Effects of Seeding Rate and Poultry Litter on Weed Suppression from a Rolled Cereal Rye Cover Crop

Author(s): Matthew R. Ryan, William S. Curran, Alison M. Grantham, Laura K. Hunsberger, Steven B. Mirsky, David A. Mortensen, Eric A. Nord, and Dave O. Wilson

Source: Weed Science, 59(3):438-444.
Published By: Weed Science Society of America
https://doi.org/10.1614/WS-D-10-00180.1
URL: http://www.bioone.org/doi/full/10.1614/WS-D-10-00180.1

Weed Science 2011 59:438–444

Effects of Seeding Rate and Poultry Litter on Weed Suppression from a Rolled Cereal Rye Cover Crop

Matthew R. Ryan, William S. Curran, Alison M. Grantham, Laura K. Hunsberger, Steven B. Mirsky, David A. Mortensen, Eric A. Nord, and Dave O. Wilson*

Growing enough cover crop biomass to adequately suppress weeds is one of the primary challenges in reduced-tillage systems that rely on mulch-based weed suppression. We investigated two approaches to increasing cereal rye biomass for improved weed suppression: (1) increasing soil fertility and (2) increasing cereal rye seeding rate. We conducted a factorial experiment with three poultry litter application rates (0, 80, and 160 kg N ha^{-1}) and three rye seeding rates (90, 150, and 210 kg seed ha^{-1}) in Pennsylvania and Maryland in 2008 and 2009. We quantified rye biomass immediately after mechanically terminating it with a roller and weed biomass at 10 wk after termination (WAT). Rye biomass increased with poultry litter applications (675, 768, and 787 g m^{-2} in the 0, 80, and 160 kg N ha^{-1} treatments, respectively), but this increased rye biomass did not decrease weed biomass. In contrast, increasing rye seeding rate did not increase rye biomass, but it did reduce weed biomass (328, 279, and 225 g m^{-2} in the 90, 150, and 210 kg seed ha^{-1} treatments, respectively). In 2009, we also sampled ground cover before rolling and weed biomass and density at 4 WAT. Despite no treatment effects, we found a correlation between bare soil before rolling (%) and weed biomass at 4 WAT. Our results suggest that increased rye seeding rate can effectively reduce weed biomass and that ground cover in early spring can influence weed biomass later in the growing season.

Nomenclature: Cereal rye, *Secale cereale* L.
Key words: Cover crops, cereal rye, organic.

There is interest in reducing preplant tillage among growers because of soil health benefits (Doran and Zeiss 2000) and potential time savings. In organic crop production, one relatively new method of reducing preplant tillage while maintaining adequate weed suppression is rotational no-till (Peigne et al. 2007). *Organic rotational no-till* is a term used to describe the practice in which organic cash crops are no-till planted into winter annual cover crops that are established with tillage the preceding fall (Ryan et al. 2011). In the mid-Atlantic region, farmers are experimenting with no-till planting organic soybean [*Glycine max* (L.) Merr.] into mechanically killed cereal rye cover crops (Mirsky et al. 2011; Smith et al. 2011). This approach relies on cover crops to provide in situ mulch to suppress weeds (Mohler and Teasdale 1993). Mulch from cover crops can suppress weeds by reducing light availability, lowering soil surface temperature, and physically blocking weed growth and through allelopathy (Creamer et al. 1996; Teasdale and Mohler 2000).

In the past, growers rarely used mechanically terminated cover crops as mulch to suppress weeds on a large scale because the resulting mulches were not persistent, uniform, or cost effective. Most challenges were due to equipment limitation, with mowing as the most widely available option for mechanically terminating cover crops (Creamer et al. 1996; Creamer and Dabney 2002). However, mowing macerates cover crop tissue, which accelerates decomposition and decreases the longevity of weed suppression provided by cover crop residue (Creamer et al. 1996; Creamer and Dabney 2002). Mowing cover crops can also result in inconsistent ground cover, especially with rotary mowers that do not evenly distribute residue. Uniform ground cover is important because weeds capitalize on available niche space and emerge in areas without residue. Roller-crimpers overcome these challenges by uniformly laying the cover crop down, crimping the vascular tissue, and leaving plants intact and attached to their roots (Creamer and Dabney 2002; Davis 2010).

Growing large amounts of cover crop biomass is critical because weed suppression increases with mulch rate and successful, season-long weed suppression depends on the amount of biomass cover crops accumulate before being terminated (Mohler and Teasdale 1993). Supplementing with additional mulch material is possible for small-scale growers, but for extensive acreage, increasing cover crop growth and biomass production is the only practical option. One of the most commonly used cover crops in mid-Atlantic region is cereal rye, and there are several ways of enhancing its biomass including seeding early in the fall and delaying termination in the spring (Mirsky et al. 2009; Saini et al. 2008). In Pennsylvania, Mirsky et al. (2009) manipulated rye seeding and termination dates in a factorial experiment and found that the termination date in the spring influenced cover crop biomass more than the seeding date in the fall. Biomass increased approximately 200 g m^{-2} for every 10-d delay in the spring; whereas, a 45-d differential in rye seeding date was necessary to achieve the same increase in the fall. Rye cultivar selection can also influence biomass production. In the same experiment, Mirsky et al. (2009) reported that 'Aroostook' consistently produced more biomass than 'Wheeler'.

