (determined by measuring the mass loss on ignition at 500 C) ranged from 3.4 to 3.6%. Due to the previous conventional management, this experiment represents crop production under the first year of organic transition.

A spatially balanced split-block design with four replications was used with management treatments (HRC and SNT) as main plots and cover crop seeding ratio treatments as subplots. In addition to HRC and SNT, a management treatment consisting of no cover crop, tilled soil, and interrow cultivation (IRC) was included in plots adjacent to the experiment to evaluate soybean performance under typical organic soybean management. Although this management treatment was not included in a formal statistical analysis, it served as an external control that was superior to the county average because it represented no-herbicide management conditions. In 2012 and 2013 barley and cereal rye were seeded in a replacement series with three seeding ratio treatments. Each cover crop was planted in monoculture (barley: cereal rye, 0:100 and 100:0) and in biculture (50:50). Cover crop seeding rates were based on the rate used for the cereal rye monoculture (547 seeds m^{-2}, 136 kg ha^{-1}), which is similar to the standard practice of seeding a fall-sown cereal rye cover crop at a rate of 126 kg ha^{-1}. The seeding rates for the barley monoculture and mixture were determined volumetrically, such that the same volume was seeded in all plots. As barley seeds are larger than cereal rye seeds, the volumetrically equivalent seeding rate for the barley monoculture was 355 seeds m^{-2}, and the biculture rate was 296 and 150 seeds m^{-2} for cereal rye and barley, respectively. When a replacement series is used to study metrics of plant competition, such as interference and niche differentiation, interpretations of the results can be limited (Connolly 1986; Connolly et al. 2001; Firbank and Watkinson 1985; Inouye and Schaffer 1981; Jolliffe 2000; Taylor and Aarssen 1989). However, many of these limitations might not apply if the research objective is to compare yields between monocultures and mixtures (Jolliffe 2000). As we were not assessing plant competition, and density dependence was not detrimental to testing our hypotheses, we implemented a practical approach to cover crop seeding that is common among farmers. Each subplot measured 6.1 by 9.1 m in size, which was large enough to facilitate farm-scale equipment and destructive sampling of the cover crops.

Field Operations. Prior to the cover crops being planted in fall 2012 and 2013, the field was moldboard plowed and prepared with a field cultivator (Perfecta II, Unverferth Manufacturing, Kalida, OH), and poultry litter (5–4–3, N–P_2O_5–K_2O [Krehers Enterprises, Clarence, NY]) was broadcast applied with a box-spreader at 56 kg total N ha^{-1}. After the poultry litter was incorporated with a cultimulcher (Model 950, Deere & Company, Moline, IL), barley 'Valor' and cereal rye 'Aroostook' were seeded with a drill (Model 450, Deere & Company, Moline, IL) on September 17, 2012, in year 1, and September 7, 2013, in year 2. The cover crops were seeded with 19 cm row spacing at a depth of 2.5 cm.

As barley matures earlier than cereal rye, cover crop termination was delayed until after cereal rye had reached anthesis, with rolling occurring on June 19, 2013, and June 16, 2014, for years 1 and 2, respectively (Table 1). Front mounted on a tractor and driven at approximately 7 km h^{-1}, the 3-m-wide roller-crimper (I & J Manufacturing, Gordonville, PA)

Table 1. Dates of field operations in 2013 and 2014 for the standard no-till (SNT) and high-residue cultivation (HRC) management treatments and the tillage-based interrow cultivation (IRC) comparison in the experiment in Aurora, NY.

	Management treatment					
	SNT		HRC		IRC	
Field operation	2013	2014	2013	2014	2013	2014
Preplant tillage[a]	—[b]	—	—	—	June 1 to 7	May 25 to 31
Rolling-crimping	June 19	June 16	June 19	June 16	—	—
Soybean planting	June 19	June 16	June 19	June 16	June 19	June 16
HRC	—	—	July 16	August 11	—	—
IRC	—	—	—	—	July 15	July 2
	—	—	—	—	July 25	July 9
	—	—	—	—	—	July 16
Soybean harvest	October 17	November 3	October 17	November 3	October 17	November 3

[a] Preplant operations included moldboard plowing, disking, and cultipacking.
[b] A dash (—) indicates that the operation was not conducted.

was filled with water for a total mass of 1,195 kg. The cover crops were rolled perpendicular to the direction of sowing to achieve more uniform ground cover and improve soybean seed placement (Kornecki et al. 2005). For IRC management, a field cultivator was used to bury any weeds that had emerged, and then a cultimulcher was used to prepare the seedbed for planting. On the same date as cover crop termination, rhizobium-inoculated soybean 'HS13A11' (maturity group I) was planted through the rolled cover crop mulch (HRC and SNT) or bare soil (IRC) at a depth of 3 cm using a four-row planter (MaxEmerge 7200, Deere & Company, Moline, IL). As the soil was particularly dry at planting in 2014, we added 318 kg of weight to the four-row planter to increase the down pressure and ensure seed placement was at the targeted depth. Soybean was no-till planted in 76-cm-wide rows parallel to the direction of cover crop rolling at a high seeding rate of 740,000 seeds ha^{-1}. Although this is more than double the recommended seeding rate of 321,000 seeds ha^{-1} for conventional soybean production at 76 cm row spacing in New York (Cox and Cherney 2011; Orlowski et al. 2012), the high rate was used as a cultural weed management tactic. Soybean canopy closure is attained earlier at higher seeding rates, which contributes to weed suppression through increased shading (Arce et al. 2009; Bastiaans et al. 2008; Place et al. 2009; Ryan et al. 2011b).

For HRC management, a four-row no-till high-residue cultivator (Model 886, Deere & Company, Moline, IL) was used on July 16, 2013, in year 1 and August 11, 2014, in year 2. The SNT treatment did not include any supplemental weed management. For weed control under IRC management in 2013, an interrow cultivator was used on July 15 and July 25. In 2014 interrow cultivation occurred on July 2, July 9, and July 16. A 7 to 10 d interval between cultivation events was used to provide enough time for recently germinated summer annual weeds to emerge, thereby enhancing the efficacy of the following cultivation.

Sampling and Data Collection. On the same day as cover crop termination and prior to rolling-crimping, photosynthetically active radiation (PAR) transmittance through the canopy was measured with a line quantum sensor (LI-191, LI-COR, Lincoln, NE) linked to a point quantum sensor (LI-190, LI-COR, Lincoln, NE) at solar noon. The line sensor was placed on the soil surface between two rows of cover crops, and the point sensor was mounted on a telescoping monopod extended above the canopy to obtain reference values for instantaneous calculation of PAR transmittance. Also before rolling-crimping, aboveground cover crop stem density and biomass were quantified within each plot. Before the biomass was removed, cover crop stem density was assessed by counting stems with seed heads by species within the quadrats. For determination of biomass, barley and cereal rye vegetation was clipped at the soil surface within a 0.5 m^2 quadrat, and then samples were oven-dried at 50 C for approximately 1 wk and weighed.