Increasing rye seeding rate and soil fertility are two additional ways to increase rye cover crop biomass. In an experiment conducted in Salinas, CA, increasing cereal rye 'Merced' seeding rate initially increased rye growth and

DOI: 10.1614/WS-D-10-00180.1

* First, second, sixth, and seventh authors: Postdoctoral Researcher, Professor, Professor, and Postdoctoral Researcher, Department of Crop and Soil Sciences, 116 Agriculture Sciences and Industries Building, The Pennsylvania State University, University Park, PA 16802; third and eighth authors: Research Manager and Research Agronomist, The Rodale Institute, Kutztown, PA 19530; fourth author: Extension Associate, Lower Eastern Shore Research and Education Center, University of Maryland, Salisbury, MD 21801; fifth author: Research Ecologist, Sustainable Agricultural Systems Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Beltsville, MD 20705. Current address of the third author: Penn State Cooperative Extension, 110 Greystone Building, Gracedale Complex, 14 Gracedale Avenue, Nazareth, PA 18064. Current address of the fourth author: Cornell University Long Island Horticulture Research and Extension Center, 3059 Sound Avenue, Riverhead, NY 11901. Current address of the eighth author: King's Agriseeds Inc., 96 Paradise Lanes, Ronks PA, 17572. Corresponding author's E-mail: matt.ryan@psu.edu

Table 1. Soil phosphorus (P_2O_5), potassium (K_2O), loss-on-ignition organic matter (OM), and cation exchange capacity (CEC) for each site-year based on a composite sample that was collected between November and January after cereal rye was seeded.

Site	Year	P	K	OM	CEC
		——— Kg ha^{-1} ———		%	meq 100 g^{-1}
Pennsylvania	2008	504	136	5.2	10.4
	2009	1,409	289	5.3	14.3
Maryland	2008	401	110	1.0	4.5
	2009	659	182	0.9	2.7

biomass in early winter but the increase did not persist into the spring (Boyd et al. 2009). In the mid-Atlantic region, growers use cereal rye primarily to scavenge nitrogen in the soil profile that would otherwise leach out over the winter (Coale et al. 2001; Shipley et al. 1992). Thus applying fertilizer may seem counterintuitive. However, when using cereal rye for weed suppression in organic no-till planted crops, optimal agronomic management of the rye cover crop is important to achieve high levels of biomass for maximum weed suppression. We examined the role of fertilizer rate and cereal rye seeding rate on rye biomass production and subsequent weed suppression. The objective of this research was to determine if (1) applying poultry litter and increasing cereal rye seeding rate increases rye biomass, and (2) increasing rye biomass improves weed suppression. We hypothesized that rye biomass and weed suppression would increase with poultry litter application and cereal rye seeding rate.

Materials and Methods

Field Sites. We conducted the field experiment in 2008 and 2009 at the Rodale Institute in Kutztown, PA, and at the Lower Eastern Shore Research and Extension Center in Salisbury, MD, which provided four site-years. Plots at the Pennsylvania site had been managed organically for over 30 years; whereas, plots at the Maryland site had been managed organically for 5 years. The Pennsylvania plots were located on a shaley, silt loam of the Clarksburg series. At the Pennsylvania site, cereal rye followed legume crops in both years; rye followed soybean in 2007–2008 and alfalfa-orchard grass hay in 2008–2009. The Pennsylvania field sites were also amended with dairy manure–leaf litter compost (2.6–1–1.3) at approximately 22,500 kg ha^{-1} 2 yr prior in year 1 and immediately prior to cereal rye establishment in year 2. Soil at the Maryland site was Fort Mott loamy sand and Rosedale loamy sand, and foxtail millet [*Setaria italica* (L.) P. Beauv. subsp. *italica*] preceded rye in both years of the experiment. Although we did not quantify soil nitrogen, fields at the Maryland site were probably somewhat nitrogen deficient; whereas, fields at the Pennsylvania site probably had sufficient nitrogen due to the preceding leguminous crops and compost amendments. We tested soil fertility in the upper 20 cm in each field between November and January after planting cereal rye; soil from Pennsylvania was analyzed at Agri-Analysis[1] and soil from Maryland was analyzed at A&L Eastern Laboratories, Inc.[2] Soil P and K were substantially higher in the 2009 Pennsylvania site than the other three site-years (Table 1).

Cereal rye seeding rate and fertility rate treatments were arranged in a randomized split-block design. Plots were 9.1 by 6.1 m in 2008 but were reduced to 2.6 by 2.6 m in 2009 to better optimize available space. Cereal rye Aroostook was drill-seeded into a seedbed that had been prepared with tillage between early October and early November at all locations (Table 2). Rye was drill-seeded at three rates: 90, 150, and 210 kg seed ha^{-1}. In the mid-Atlantic region, cereal rye is typically seeded at 90 kg ha^{-1}, and thus our seeding rate range represented 1, 1.6, and 2.3 times the standard rate for the region. In early April of each year, poultry litter (Perdue AgriRecycle [4–2–3])[3] was applied by hand at 0, 80, and 160 kg total N ha^{-1}. We assumed half of this nitrogen would be available to the rye cover crop (D. Beegle, personal communication). Poultry litter pellets were made by a process that heats litter to between 82 and 107 C before milling and pelletizing, which reduces the likelihood of weed seed survival and unwanted dispersal from pellet applications.

The rye cover crop was terminated at 50% anthesis using a front-mounted 3.04-m-wide roller-crimper with a chevron pattern that reduces vibration (Raper et al. 2004). Although similar, the roller-crimper at the Pennsylvania site was custom built (Sayre 2003); whereas, the one at the Maryland site was purchased from a commercial supplier.[4] Roller-crimpers weighed approximately 725 kg when used in this experiment. The rye cover crop was rolled perpendicular to the direction it was drilled to improve mulch uniformity (Ryan 2003). Rye cover crops were successfully terminated with the roller-crimper in all site-years.

Sampling and Data Collection. We collected data on rye biomass and assessed weed suppression over a 10-wk period

Table 2. Dates of field operations and sampling events across site-years.