Weed biomass samples were collected approximately 11 wk after planting, just prior to maturation of several dominant weeds in the experiment. Weeds were clipped at the soil surface within a 0.5 m^2 quadrat and separated according to species as follows: (1) common ragweed, (2) giant foxtail and yellow foxtail, and (3) all other weed species. Common ragweed and the two foxtail species were separated from all other weeds, because they were identified as the most abundant (i.e., dominant) species in the experiment based on visual estimates of weed cover. Weed biomass samples were dried and weighed as described for the cover crop samples. Soybean population was assessed by counting individual plants within a 0.5 m^2 quadrat at soybean harvest on October 17, 2013, for year 1 and November 3, 2014, for year 2. Soybean yield was determined by harvesting mature plants with a two-row plot combine (ALMACO SP20, Nevada, IA) and adjusting grain moisture to 13%.

Statistical Analyses. Data were analyzed using R v. 3.1.0 (R Core Team 2014). We used linear mixed-effects models (*lmer* function in the 'lme4' package in R; Bates et al. 2015) with block as a random effect to test for relationships among seeding ratio, management treatment, PAR transmittance, cover crop biomass, weed biomass, common ragweed biomass, soybean population, and soybean yield. Interactions between these factors and year were also tested, and year was removed during model simplification if the interaction or main effect of year was not significant ($P > 0.05$).

For linear mixed-effects models, calculating the coefficient of determination (R^2) can lead to many issues, such as a decreasing or negative R^2 when additional independent variables are introduced (Nakagawa and Schielzeth 2013). To overcome these deficiencies, we used the *r.squaredGLMM* function ('MuMIn' package; Bartoń 2015) to calculate two types of R^2: the marginal coefficient of determination $\left(R^2_m\right)$ and conditional coefficient of determination $\left(R^2_c\right)$. The R^2_m represents the proportion of response variance that is associated with the fixed effects only, whereas the R^2_c describes the variance explained by both fixed and random effects (Nakagawa and Schielzeth 2013).

When two predictor variables in a model are linearly related, the presence of collinearity (or multicollinearity when there are more than two predictors) can result in unstable parameter estimates and inflated standard errors (Dormann et al. 2013). Particularly problematic is the inability to separate the unique effects of each variable, which in some instances is the primary motivation for using multiple regression. To measure the degree of collinearity between two predictor variables, we used the *vif* function ('car' package; Fox and Weisberg 2011) for the variance-inflation factor (VIF) calculation (Marquardt 1970), which is described as

$$\mathrm{VIF}_i = \frac{1}{1-R_i^2} \qquad [1]$$

where R_i^2 is the multiple correlation coefficient of X_i regressed on the remaining predictor variables (Belsley et al. 1980). If the predictor variables are uncorrelated, then $R_i^2=0$ and VIF_i will be the minimum value of 1 (Fox and Monette 1992). VIF is widely used as diagnostic measurement, and many competing "rules of thumb" have been proposed for identifying severe or excessive collinearity when assessing a VIF (O'Brien 2007). Most commonly, it has been suggested that a $\mathrm{VIF} > 10$ indicates severe collinearity (Kutner et al. 2005; Marquardt 1970). However, Fox (1997) proposed that the precision of estimation (square root of the VIF) is seriously degraded at a $\mathrm{VIF} > 4$, and it has even been suggested that a VIF as low as 2 can indicate problematic collinearity (Graham 2003). Condition indices (CI) are a complementary diagnostic tool for identifying collinearity, with a $\mathrm{CI} > 30$ commonly used as an indicator of severe collinearity (Belsley et al. 1980; Rawlings et al. 1998). We used the *colldiag* function ('perturb' package; Hendrickx 2015) to obtain condition indices for the two predictors.

For our multiple regression analysis, we were specifically interested in calculating semipartial and partial R^2 to partition the proportion of variance in weed biomass that each predictor variable (PAR transmittance and cover crop biomass) accounted for. The formulae for the semipartial correlation (sr_i) between each predictor and the response can be described as

$$sr_1 = \frac{r_{Y1}-r_{Y2}r_{12}}{\sqrt{1-r_{12}^2}} \text{ and} \qquad [2.1]$$

$$sr_2 = \frac{r_{Y2}-r_{Y1}r_{12}}{\sqrt{1-r_{12}^2}} \qquad [2.2]$$

where sr_1 and sr_2 express the correlation between the entirety of weed biomass (Y) and a predictor variable from which the other predictor has been "partialed" or controlled for (Cohen et al. 2003); r_{Y1} is the bivariate correlation between Y and PAR transmittance (X_1); r_{Y2} is the bivariate correlation between Y and cover crop biomass (X_2); and r_{12} is the bivariate correlation between the two predictor variables, X_1 and X_2. These are considered semipartial correlations, because the effects of X_2, for example, have been uncoupled from X_1 but not from Y (Cohen et al. 2003). Squaring the semipartial correlation represents sr_i^2, which can be understood as the proportion of variance in Y explained by a given predictor beyond that which is explained by the partialed predictor (Preacher 2006).

Partial correlation (pr_i) is the correlation between X_i and Y in which the other predictor has been partialed from both X_i and Y. This relationship is given by

$$pr_1 = \frac{r_{Y1} - r_{Y2} r_{12}}{\sqrt{1-r_{Y2}^2}\sqrt{1-r_{12}^2}} \text{ and} \qquad [3.1]$$

$$pr_2 = \frac{r_{Y2} - r_{Y1} r_{12}}{\sqrt{1-r_{Y1}^2}\sqrt{1-r_{12}^2}} \qquad [3.2]$$

where pr_1 represents the partial correlation between X_1 and Y after controlling for the effect of X_2 on both X_1 and Y, and pr_2 is the corresponding relationship with respect to X_2. Of the variance in Y that is not estimated by the other predictor in the model, the coefficient of partial determination $\left(pr_i^2\right)$ represents the amount of that remaining Y variance explained by X_i (Cohen et al. 2003). Semipartial and partial correlations were determined in R with the *spcor* and *pcor* functions ('ppcor' package; Kim 2015), respectively.

Mixed-effects analysis of covariance (ANCOVA) was used to evaluate the effect of management treatment (SNT and HRC) and year (2013 and 2014) on weed biomass, common ragweed biomass, soybean population, and soybean yield while accounting for seeding ratio or cover crop biomass as covariates and block as a random effect. Diagnostic tests were performed to ensure that there was independence of the covariate and the treatment effects and homogeneity of the regression slopes. Tukey's honest significant difference (HSD) test was performed with the *HSD.test* function ('agricolae' package; Mendiburu 2015) to compare the means of cover crop biomass production. Data for all analyses were tested to ensure that the errors exhibited homogeneity of variance, independence, and normal distribution.

Results and Discussion

Weather and Field Conditions. The cover crop and soybean growing seasons for years 1 and 2 were characterized by highly variable precipitation (Figure 1) and temperatures similar to the long-term average (1956 to 2014) (Northeast Regional Climate Center 2015). Compared with the long-term average, precipitation was greater by 6% or less during the cover crop growing season in years 1 and 2. However, there was 28% more precipitation during the 2013 soybean growing season and 7% less precipitation in 2014 compared with the long-term average. Notably, June and August in 2013 were much wetter than the long-term average for each month, with 65 and 73% more precipitation, respectively.

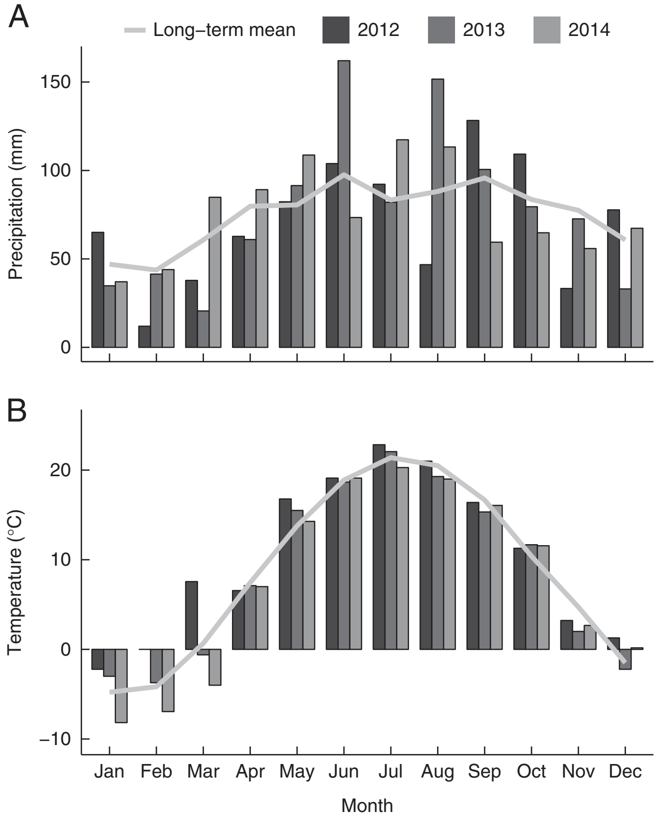

Figure 1. (A) Monthly precipitation from 2012 to 2014 and the long-term mean. (B) Mean monthly temperatures and the long-term mean. Data are from the Northeast Regional Climate Center (2015).

Average monthly temperatures were similar to the long-term average during the cover crop growing seasons (September 17, 2012, to June 19, 2013, and September 7, 2013, to June 16, 2014) and soybean growing seasons (June 19, 2013, to October 17, 2013, and June 16, 2014, to November 3, 2014). A total of 2,161 and 2,096 growing degree days (GDD, base 10 C) accumulated from June 1 to October 31 in 2013 and 2014, respectively (Northeast Regional Climate Center 2015). The long-term average for this site is 2,218 GDD.

In 2014 precipitation was above average from March through May and below average, overall, from June through October. Tile drainage in the 2014 field site did not function as well as the tile drainage in 2013, which exacerbated the effects of above-average rainfall in the spring. In some plots, this resulted in a 10-fold increase in biomass production directly above the irregularly spaced tiles compared with adjacent, poorly drained areas. Areas affected by poor tile drainage were mapped, and data from plots within these areas were excluded from analyses after statistical procedures, such as measuring Cook's distance, were used to verify whether the outliers were influential.

Cover Crop Biomass Production and PAR Transmittance. Cover crop biomass production was more variable in 2014 than 2013, which was likely due to poor drainage in the 2014 field site. As the proportion of cereal rye increased in 2013, mean cover crop biomass increased from 2.6 Mg ha^{-1} in the barley monoculture to 5.2 Mg ha^{-1} in the cereal rye monoculture (Figure 2). In 2014 mean cover crop biomass was again greatest in the cereal rye monoculture at 4.5 Mg ha^{-1}, but the biculture was the least productive seeding ratio treatment, accumulating 2.1 Mg ha^{-1} of barley and cereal rye biomass combined. In all cases, total biomass production was substantially less than the recommended 8.0 Mg ha^{-1} threshold for adequate weed suppression. Whereas cover crop biomass increased, PAR transmittance through the cover crop canopy decreased as the proportion of cereal rye in the seeding ratio increased (Figure 3). This reduction in PAR transmittance was from 64% in the barley monoculture to 41% in the cereal rye monoculture ($P < 0.001$). Data were pooled over 2013 and 2014 because there was no interaction or main effect of year.

We seeded barley and cereal rye based on volume rather than seed density because cover crop seeding rates are more commonly established on a volume or mass basis by farmers. Although cereal rye is known to be highly competitive (Beres et al. 2010), barley and cereal rye production in the 50:50 mixture was notably uneven. For example, cereal rye comprised 82% of the biomass and 67% of the stem density in the 50:50 mixture in 2013 (unpublished density data). Biomass production and stem density was even more disproportionate in 2014, with the biculture consisting of 83% cereal rye stems, representing 93% of the biomass in the 50:50 mixture.

The amount of PAR transmittance decreased as the proportion of cereal rye increased, closely mirroring the relationship between cover crop biomass and cereal rye proportion. Although cover crop biomass was statistically equivalent across the three seeding ratios in 2014, the difference between the biculture and the cereal rye monoculture exceeded 2.0 Mg ha^{-1}. Despite this substantial difference in biomass, PAR interception was lowest in the barley monoculture, not the biculture. Minor

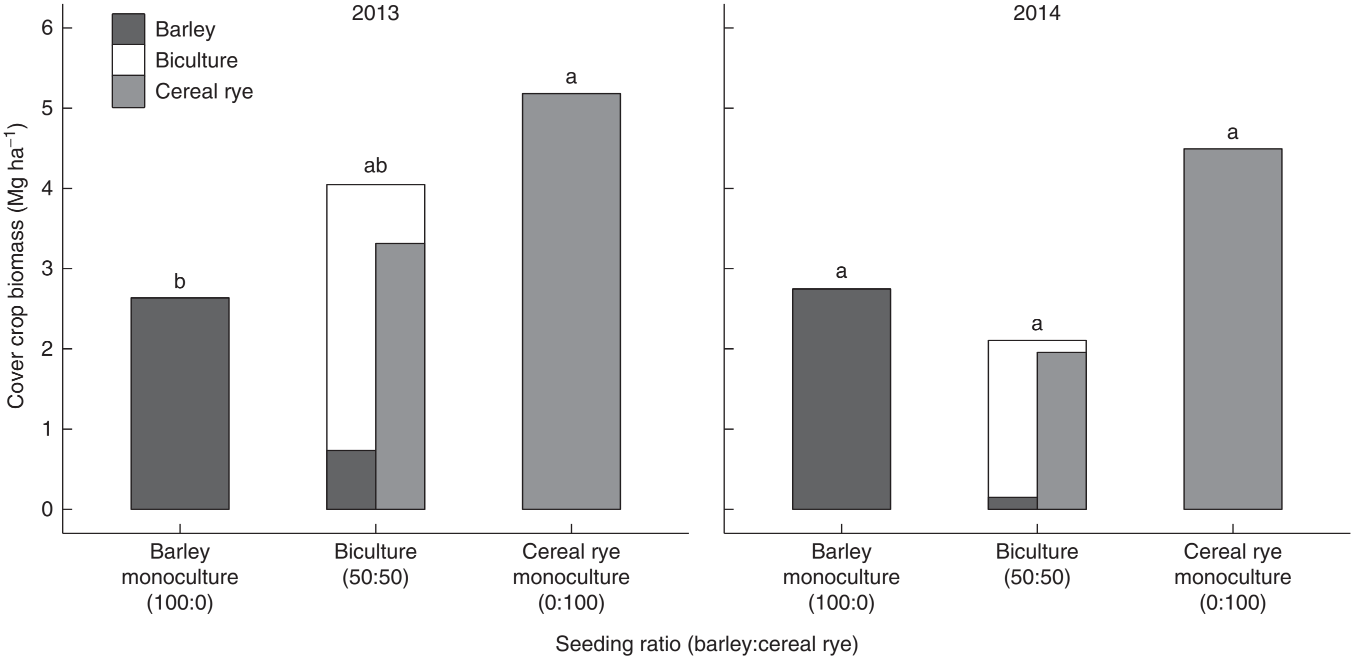

Figure 2. Cover crop biomass production of barley and cereal rye in monoculture and biculture in 2013 and 2014. Similar letters above bars indicate no significant difference ($P < 0.05$) among seeding ratios based on Tukey's honest significant difference test.