	Pennsylvania		Maryland	
Operation[a]	2008	2009	2008	2009
Rye seeding	Nov. 1, 2007	Oct. 3, 2008	Nov. 2, 2007	Oct. 16, 2008
Manure application	Apr. 4, 2008	Apr. 7, 2009	Apr. 11, 2008	Apr. 8, 2009
Ground cover 1 WAF	—	Apr. 14, 2009	—	Apr. 16, 2009
Rye termination	Jun. 13, 2008	May 19, 2009	May 15, 2008	May 8, 2009
Ground cover 1 WAT	—	May 26, 2009	—	May 15, 2009
Rye biomass	Jun. 17, 2008	May 26, 2009	May 20, 2008	May 21, 2009
Ground cover 4 WAT	—	Jun. 16, 2009	—	Jun. 5, 2009
Weed density 4 WAT	—	Jun. 16, 2009	—	Jun. 6, 2009
Weed biomass 4 WAT	—	Jun. 16, 2009	—	Jun. 6, 2009
Ground cover 10 WAT	—	Jul. 28, 2009	—	Jul. 17, 2009
Weed density 10 WAT	Aug. 22, 2008	Jul. 28, 2009	Aug. 4, 2008	Jul. 17, 2009
Weed biomass 10 WAT	Aug. 22, 2008	Jul. 28, 2009	Aug. 4, 2008	Jul. 17, 2009

[a] Abbreviations: WAF, weeks after fertilization; WAT, weeks after termination.

after terminating the rye cover crop. Rye biomass was quantified in each experimental unit by clipping and removing residue in a 0.5-m^2 quadrat approximately 5 d after rolling (Table 2). Rye biomass samples were placed in cloth bags, oven-dried at 50 C, and then weighed. Weed density, biomass, and species composition were quantified at 10 wk after termination (WAT) by clipping and removing all weeds within a 0.5-m^2 quadrat in each experimental unit (Table 2). Individual plants were counted by species prior to clipping. Weed biomass samples were dried and weighed as described for rye. In 2009 only, weed density and biomass were also quantified in each experimental unit at 4 WAT by using the same method described above.

Percentage Bare Soil. In 2009 at both the Maryland and Pennsylvania sites, photographs were taken in each plot (n = 36) at 1 wk after fertilization (WAF) and at 1 WAT. As much as possible, photographs were taken on overcast days before 10:00 A.M., for improved light quality and ability to distinguish colors. The sample area in the photograph was held constant by placing a meter stick on the ground, perpendicular to the direction of the planted rye rows to serve as a reference just inside the vertical borders of the viewfinder. Photographs were taken in the downward position using the automatic settings for white balancing, shutter speed, and aperture. The camera used at the Pennsylvania site was a Cannon Powershot S2 IS, and a Kodak EasyShare V1003 was used at the Maryland site. Images were cropped to remove the meter stick and percentage of bare soil was estimated using image analysis software. In brief, each pixel in an image was classified as bare soil, vegetation, or residue on the basis of the pixel color in red–green–blue color space. Vegetation was classified by a low ratio of red to green or a low ratio of green to blue. Bare soil was classified by low intensity (sum of red, green, and blue). Images from each combination of date and location were batch analyzed, and the threshold values used for pixel classification were determined by sampling pixels from several images from each batch (Nord et al. 2009). Details on the open source software, protocol, and computer code for this analysis are available online.[5]

Statistical Analyses. We used several statistical procedures to assess treatment effects and relationships between measured variables. First, we used analysis of variance (ANOVA) to test differences in rye biomass and weed biomass between treatments. We then used structural equation modeling (SEM) (Grace 2006) to help explain these results and to gain further insight into the study system. Finally we explored the effect of poultry litter and rye seeding rate on weed species diversity and tested for associations between dominant weed species and treatment levels using indicator species analysis (ISA) (Dufrene and Legendre 1997).

We used ANOVA to test for treatment differences in rye biomass, weed biomass, weed density, and weed species diversity. Weed biomass data were $\log(x + 1)$ transformed before analysis to meet the assumption of homogeneity of variance. Because the experiment was repeated at two locations over 2 yr, two different split-block mixed effect models were used to analyze rye biomass and weed biomass at 10 WAT. One model treated year as a random and site as a fixed effect; whereas, the other treated site as random and year as a fixed effect. Analyses were conducted using the MIXED and REG procedures in SAS v.9.1 statistical analysis software.[6] Means were compared using the Tukey-Kramer method. Treatment effects were considered significant at $P < 0.05$ for all analyses.

We used SEM to assess the effects of early ground cover on weed biomass at 4 WAT. We compared the direct effect of early ground cover on weed biomass to the indirect effect of early ground cover on weed biomass mediated by weed density using the software Amos 5.0.1 (Arbuckle 2007). Maximum likelihood estimation is used in SEM, which reduces bias and provides a more robust estimation of model parameters than multiple regression (Grace 2006). Although rarely used in weed science, SEM has been suggested as a complementary statistical approach for understanding relationships between multiple variables (Davis 2010).

We used ISA to test for associations between weed species and treatments using PC-ORD version 5.10 statistical software.[7] Indicator values for each species were calculated by multiplying the relative abundance across all three levels of each treatment (poultry litter or rye seeding rate) by the relative frequency across blocks within each treatment. Indicator values range from 0 (not detected) to 100 (exclusive association). Indicator values were tested using a Monte Carlo procedure with 1,000 runs and were considered significant at a $P < 0.05$.

Results and Discussion

Rye Biomass. Cereal rye growth was moderate in all site-years and biomass ranged from 630 to 807 g m^{-2} (6.3 to 8.1 Mg ha^{-1}). Rye cover crop biomass typically ranges from 450 to 1,150 g m^{-2} in the mid-Atlantic region depending on growing conditions (Mirsky et al. 2011). We observed relatively little difference in rye biomass between sites, possibly due to long-term organic management that included soil-building practices such as cover cropping and compost applications.