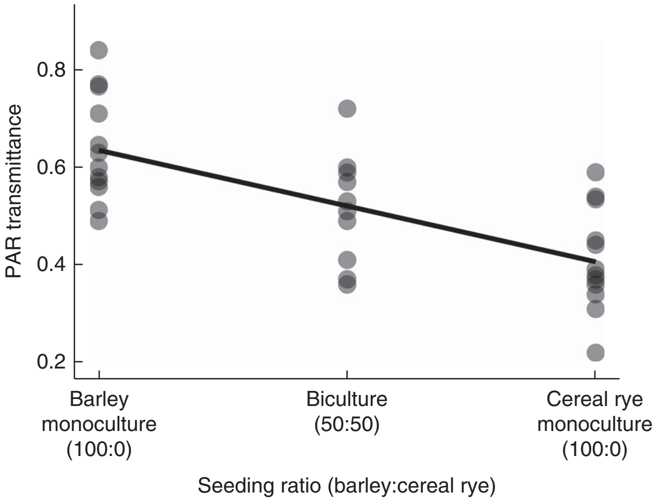

Figure 3. Photosynthetically active radiation (PAR) transmittance through the cover crop canopy across seeding ratio treatments. Data were pooled over both years and block was included as a random effect ($y = 0.635 - 0.002x$, $R^2_m = 0.43$, $R^2_c = 0.70$, $P < 0.001$).

differences in plant architecture and resource partitioning might help explain this, but it is the cumulative effect on weed suppression that is of practical importance.

Compared with cereal rye, barley is typically less tolerant of wet soil and the increase in ethylene that is associated with anaerobic conditions (Drew and Lynch 1980; Smith and Restall 1971; Smith and Robertson 1971). Nonuniform soil drainage in 2014 coupled with above-average precipitation from March to May (Figure 1) might have reduced root growth and the competitive ability of barley more so than cereal rye. Injury is often less severe when short-term flooding occurs during more mature barley growth stages, but recovery is typically limited, resulting in reduced tillering, biomass production, and grain yield (Leyshon and Sheard 1974). This occurrence would help explain the highly disproportionate density and biomass in the 50:50 biculture in 2014, but the mixture was also uneven in 2013. Although we can draw conservative inferences based on field notes, observations, and biomass data to help explain the uneven biculture proportions, our replacement series was not designed to directly assess interspecific plant competition.

Weed Response to Seeding Ratio and Management Treatments. Across all seeding ratios and management treatments, common ragweed was the dominant weed, accounting for 65% of the aboveground biomass among all weed species in 2013 and 84% in 2014. The dominance of this summer annual weed species is illustrated in Figure 4 by allowing the symbol size to vary proportionally with the amount of common ragweed biomass. Giant foxtail and yellow foxtail were also prominent at the 2013 study site, comprising 25% of the total weed biomass. In 2014 the proportion of foxtail species was only 7% of the aboveground weed biomass. Based on the ANCOVA (Table 2), the interaction between seeding ratio and management treatment was not significant ($P > 0.05$), which indicates that the relationship between weed biomass (response) and seeding ratio (covariate) was similar for the SNT and HRC management treatments. Also, these data were pooled over 2013 and 2014, because the ANCOVA showed no interaction or main effect of year. Mean weed biomass decreased as the proportion of cereal rye increased (Figure 4), ranging from 1.2 to 0.6 Mg ha^{-1} under SNT management and 1.0 to 0.4 Mg ha^{-1} under HRC management.

Overall, HRC reduced weed biomass by 26% compared with SNT ($P = 0.04$). This is congruent with previous research showing the weed-suppression benefit of high-residue cultivation in cover crop–based organic no-till planted soybean (Mirsky et al. 2013). Tillage-based IRC management effectively eliminated all weeds in 2013 and 2014, reducing weed biomass to 1% or less of the biomass levels found in HRC and SNT (unpublished data). In other comparisons between no-till and tillage in organic soybean production (Bernstein et al. 2011, 2014), weed suppression was not significantly better under tillage-based management.

Common ragweed produced the greatest proportion of biomass across all treatments, which has been found in other experiments on cover crop–based organic no-till planted soybean systems in the northeastern United States (Nord et al. 2012; Ryan et al. 2011a). As common ragweed typically emerges prior to cover crop termination (Myers et al. 2004), the operation of a no-till planter can contribute to low within-row common ragweed abundance by physically cutting, burying, or uprooting seedlings. With common ragweed found primarily between rows in these systems, HRC can provide particularly effective control of this problematic species. The timing of high-residue cultivation, however, presents a trade-off: earlier cultivation can provide better control of species that emerge prior to rolling-crimping, but species that emerge later might actually be stimulated by the disturbance. A separate ANCOVA was used to test for interactions among and effects of seeding ratio, management treatment, and year on common ragweed biomass. No

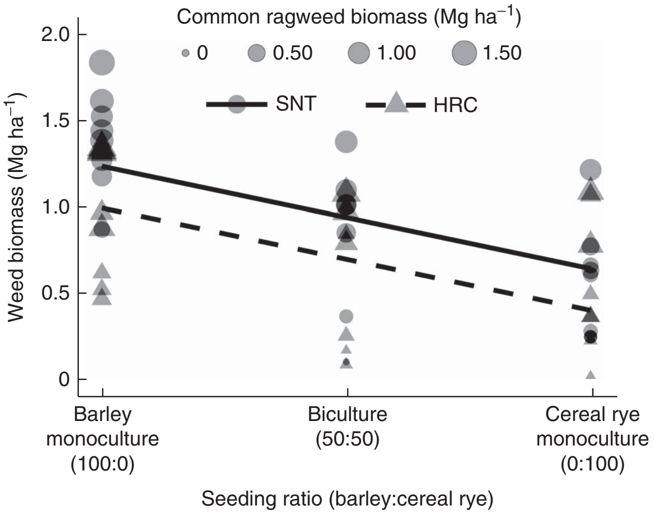

Figure 4. Weed biomass production in the standard no-till (SNT) and high-residue cultivation (HRC) management treatments across seeding ratios. The data were pooled over both years, and block was included as a random effect (R^2_m=0.35, R^2_c=0.35). Interactions were not observed ($P > 0.05$), but the effects of seeding ratio ($P < 0.001$) and management treatment ($P = 0.04$) were significant. For SNT management, $y = 1.241 - 0.006x$; for HRC management, $y = 0.999 - 0.006x$. Symbol size increases as the proportion of common ragweed in total weed biomass increases.

interactions were observed, but the effects of seeding ratio ($P < 0.001$), management treatment ($P = 0.02$), and year ($P = 0.01$) were all significant. Compared with SNT management, HRC reduced common ragweed biomass by 52% in 2013 but only by 22% in 2014, when the operation occurred later in the season (Table 1). In general, HRC was not as effective at controlling foxtail species. As giant foxtail and yellow foxtail tend to emerge after rolling-crimping (Myers et al. 2004), HRC might have helped stimulate germination in 2013, resulting in a 113% increase in biomass compared with SNT. Later HRC in 2014 provided more effective control of both foxtail species, which was likely due to a greater proportion of the two species emerging prior to the cultivation event.