Rye biomass increased when poultry litter was applied, but increasing rye seeding rate did not increase rye biomass (Table 3). Rye biomass was lower in plots that did not receive poultry litter (mean 675 g m^{-2}) and increased by 93 and 112 g m^{-2} with 80 and 160 kg N ha^{-1}, respectively (Figure 1). However, there was a year × litter rate × seeding rate interaction ($P = 0.043$, Table 3). This three-way interaction was a result of differences in rye biomass between treatments in 2008 but not 2009. In 2008, within the lowest rye seeding rate (90 kg seed ha^{-1}), rye biomass was lower in the no litter treatment compared with the 80 and 160 kg N ha^{-1} treatments ($P = 0.0489$ and $P = 0.0492$, respectively). Another difference in 2008 that was not observed in 2009 was between the lowest seeding rate with no litter and the intermediate seeding rate and highest litter application.

Our results agree with Boyd et al. (2009), who found that increasing rye seeding rate did not result in increased rye biomass at rye maturity and concluded that lack of seeding rate effect on rye biomass at their last sampling date was due to compensatory growth through increased rye tillering. We did not quantify rye tiller density so cannot test for this effect. Future work should more comprehensively evaluate the extent to which rye can compensate for lower seeding rates by increasing tiller production.

Table 3. Results from ANOVA on cereal rye biomass at 1 wk after termination (1 WAT) and weed biomass at 10 wk after termination (10 WAT). Two model parameterizations were used to test for treatment effects with either year or site as a fixed effect. Year was a random effect in the first parameterization (left column) and site was a random effect in the second parameterization (right column).

	Rye biomass		Weed biomass	
Effect	Year random	Site random	Year random	Site random
	P-value			
Site	0.379	na	0.919	na
Year	na	0.705	na	0.626
Litter rate	0.005	0.005	0.826	0.822
Site × litter rate	0.165	na	0.464	na
Year × litter rate	na	0.101	na	0.795
Seed rate	0.438	0.465	0.014	0.018
Site × seed rate	0.217	na	0.012	na
Year × seed rate	na	0.639	na	0.037
Litter rate × seed rate	0.366	0.329	0.728	0.752
Site × litter rate × seed rate	0.227	na	0.836	na
Year × litter rate × seed rate	na	0.043	na	0.990

Weed Biomass and Density. Weed biomass at 10 WAT ranged from 2 to 665 g m^{-2} and was lower at the Pennsylvania site (mean 90 g m^{-2}) than the Maryland site (mean 291 g m^{-2}). We did not detect a difference in weed biomass between soil fertility treatments even though applying poultry litter led to an increase in cereal rye biomass. On the other hand, weed biomass decreased with increasing cereal rye seeding rate; means were 328, 279, and 225 g m^{-2} in the 90, 150, and 210 kg seed ha^{-1} treatments, respectively (Figure 2). Significant site × seeding rate and year × seeding rate interactions indicate effects of seeding rate varied by site and year (Table 3). Interactions were a result of the negative relationship between weed biomass and seeding rate being stronger at the Maryland than the Pennsylvania site and in 2008 than in 2009. Unlike weed biomass, weed density at 10 WAT was not different between treatments (data not shown). The disconnection between rye and weed biomass was also observed by Boyd (2009), who reported that increasing seeding rate did not affect final rye biomass, but it did reduce weed biomass.

Contrary to our hypothesis, increasing rye biomass by applying poultry litter did not decrease weed biomass, suggesting weed suppression may be influenced by factors other than the physical suppression provided by rye biomass. Wells et al. (2010) recently showed that rolled cereal rye cover crops can cause a dramatic nitrogen immobilization effect in the soil profile. If decreased nitrogen availability contributes to weed suppression, increasing nitrogen availability would negate the effects of increased rye biomass on weed suppression and may explain the disconnection between rye biomass and weed biomass.

To explore this effect we examined the relationship between rye biomass and weed biomass within each of the fertility and seeding rate treatments (Figure 3). Rye biomass was not related to weed biomass in seeding rate treatments when data were pooled across fertility levels (Figure 3, top), indicating poultry litter dampened the weed suppression effect of increased rye biomass. There was a significant negative relationship between rye biomass and weed biomass in the highest poultry litter application rate (160 kg N ha^{-1}). The gradient of rye biomass in this case was created by the three rye seeding rates, indicating that at high fertility levels increasing rye seeding rate decreases weed biomass. The apparent weak relationship between rye biomass and weed biomass at lower fertility levels may be due to the relatively narrow range of rye biomass that was produced in our experiment (Figure 3, bottom).

Early Weed Biomass and Density. In 2009, we also quantified weed biomass and density at 4 WAT. Weed

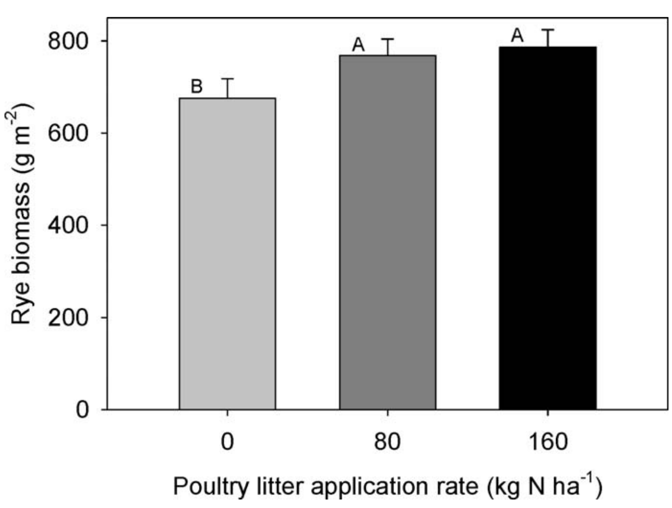

Figure 1. Mean cereal rye biomass at 1 wk after termination (1 WAT) across poultry litter application treatments. Data were pooled across site-years. Error bars represent standard error and similar letters to the left indicate no significant difference.