As with any weed management tactic, timing is critical to the success of high-residue cultivation. Common ragweed is known to be problematic in these rotational no-till systems in the northeastern United States, so it might be advantageous to forgo some control of later-emerging species in favor of greater common ragweed suppression. Similar to the relationship between seeding ratio and PAR transmittance, weed biomass tended to be lower in cover crop seeding ratio treatments that were more productive. Our hypothesis that mixtures of barley and cereal rye would provide greater weed suppression than either species in monoculture was not supported by these results.

Relationships among Cover Crops, PAR Transmittance, and Weeds. Comparing the R^2_i from simple linear regression analyses, PAR transmittance explains a greater proportion of the variance in weed biomass than cover crop biomass in both 2013 and 2014 (Table 3). However, this approach does not reveal the degree of redundancy that likely exists between the two predictors. Although cover crop biomass is intrinsically correlated with the amount of PAR that passes through the cover crop canopy (or, inversely, the amount intercepted by the canopy), it also contributes to weed suppression as rolled mulch. This helps differentiate the effect of cover crop biomass on weed biomass from the effect of PAR transmittance prior to cover crop termination. Without the confounding

Table 2. Results from the mixed-effects analysis of covariance (ANCOVA) on weed biomass and soybean yield.[a]

Effect[b]	Weed biomass	Soybean yield
	P-value	
Seeding ratio	<0.001	0.904
Management	0.036	0.890
Year	—[c]	0.003

[a] Block was included as a random effect. The covariate was seeding ratio treatment (barley:cereal rye, 100:0, 50:50, and 0:100), and the other factors were management treatment (SNT and HRC) and year (2013 and 2014).

[b] All three-way and two-way interactions were tested and removed from the models because they were not significant ($P > 0.05$).

[c] Year did not have an effect ($P > 0.05$) on weed biomass, so it was removed from the model.

Table 3. The proportion of variance in weed biomass (Y) in 2013 and 2014 as explained by bivariate $\left(R^2_i\right)$, partial $\left(pr^2_i\right)$, and semipartial $\left(sr^2_i\right)$ coefficients of determination for two predictor variables: photosynthetically active radiation (PAR) transmittance (X_1) and cover crop biomass (X_2).[a]

				Coefficients of determination		
Year	VIF[b]	CI[c]	Predictor	R^2_i	pr^2_i	sr^2_i
2013	2	19	PAR transmittance, X_1	0.666	0.354	0.174
			Cover crop biomass, X_2	0.600	0.225	0.111
2014	3	17	PAR transmittance, X_1	0.471	0.399	0.135
			Cover crop biomass, X_2	0.192	0.082	0.028

[a] Collinearity between the two predictors was assessed with variance-inflation factors (VIFs) and condition indices (CIs).

[b] As a general rule, a VIF > 10 signifies severe collinearity.

[c] Severe collinearity is also commonly indicated by a CI > 30.

presence of severe collinearity (VIF < 10 and CI < 30 in both years; Table 3), we were able to assess the proportion of variance in weed biomass that was uniquely explained by PAR transmittance and cover crop biomass. To do this, we used multiple linear regression and compared the sr_i^2 and pr_i^2 for each predictor variable (Table 3).

The sr_i^2 was 0.17 and 0.14 for PAR transmittance and 0.11 and 0.03 for cover crop biomass in 2013 and 2014, respectively. This indicates that PAR transmittance explains 17% of the variance in weed biomass in 2013 and 14% in 2014 when the effect of cover crop biomass has been partialed from PAR transmittance. In comparison, cover crop biomass explains 11% of the variance in weed biomass in 2013 and 3% in 2014 when the effect of PAR transmittance has been partialed from cover crop biomass. In other words, when X_i is added to a model that already contains the other predictor, sr_i^2 represents the incremental increase in explained variance in weed biomass that is uniquely due to X_i.

For the pr_i^2 analysis, PAR transmittance uniquely accounted for 35% of the variance in weed biomass after partialing the effect of cover crop biomass from both PAR transmittance and weed biomass in 2013. Conversely, cover crop biomass uniquely accounted for 23% of the variance in weed biomass after partialing the effect of PAR transmittance from both cover crop biomass and weed biomass in 2013. Similarly, in 2014 the amount of variance in weed biomass that was uniquely explained by PAR transmittance was greater than the proportion of variance explained by cover crop biomass.

It is worth reiterating that both PAR transmittance and cover crop biomass were measured prior to cover crop termination but the effect of cover crop biomass on weed suppression extends (as mulch) until soybean canopy closure and, to a lesser degree, until soybean harvest. Despite influencing weed suppression over a longer period of time, cover crop biomass uniquely explained less of the variance in weed biomass than PAR transmittance. These observations are consistent with previous research demonstrating that the percent ground cover prior to cereal rye jointing (Zadoks 31) was a strong predictor of weed biomass later in the season, after cover crop termination (Ryan et al. 2011a). Acknowledging that adequate cover crop biomass production is critical to the success of organic no-till planted soybean, our results suggest that farmers should consider implementing management practices that optimize shading prior to cover crop termination.

Soybean Population and Yield. In 2013 and 2014 the no-till planter was calibrated to dispense 740,000 seeds ha^{-1}. Final soybean stand counts in 2013 revealed that this high rate was exceeded with an average of 757,000 plants ha^{-1} at harvest. In 2014 average soybean population across treatments was only 545,000 plants ha^{-1}. We tested the effects of cover crop biomass and year on soybean population using ANCOVA and found an interaction between cover crop biomass and year ($P = 0.01$). Assessing each year separately using linear regression, soybean population decreased by 29,100 plants ha^{-1} for each 1 Mg ha^{-1} increase in cover crop biomass in 2013 ($P = 0.05$), but there was no relationship ($P = 0.35$) between cover crop biomass and soybean population in 2014 (Figure 5). Although high soybean seeding rates can cause lodging, this was not observed in our experiment. Within year, no differences ($P > 0.05$) in soybean yield between seeding ratio, no-till management treatment, or their interaction were detected in 2013 or 2014 (Table 2). However, soybean yield was higher ($P = 0.003$) at 2.9 Mg ha^{-1} in 2013 compared with 2.6 Mg ha^{-1} in 2014. Soybean yield under no-till management (HRC and SNT) was lower than the tillage-based on-site comparison (IRC management) across all seeding ratios, producing 98% of the yield obtained with IRC management in 2013 and 79% in 2014. The low weed biomass across treatments might help

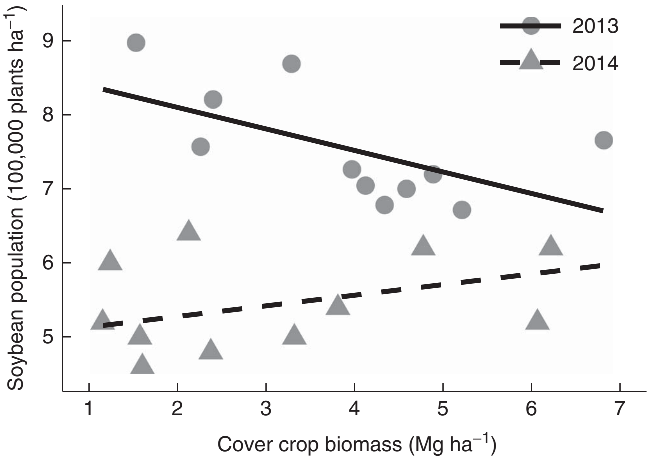

Figure 5. Soybean population at harvest as affected by cover crop biomass in 2013 and 2014. The interaction between cover crop biomass and year was significant ($P = 0.01$), and block was included as a random effect ($R^2_m=0.75$, $R^2_c=0.82$). Analyzing each year separately, there was a significant ($P = 0.05$) reduction in soybean population as cover crop biomass increased in 2013 ($y = 8.682 - 0.291x$, $R^2_m=0.31$, $R^2_c=0.53$), but there was no relationship ($P = 0.35$) between soybean population and cover crop biomass in 2014 ($y = 4.988 + 0.144x$, $R^2_m=0.09$, $R^2_c=0.09$).

explain why we observed no differences in soybean yield within year, but these results were still surprising, given the treatment differences among cover crop biomass, PAR transmittance, and weed biomass.

Despite accumulating less than 8.0 Mg ha^{-1} of cover crop biomass in each of the seeding ratio treatments, reduced soybean populations were observed in plots with more cover crop biomass—and thus more cereal rye biomass—in 2013. This relationship was not observed in 2014, possibly due to more challenging planting conditions and the relatively low soybean populations across all cover crop biomass levels. Other researchers have also reported lower crop populations in high-residue management systems, typically attributing the reduction to a decrease in soil moisture associated with the cover crop (De Bruin et al. 2005; Wells et al. 2015) or as a result of impaired planter function (e.g., hair-pinning) and poor seed-to-soil contact (Eckert 1988; Liebl et al. 1992; Mitchell and Teel 1977). Although soybean population at harvest in 2013 decreased as cover crop biomass increased, yield loss at lower populations can be avoided through increased branching, pod formation, and more seeds per plant (Carpenter and Board 1997; Lueschen and Hicks 1977; Weber et al. 1966). Despite this phenotypic plasticity, soybean yield can be reduced when excessive cover crop biomass prevents adequate planter function and seed placement (Liebl et al. 1992).

Weight was added to the no-till planter in 2014 in an effort to overcome the hard, dry soil conditions, but inadequate seed-to-soil contact and low soil moisture resulted in an average soybean population that was much lower than the targeted planting rate. In addition to a reduced soybean population, the below-average precipitation during June 2014 (Figure 1) might help explain the lower soybean yield in 2014 compared with 2013. Previous research has found that soil moisture loss through transpiration before cover crop rolling-crimping and after incomplete termination can substantially reduce soil water content (Ashford and Reeves 2003; Moschler et al. 1967; Munawar et al. 1990). This effect can be more pronounced when precipitation is low, with dry soil conditions resulting in low soybean emergence, seedling mortality, poor stands, and lower yields (De Bruin et al. 2005; Eckert 1988; Helms et al. 1996; Liebl et al. 1992; Wells et al. 2015). Regardless of the suite of factors that affected soybean yield in the experiment, our hypothesis that soybean yield would be greater with the addition of HRC than with SNT management alone was not supported. Considering the similarity in soybean yields between the two no-till treatments and the tillage-based management, organic farmers in the northeastern United States can, however, potentially realize greater profits when using the cover crop–based organic no-till planted soybean system due to the associated cost reductions from less labor and fuel use (Mirsky et al. 2012).

Management Implications. Although this experiment was managed without synthetic inputs, routine chemical herbicide use at the research farm in previous years likely contributed to the low weed populations and relative lack of weed species diversity observed. These conditions are not typical of most organically managed cropping systems (Bernstein et al. 2014; Thelen et al. 2004), because the legacy of low weed populations from previous herbicide use would only be present in fields that had recently been transitioned from conventional to organic production practices. Thus, it is important to consider the effects of past management practices, such as crop rotation (Ball 1992; Cardina et al. 2002; Liebman and Dyck 1993; Wortman et al. 2010) and tillage regime (Buhler 1995; Clements et al. 1996; Mohler and Callaway 1995; Murphy et al. 2006), on weed seedbank dynamics, as well as aboveground weed diversity, density, and abundance. Mirsky et al. (2012) found that high-residue cultivation decreased weed biomass by 66% and increased soybean yield by 23% compared with standard no-till. As weed biomass was greater in the Mirsky et al. (2012) study than in our experiment, the weed biomass reduction from high-residue cultivation likely had a greater impact on soybean yield.

Our results suggest that weed biomass can be reduced by enhancing cover crop shading prior to termination; however, mixtures of barley and cereal rye did not intercept more PAR than cereal rye grown in monoculture. Although our barley–cereal rye mixture did not provide increased shading, this objective might be achieved by seeding other species combinations. In the northeastern United States, cover crops used for mulch in organic no-till planted soybean production must be winter hardy and early maturing. In addition to these region-specific traits, an ideal cover crop mixture would include species that matured at approximately the same time to optimize the efficacy of rolling-crimping. Preferably, each cover crop species would also be nonleguminous for greater complementarity with the soybean cash crop, thereby enhancing the relative competitive ability of soybean, compared with weeds, through increased soil nitrogen depletion. Mixing a *Brassica* species with cereal rye might provide superior shading as a grass-broadleaf biculture, but research is required to determine optimal management. If a cover crop monoculture is used, selecting a winter cereal species with greater leaf area than cereal rye, such as triticale (× *Triticosecale* Witt.), also has the potential to enhance PAR interception. However, an assessment of any alternative winter cereal species must consider maturation and termination timing as they relate to soybean planting and yield potential.

Until these alternative mixtures or species have been evaluated, farmers can improve cover crop shading by modifying cereal rye monoculture seeding methods. For example, using narrower row spacing or drilling half of the seeding rate and broadcasting the remaining half might provide earlier, more complete ground cover. Increasing cereal rye seeding rates can also be effective for increasing weed suppression without increasing cover crop biomass (Ryan et al. 2011a). Thus, future research should focus on a multitactic approach to weed management that attains adequate—rather than maximum—biomass production and reduces the need for high-residue cultivation by enhancing shading prior to cover crop termination.

Acknowledgments

We would like to thank Chris Pelzer, Brian Caldwell, and all other members of the Sustainable Cropping Systems Lab at Cornell University for their assistance with in-field data collection, as well as Paul Stachowski and his staff at the Musgrave Research Farm for all of their assistance with field operations. We would also like to thank Fulbright Canada and the Natural Sciences and Engineering Research Council of Canada for financially supporting this research. This research was also partially supported with Hatch funding (2013-14-425, “Expanding the Role of Cover Crops in Sustainable Cropping Systems”).