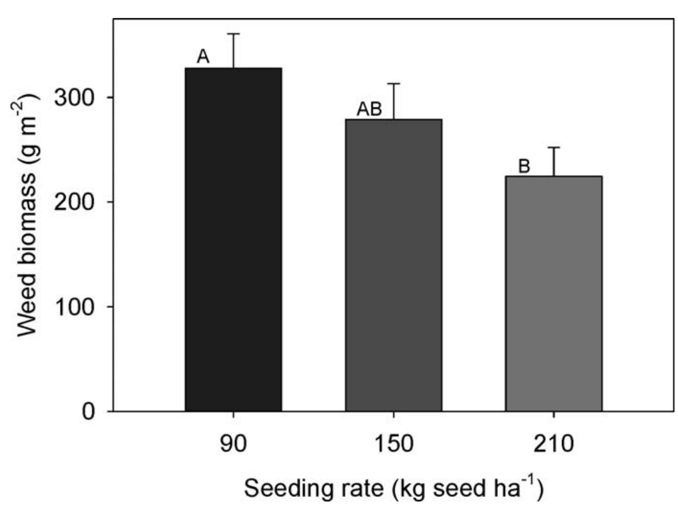

Figure 2. Mean weed biomass at 10 wk after rye termination (10 WAT) across cereal rye seeding rate treatments. Data were pooled across site-years. Error bars represent standard error and similar letter to the left indicate no significant difference.

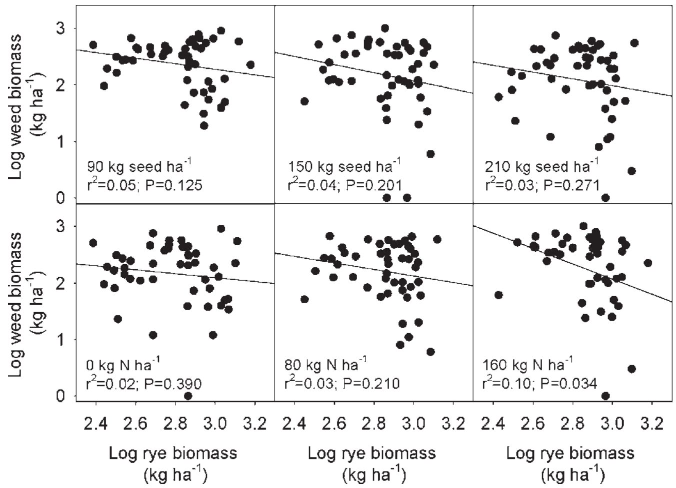

Figure 3. Relationship between rye and weed biomass in each fertility (lower) or seeding (upper) rate treatment.

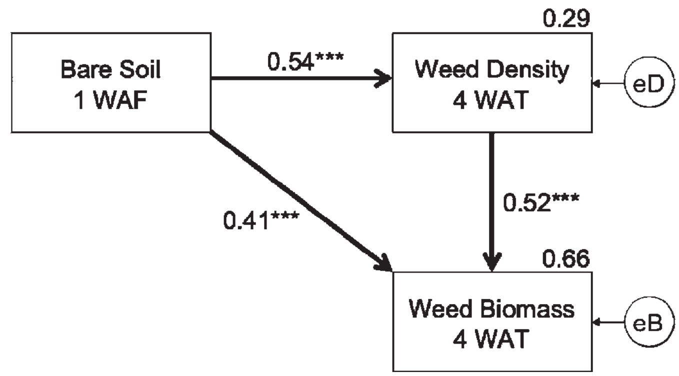

Figure 4. Path model used to compare the direct and indirect effects of ground cover in April on weed biomass in June. All path coefficients (standardized regression weights) were significant (***P < 0.001). Squared multiple correlations are listed above weed density at 4 wk after treatment (WAT) (r^2 = 0.29) and weed biomass at 4 WAT (r^2 = 0.66). Unexplained variance is represented by a circle to the right of each endogenous variable.

biomass at 4 WAT ranged from 0 to 164 g m^{-2} and was lower at the Pennsylvania site (mean 2 g m^{-2}) than at the Maryland site (mean 59 g m^{-2}), which was surprising given that soil fertility levels were higher at the Pennsylvania site (Table 1). Weed biomass at 4 WAT was not different across poultry litter application or rye seeding rate treatments in 2009. Similar to weed biomass, weed density at 4 WAT ranged from 0 to 120 plants m^{-2} and was lower at the Pennsylvania site (11 plants m^{-2}) than the Maryland site (34 plants m^{-2}). Early weed density was not different between fertility and seeding rate treatments (data not shown). Larger quadrats and multiple samples per experimental unit may have increased our ability to detect differences.

Early Ground Cover Affects Weed Biomass. Bare soil (%) was quantified using photographic analysis in 2009 to better understand the disconnection between rye biomass and weed biomass at 10 WAT. Similar to weed abundance at 4 WAT, rye seeding rate and fertility treatments did not affect bare soil 1 WAF (April) or 1 WAT (May) (data not shown). However, rye biomass was negatively correlated with bare soil at 1 WAF (r = −0.84; P < 0.001) and 1 WAT (r = −0.44; P < 0.001). Weed biomass at 4 WAT was positively correlated with bare soil at 1 WAF (r = 0.42; P < 0.001), but was not correlated with bare soil at 1 WAT (r = −0.06; P = 0.592). Weed density at 4 WAT was positively correlated with bare soil at 1 WAF (r = 0.47; P < 0.001), but was not correlated at 1 WAT (r = 0.10; P = 0.395). The lack of correlation between bare soil 1 WAT and weed biomass and density may be a result of covering previously exposed soil with rye residue during rolling (termination).

To further explore the effects of ground cover on weed abundance, we used SEM to compare the direct effect of bare soil at 1 WAF on weed biomass at 4 WAT to an indirect pathway that is mediated by weed density (Figure 4). Rye biomass was also evaluated for inclusion in the SEM model, but it did not improve model fit and was excluded. Bare soil at 1 WAF was a strong predictor of weed density at 4 WAT (standardized regression weight = 0.54, P < 0.001) and weed density was a strong predictor of weed biomass at 4 WAT (standardized regression weight = 0.52, P < 0.001). Thus, ground cover may have influenced weed biomass indirectly by regulating weed seedling recruitment from the soil weed seed bank. The direct effect of bare soil on weed biomass was slightly weaker (standardized regression weight = 0.41, P < 0.001), indicating ground cover may also directly influence weed biomass by other mechanisms such as light quality. Previous research has demonstrated that changes in the red to far-red light ratio (R : FR) originating from neighboring plants, or in this case a growing rye cover crop, may trigger a physiological shade avoidance response that reduces plant growth and fitness (Liu et al. 2009). This effect likely occurs early, prior to resource competition, and persists throughout the life of the plant (Rajcan et al. 2004). These results also suggest that ground cover early in the growing season before rolling-crimping (rye tillering stage, Zadoks 21–26) may be a good predictor of cover crop performance and associated weed suppression.

Weed Diversity. Dominant weed species, accounting for 75% of the total weed biomass (10 WAT) in each of the site-years, are listed in Table 4. We expected differences in weed diversity; however, ANOVA showed no difference in weed species richness, species evenness, Simpson's index, or Shannon index across treatments. We conducted an indicator species analysis to determine if any weed species was associated with poultry litter or rye seeding rate treatments. Across all site-years there were seven cases in which a weed species was associated (P < 0.05) with a particular poultry litter application rate or rye seeding rate treatment (Table 5). In the Pennsylvania 2008 site-year, hairy galinsoga [*Galinsoga ciliata* (Raf.) Blake] and common lambsquarters (*Chenopodium album* L.) were associated with the high poultry litter rate treatment. Both of these species occur in nitrogen rich soil (Ellenberg et al. 1991; Schaffers and Sykora 2000). The pattern observed in Pennsylvania for *C. album* did not hold in Maryland 2009. In Maryland, *C. album* was associated with the no litter treatment, indicating the relationship between soil fertility and this species is unclear (Table 5). However, *C. album* had a lower indicator value (IV) and higher P-value in Maryland 2009 (IV = 33, P = 0.029) compared with Pennsylvania 2008 (IV = 70, P = 0.001).

Two species, hedge bindweed [*Calystegia sepium* (L.) R. Br.] and hairy vetch (*Vicia villosa* Roth), were associated with the high rye seeding rate treatment (210 kg seed ha^{-1}). Both of

Table 4. Dominant weed species accounting for over 75% of total weed biomass across site-years. The proportion of total weed biomass that each species represents is presented for each site-year.

Site	Year	Common name	Species	Proportion of total
Pennsylvania	2008	Common ragweed	*Ambrosia artemisiifolia* L.	0.46
		Common lambsquarters	*Chenopodium album* L.	0.15
		Giant foxtail	*Setaria faberi* Herrm.	0.14
	2009	Common chickweed	*Stellaria media* (L.) Vill.	0.26
		Yellow foxtail	*Setaria glauca* (L.) Beauv.	0.17
		Redroot pigweed	*Amaranthus retroflexus* L.	0.10
		Yellow nutsedge	*Cyperus esculentus* L.	0.09
		Dandelion	*Taraxacum officinale* G.H. Weber ex Wiggers	0.07
		Ladysthumb	*Polygonum persicaria* L.	0.04
		Quackgrass	*Elytrigia repens* (L.) Desv. ex B.D. Jackson	0.04
Maryland	2008	Large crabgrass	*Digitaria sanguinalis* (L.) Scop.	0.56
		Common groundsel	*Senecio vulgaris* L.	0.16
	2009	Witchgrass	*Panicum capillare* L.	0.38
		Common groundsel	*Senecio vulgaris* L.	0.25
		Goosegrass	*Eleusine indica* (L.) Gaertn.	0.18

these species have a vine habit; however, *C. sepium* is a tenacious perennial weed, whereas *V. villosa* is a winter annual legume that is used as a cover crop at both sites. The lack of consistency across site-years makes drawing conclusions about the importance of these associations difficult. To better assess the effect of seeding rate and fertility on weed communities, weed seeds could be supplemented to standardize the initial weed community before applying treatments.

Conclusion

We set out to determine if increasing in situ cereal rye biomass by increasing soil fertility and seeding rate would result in greater weed suppression. Increasing soil fertility increased rye biomass; whereas, increasing rye seeding rate did not. This suggests that rye biomass potential at these sites was nutrient rather than seed limited. Interestingly, we did not observe a decrease in weed biomass with poultry litter, but increasing rye seeding rate did decrease weed biomass. Our results are consistent with a similar experiment that compared the effects of increasing seeding rate of a cover crop mixture that contained *Vicia* spp. and *Pisum* spp. (90% by weight) and oats (*Avena sativa* L.) in California (Brennan et al. 2009). As seeding rate increased, weed biomass decreased from approximately 30 g m^{-2} at the low seeding rate (112 kg seed ha^{-1}) to < 10 g m^{-2} at the high rate (336 kg seed ha^{-1}) (Brennan et al. 2009). Increasing cover crop seeding rate in that experiment did not affect final cover crop biomass; however, they concluded that it may be a cost-effective tactic because of the weed suppression benefits (Brennan et al. 2009).