Literature Cited

Arce GD, Pedersen P, Hartzler RG (2009) Soybean seeding rate effects on weed management. Weed Technol 23:17–22

Ashford DL, Reeves DW (2003) Use of a mechanical roller-crimper as an alternative kill method for cover crops. Am J Alternative Agr 18:37–45

Ball DA (1992) Weed seedbank response to tillage, herbicides, and crop rotation sequence. Weed Sci 40:654–659

Bartoń K (2015) MuMIn: multi-model inference. R package version 1.15.6. http://CRAN.R-project.org/package=MuMIn. Accessed February 12, 2016

Bastiaans L, Paolini R, Baumann DT (2008) Focus on ecological weed management: what is hindering adoption? Weed Res 48:481–491

Bates D, Maechler M, Bolker B, Walker S (2015) lme4: linear mixed-effects models using Eigen and S4. R package version 1.1-8. http://CRAN.R-project.org/package=lme4. Accessed January 17, 2016

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793–814

Belsley DA, Kuh E, Welsch RE (1980) Regression Diagnostics: Identifying Influential Data and Sources of Collinearity. Hoboken, NJ: Wiley. Pp 85–191

Beres BL, Harker KN, Clayton GW, Bremer E, Blackshaw RE, Graf RJ (2010) Weed-competitive ability of spring and winter cereals in the northern Great Plains. Weed Technol 24: 108–116

Bernstein ER, Posner JL, Stoltenberg DE, Hedtcke JL (2011) Organically managed no-tillage rye–soybean systems: agronomic, economic, and environmental assessment. Agron J 103:1169–1179

Bernstein ER, Stoltenberg DE, Posner JL, Hedtcke JL (2014) Weed community dynamics and suppression in tilled and no-tillage transitional organic winter rye–soybean systems. Weed Sci 62:125–137

Boutin C, Strandberg B, Carpenter D, Mathiassen SK, Thomas PJ (2014) Herbicide impact on non-target plant reproduction: what are the toxicological and ecological implications? Environ Pollut 185:295–306

Buhler DD (1995) Influence of tillage systems on weed population dynamics and management in corn and soybean production in the central USA. Crop Sci 35:1247–1257

Cardina J, Herms CP, Doohan DJ (2002) Crop rotation and tillage system effects on weed seedbanks. Weed Sci 50:448–460

Carpenter AC, Board JE (1997) Branch yield components controlling soybean yield stability across plant populations. Crop Sci 37:885–891

Clements DR, Benott DL, Murphy SD, Swanton CJ (1996) Tillage effects on weed seed return and seedbank composition. Weed Sci 44:314–322

Cohen J, Cohen P, West SG, Aiken LS (2003) Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences, 3rd edn. Mahwah, NJ: Erlbaum. Pp 64–100

Connolly J (1986) On difficulties with replacement-series methodology in mixture experiments. J Appl Ecol 23:125–137

Connolly J, Wayne P, Bazzaz FA (2001) Interspecific competition in plants: how well do current methods answer fundamental questions? Am Nat 157:107–125

Cox WJ, Cherney JH (2011) Growth and yield responses of soybean to row spacing and seeding rate. Agron J 103: 123–128

Creamer NG, Dabney SM (2002) Killing cover crops mechanically: review of recent literature and assessment of new research results. Am J Alternative Agr 17:32–40

Davis AS (2010) Cover-crop roller-crimper contributes to weed management in no-till soybean. Weed Sci 58:300–309

De Bruin JL, Porter PM, Jordan NR (2005) Use of a rye cover crop following corn in rotation with soybean in the upper Midwest. Agron J 97:587–598

Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carré G, Marquéz JRG, Gruber B, Lafourcade B, Leitão PJ, Münkemüller T, McClean C, Osborne PE, Reineking B, Schröder B, Skidmore AK, Zurell D, Lautenbach S (2013) Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36:27–46

Drew MC, Lynch JM (1980) Soil anaerobiosis, microorganisms, and root function. Annu Rev Phytopathol 18:37–66

Eckert DJ (1988) Rye cover crops for no-tillage corn and soybean production. J Prod Agric 1:207–210

Firbank LG, Watkinson AR (1985) On the analysis of competition within two-species mixtures of plants. J Appl Ecol 22:503–517

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570–574

Fox J (1997) Applied Regression Analysis, Linear Models, and Related Methods. Thousand Oaks, CA: Sage. Pp 337–366

Fox J, Monette G (1992) Generalized collinearity diagnostics. J Am Stat Assoc 87:178–183

Fox J, Weisberg S (2011) An R Companion to Applied Regression. 2nd edn. Thousand Oaks, CA: Sage. Pp 285–329

Graham MH (2003) Confronting multicollinearity in ecological multiple regression. Ecology 84:2809–2815

Helms TC, Deckard E, Goos RJ, Enz JW (1996) Soybean seedling emergence influenced by days of soil water stress and soil temperature. Agron J 88:657–661

Hendrickx J (2015) perturb: tools for evaluating collinearity. R package version 2.05. http://CRAN.R-project.org/package=perturb. Accessed March 5, 2016

Inouye RS, Schaffer WM (1981) On the ecological meaning of ratio (de Wit) diagrams in plant ecology. Ecology 62:1679–1681

Jolliffe PA (2000) The replacement series. J Ecol 88:371–385

Kim S (2015) ppcor: partial and semi-partial (part) correlation. R package version 1.1. http://CRAN.R-project.org/package=ppcor. Accessed February 7, 2016

Kornecki TS, Price AJ, Raper RL, Arriaga FJ (2009) New roller crimper concepts for mechanical termination of cover crops in conservation agriculture. Renew Agr Food Syst 24:165–173

Kornecki TS, Raper RL, Arriaga FJ, Balkcom KS, Price AJ (2005) Effects of rolling/crimping rye direction and different row-cleaning attachments on cotton emergence and yield. Pages 169–177 *in* Proceedings of the 27th Southern Conservation Tillage Conference. Florence, SC: Southern Extension and Research Activity

Kutner MH, Nachtsheim CJ, Neter J, Li W (2005) Applied Linear Statistical Models. 5th edn. New York: McGraw-Hill/Irwin. Pp 406–414

Lal R (1991) Tillage and agricultural sustainability. Soil Till Res 20:133–146

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627

Leyshon AJ, Sheard RW (1974) Influence of short-term flooding on the growth and plant nutrient composition of barley. Can J Soil Sci 54:463–473

Liebl R, Simmons FW, Wax LM, Stoller EW (1992) Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol 6:838–846

Liebman M, Dyck E (1993) Crop rotation and intercropping strategies for weed management. Ecol Appl 3:92–122

Logan TJ, Lal R, Dick WA (1991) Tillage systems and soil properties in North America. Soil Till Res 20:241–270

Lueschen WE, Hicks DR (1977) Influence of plant population on field performance of three soybean cultivars. Agron J 69:390–393

Marquardt DW (1970) Generalized inverses, ridge regression, biased linear estimation, and nonlinear estimation. Technometrics 12:591–612

McDaniel MD, Tiemann LK, Grandy AS (2014) Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol Appl 24:560–570