The fact that weed biomass did not decrease, despite the increased rye biomass from poultry litter, suggests that weed suppression from rolled rye cover crops may be partially due to decreased nitrogen availability. Because weeds disproportionally benefit from overabundant soil fertility, crop competitiveness can be increased by temporally and spatially managing soil nutrient availability. This concept has been demonstrated in organic cropping systems in which the availability of nutrients in soil tends to be more synchronized with crop demand and may contribute to an increase in the relative competitive ability of crops (Crews and Peoples 2005; Kramer et al. 2002; Ryan et al. 2010). Whitehouse et al. (2009) proposed managing soil carbon to nitrogen ratios as a cultural weed management practice. This strategy can be particularly effective in legume crops such as soybean, in which the crop has a competitive advantage over weeds when soil nitrogen levels are low (Phelan et al. 2008). However, it is important to anticipate and match crop fertility demand to avoid compromising the competitive ability of crops when extrapolating data from our experiment to cropping situations.

In addition to the importance of soil fertility management, our results also demonstrate the role of cover crop ground cover in weed suppression. Ground cover at 1 WAF directly and indirectly affected weed biomass at 4 WAT. Although, we were unable to show that our treatments influenced early ground cover, results from this model suggest that early ground cover is an important driver of weed suppression. We speculate that shifts in R : FR from rye growth early in the spring may contribute to weed suppression after rye is rolled. Future research on organic no-till planted soybean should focus on elucidating this effect and testing rye cover crop management practices that maximize ground cover and minimize soil nitrate availability. These results also suggest that photographs or other ground cover assessment methods early in the growing season may assist organic growers in deciding if they have a sufficient cover crop stand to proceed

Table 5. Results from the indicator species analysis for each site-year showing the seven species that were associated with a treatment level. Indicator values (IV) are presented with P-value and the associated level for poultry litter application and cereal rye seeding rate treatments.

				Litter rate			Seeding rate		
Year	Site	Common name	Species name and authority	IV	P-value	kg N ha^{-1}	IV	P-value	kg seed ha^{-1}
2008	Pennsylvania	Hairy galinsoga	*Galinsoga ciliata* (Raf.) Blake	60	0.003	160	—	—	—
2008	Pennsylvania	Common lambsquarters	*Chenopodium album* L.	70	0.001	160	—	—	—
2008	Pennsylvania	Yellow foxtail	*Setaria glauca* (L.) Beauv.	53	0.017	80	—	—	—
2008	Pennsylvania	Annual fleabane	*Erigeron annuus* (L.) Pers.	48	0.013	80	—	—	—
2008	Pennsylvania	Hedge bindweed	*Calystegia sepium* (L.) R. Br.	—	—	—	46	0.017	210
2009	Pennsylvania	Hairy vetch	*Vicia villosa* Roth	—	—	—	33	0.029	210
2009	Maryland	Common lambsquarters	*Chenopodium album* L.	33	0.029	0	—	—	—

with no-till planting or if they should incorporate their cover crop and manage weeds with cultivation.

Source of Materials

[1] Agri-Analysis, Inc., Leola, PA 17540.

[2] A & L Eastern Laboratories, Inc., Richmond, VA 23237.

[3] Poultry litter, Perdue AgriRecycle, LLC, Seaford, DE 19973.

[4] Roller-crimper, I & J Manufacturing, Gap, PA 17527.

[5] Photographic determination of ground cover; roots.psu.edu/en/node/882.

[6] SAS statistical analysis software, SAS Institute Inc., Cary, NC 27513.

[7] PC-ORD version 5.10 statistical software, MjM Software, Gleneden Beach, OR 97388.

Acknowledgments

We would like acknowledge the assistance provided John Teasdale, Rich Smith, Mary Barbercheck, and Tom Richard for many helpful conceptual discussions and for input on drafts of this manuscript. We would also like to thank John Teasdale and Adam Davis for their assistance with statistical analyses. This research was supported by funding from the United States Department of Agriculture (USDA) Northeast Region Integrated Pest Management program.

Literature Cited

Arbuckle, J. L. 2007. Amos 16.0 User's Guide. Spring House, PA: Amos Development Corporation. 637 p.

Boyd, N. S., E. B. Brennan, R. F. Smith, and R. Yokota. 2009. Effect of seeding rate and planting arrangement on rye cover crop and weed growth. Agron. J. 101:47–51.

Brennan, E. B., N. S. Boyd, R. F. Smith, and P. Foster. 2009. Seeding rate and planting Arrangement effects on growth and weed suppression of a legume-oat cover crop for organic vegetable systems. Agron. J. 101:979–988.

Coale, F. J., J. M. Costa, G. A. Bollero, and S. P. Schlosnagle. 2001. Small grain winter cover crops for conservation of residual soil nitrogen in the mid-Atlantic Coastal Plain. Am. J. Alt. Agric. 16:66–72.

Creamer, N. G., M. A. Bennett, B. R. Stinner, J. Cardina, and E. E. Regnier. 1996. Mechanisms of weed suppression in cover crop-based production systems. HortScience 31:410–413.

Creamer, N. G. and S. M. Dabney. 2002. Killing cover crops mechanically: Review of recent literature and assessment of new research results. Am. J. Alt. Agric. 17:32–40.

Crews, T. E. and M. B. Peoples. 2005. Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review. Nutrient Cycling in Agroecosystems 72:101–120.

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

Doran, J. W. and M. R. Zeiss. 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15:3–11.

Dufrene, M. and P. Legendre. 1997. Species assemblages and indicator species: The need for a flexible asymmetrical approach. Ecol. Monogr. 67:345–366.

Ellenberg, H., H. E. Weber, R. Dull, V. Wirth, W. Werner, and D. Paulißen. 1991. Indicator values of plants in Central Europe. Scr. Geobot. 18:1–248.

Grace, J. B. 2006. Structural Equation Modeling and Natural Systems. New York: Cambridge University Press. 365 p.

Kramer, A. W., T. A. Doane, W. R. Horwath, and C. van Kessel. 2002. Combining fertilizer and organic inputs to synchronize N supply in alternative cropping systems in California. Agric. Ecosyst. Environ. 91:233–243.

Liu, J. G., K. J. Mahoney, P. H. Sikkema, and C. J. Swanton. 2009. The importance of light quality in crop–weed competition. Weed Res. 49:217–224.

Mirsky, S. B., W. S. Curran, D. A. Mortensen, M. R. Ryan, and D. L. Shumway. 2009. Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron. J. 101:1589–1596.

Mirsky, S. B., W. S. Curran, D. A. Mortensen, M. R. Ryan, and D. L. Shumway. 2011. Timing of cover crop management effects on weed suppression in no-till planted soybean using a roller-crimper. Weed Sci. 59:380–389.

Mohler, C. L. and J. R. Teasdale. 1993. Response of weed emergence to rate of Vicia-villosa Roth and Secale-cereale L residue. Weed Res. 33:487–499.

Nord, E. A., J. A. Postma, W. S. Curran, and D. A. Mortensen. 2009. Digital image analysis for determination of ground cover in cover crop systems. Pages 285–1 *in* Proceedings of the International Annual Meetings of the ASA-CSSA-SSSA. Madison, WI: ASA, CSSA, and SSSA.

Peigne, J., B. C. Ball, J. Roger-Estrade, and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use Manage. 23:129–144.

Phelan, L., D. Stinner, C. Nacci, and D. McCartney. 2008. Application of the niche concept to organic weed management. Pages 29–30 *in* Proceedings of the Midwest Organic Research Symposium. La Crosse, WI: Organic Farming Research Foundation.

Rajcan, I., K. J. Chandler, and C. J. Swanton. 2004. Red-far-red ratio of reflected light: a hypothesis of why early-season weed control is important in corn. Weed Sci. 52:774–778.

Raper, R. L., P. A. Simionescu, T. S. Kornecki, A. J. Price, and D. W. Reeves. 2004. Reducing vibration while maintaining efficacy of rollers to terminate cover crops. Appl. Eng. Agric. 20:581–584.

Ryan, M. 2003. Rye Lessons Learned Here at the Rodale Institute. http://www.rodaleinstitute.org/rye_lessons_learned. Accessed: March 26, 2011.

Ryan, M., S. Mirsky, D. Mortensen, J. Teasdale, and W. Curran. 2011. Potential synergistic effects of cereal rye biomass and soybean planting density on weed suppression. Weed Sci. 59:238–246. 59:238–246.

Ryan, M. R., D. A. Mortensen, L. Bastiaans, J. R. Teasdale, S. B. Mirsky, W. S. Curran, R. Seidel, D. O. Wilson, and P. R. Hepperly. 2010. Elucidating the apparent maize tolerance to weed competition in long-term organically managed systems. Weed Res. 50:25–36.

Saini, M., A. J. Price, E. Van Santen, F. J. Arriaga, K. S. Balkcom, and R. L. Raper. 2008. Planting and termination dates affect winter cover crop biomass in a conservation-tillage corn-cotton rotation: Implications for weed control and yield. Pages 137–141 *in* Proceedings of the 30th Southern Conservation Agricultural Systems Conference. Tifton, GA: Southern Conservation Agricultural Systems.

Sayre, L. 2003. Introducing a Cover Crop Roller without All the Drawbacks of a Stalk Chopper. http://newfarm.rodaleinstitute.org/depts/NFfield_trials/1103/notillroller.shtml. Accessed May 15, 2010.

Schaffers, A. P. and K. V. Sykora. 2000. Reliability of Ellenberg indicator values for moisture, nitrogen and soil reaction: a comparison with field measurements. J. Vegetation Sci. 11:225–244.

Shipley, P. R., J. J. Messinger, and A. M. Decker. 1992. Conserving residual corn fertilizer nitrogen with winter cover crops. Agron. J. 84:869–876.

Smith, A. N., S. C. Reberg-Horton, G. Place, A. Meijer, C. Arellano, and J. Mueller. 2011. Rolled rye mulch for weed suppression in organic no-tillage soybeans. Weed Sci. 59:224–231.

Teasdale, J. R. and C. L. Mohler. 2000. The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci. 48:385–392.

Wells, M. S., S. C. Reberg-Horton, and A. N. Smith. 2010. Nitrogen immobilization in a rye (*Secale cereale* L.) roll-killed system. Page 60044 *in* Proceedings of the International Annual Meetings of the ASA-CSSA-SSSA. Madison, WI: ASA, CSSA, and SSSA.

Whitehouse, S. E., A. DiTommaso, L. E. Drinkwater, and C. L. Mohler. 2009. Changes in weed vigor and growth in response to carbon and nitrogen ratio manipulation. Page 47 *in* Proceedings of the Sixty-Third Annual Meeting of the Northeastern Weed Science Society. Fredericksburg, PA: Northeastern Weed Science Society.

Received December 10, 2010, and approved April 4, 2011.