Mendiburu F (2015) agricolae: statistical procedures for agricultural research. R package version 1.2-3. http://CRAN.R-project.org/package=agricolae. Accessed December 11, 2015

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2009) Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J 101:1589–1596

Mirsky SB, Curran WS, Mortensen DA, Ryan MR, Shumway DL (2011) Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci 59:380–389

Mirsky SB, Ryan MR, Curran WS, Teasdale JR, Maul J, Spargo JT, Moyer J, Grantham AM, Weber D, Way TR, Camargo GG (2012) Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew Agr Food Syst 27:31–40

Mirsky SB, Ryan MR, Teasdale JR, Curran WS, Reberg-Horton CS, Spargo JT, Wells MS, Keene CL, Moyer JW (2013) Overcoming weed management challenges in cover crop-based organic rotational no-till soybean production in the eastern United States. Weed Technol 27:193–203

Mitchell WH, Teel MR (1977) Winter-annual cover crops for no-tillage corn production. Agron J 69:569–573

Mohler CL, Callaway MB (1995) Effects of tillage and mulch on weed seed production and seed banks in sweet corn. J Appl Ecol 32:627–639

Mortensen DA, Egan JF, Maxwell BD, Ryan MR, Smith RG (2012) Navigating a critical juncture for sustainable weed management. BioScience 62:75–84

Moschler WW, Shear GM, Hallock DL, Sears RD, Jones GD (1967) Winter cover crops for sod-planted corn: their selection and management. Agron J 59:547–551

Munawar A, Blevins RL, Frye WW, Saul MR (1990) Tillage and cover crop management for soil water conservation. Agron J 82:773–777

Murphy SD, Clements DR, Belaoussoff S, Kevan PG, Swanton CJ (2006) Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Sci 54:69–77

Myers MW, Curran WS, VanGessel MJ, Calvin DD, Mortensen DA, Majek BA, Karsten HD, Roth GW (2004) Predicting weed emergence for eight annual species in the northeastern United States. Weed Sci 52:913–919

Nakagawa S, Schielzeth H (2013) A general and simple method for obtaining R^2 from generalized linear mixed-effects models. Methods Ecol Evol 4:133–142

Nord EA, Curran WS, Mortensen DA, Mirsky SB, Jones BP (2011) Integrating multiple tactics for managing weeds in high residue no-till soybean. Agron J 103:1542–1551

Nord EA, Ryan MR, Curran WS, Mortensen DA, Mirsky SB (2012) Effects of management type and timing on weed suppression in soybean no-till planted into rolled-crimped cereal rye. Weed Sci 60:624–633

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. Weed Sci 60(Spec Issue 1): 31–62

Northeast Regional Climate Center. (2015) CLIMOD 2: monthly summarized data. http://www.climodtest.nrcc.cornell.edu. Accessed January 23, 2015

O'Brien RM (2007) A caution regarding rules of thumb for variance inflation factors. Qual Quant 41:673–690

Orlowski J, Cox WJ, DiTommaso A, Knoblauch W (2012) Planting soybean with a grain drill inconsistently increases yield and profit. Agron J 104:1065–1073

Paustian K, Six J, Elliott ET, Hunt HW (2000) Management options for reducing CO_2 emissions from agricultural soils. Biogeochemistry 48:147–163

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117–1123

Place GT, Reberg-Horton SC, Dunphy JE, Smith AN (2009) Seeding rate effects on weed control and yield for organic soybean production. Weed Technol 23:497–502

Pleasants JM, Oberhauser KS (2013) Milkweed loss in agricultural fields because of herbicide use: effect on the monarch butterfly population. Insect Conserv Diver 6: 135–144

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops—a meta-analysis. Agr Ecosyst Environ 200:33–41

Preacher KJ (2006) Testing complex correlational hypotheses with structural equation models. Struct Equ Modeling 13:520–543

Raper RL, Simionescu PA, inventors; the United States of America as represented by the Secretary of Agriculture, Auburn University, assignees. (2005) November 29. Smooth rolling cover crop roller. US patent 6,968,907 B1

Raper RL, Simionescu PA, Kornecki TS, Price AJ, Reeves DW (2004) Reducing vibration while maintaining efficacy of rollers to terminate cover crops. Appl Eng Agric 20:581–584

Rawlings JO, Pantula SG, Dickey DA (1998) Applied Regression Analysis: A Research Tool. 2nd edn. New York: Springer-Verlag. Pp 369–377

R Core Team. (2014) R: a language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org. Accessed July 13, 2015

Reicosky DC (1997) Tillage-induced CO_2 emission from soil. Nutr. Cycl Agroecosys 49:273–285

Relyea RA (2005) The impact of insecticides and herbicides on the biodiversity and productivity of aquatic communities. Ecol Appl 15:618–627

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

Ryan MR, Mirsky SB, Mortensen DA, Teasdale JR, Curran WS (2011b) Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci 59:238–246

Schipanski ME, Barbercheck M, Douglas MR, Finney DM, Haider K, Kaye JP, Kemanian AR, Mortensen DA, Ryan MR, Tooker J, White C (2014) A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agr Syst 125:12–22

Smith AN, Reberg-Horton SC, Place GT, Meijer AD, Arellano C, Mueller JP (2011) Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci 59:224–231

Smith KA, Restall SWF (1971) The occurrence of ethylene in anaerobic soil. J Soil Sci 22:430–443

Smith KA, Robertson PD (1971) Effect of ethylene on root extension of cereals. Nature 234:148–149

Taylor DR, Aarssen LW (1989) On the density dependence of replacement-series competition experiments. J Ecol 77: 975–988

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385–392

Thelen KD, Mutch DR, Martin TE (2004) Utility of interseeded winter cereal rye in organic soybean production systems. Agron J 96:281–284

Wagner-Riddle C, Gillespie TJ, Swanton CJ (1994) Rye cover crop management impact on soil water content, soil temperature and soybean growth. Can J Plant Sci 74:485–495

Wayman S, Cogger C, Benedict C, Burke I, Collins D, Bary A (2014) The influence of cover crop variety, termination timing and termination method on mulch, weed cover and soil nitrate in reduced-tillage organic systems. Renew Agr Food Syst, 30. doi: 10.1017/S1742170514000246

Weber CR, Shibles RM, Byth DE (1966) Effect of plant population and row spacing on soybean development and production. Agron J 58:99–102

Wells MS, Brinton CM, Reberg-Horton SC (2015) Weed suppression and soybean yield in a no-till cover-crop mulched system as influenced by six rye cultivars. Renew Agr Food Syst, 31. doi: 10.1017/S1742170515000344

Westgate LR, Singer JW, Kohler KA (2005) Method and timing of rye control affects soybean development and resource utilization. Agron J 97:806–816

Weston LA (1990) Cover crop and herbicide influence on row crop seedling establishment in no-tillage culture. Weed Sci 38:166–171

Wilkins ED, Bellinder RR (1996) Mow-kill regulation of winter cereals for spring no-till crop production. Weed Technol 10:247–252

Wortman SE, Lindquist JL, Haar MJ, Francis C (2010) Increased weed diversity, density and above-ground biomass in long-term organic crop rotations. Renew Agr Food Syst 25:281–295

Received June 6, 2016, and approved September 19, 2016.

Associate Editor for this paper: Martin M. Williams, II, USDA–ARS