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Weed Community Dynamics and Suppression in Tilled and No-Tillage Transitional Organic Winter Rye–Soybean Systems

Emily R. Bernstein, David E. Stoltenberg, Joshua L. Posner, and Janet L. Hedtcke*

Grower adoption of no-tillage (NT) approaches to organic soybean production has been limited, in part because of the perceived risks of ineffective cover crop management and lack of season-long weed suppression. We conducted research in 2008 and 2009 to assess those risks by quantifying the effects of winter rye cover-crop management (tilling, crimping, or mowing), soybean planting date (mid May or early June), and row width (19 or 76 cm) on weed recruitment, emergence patterns, season-long suppression, and late-season weed community composition in transitional organic production systems. The weed plant community consisted largely of summer annual species in each year, with velvetleaf or common lambsquarters as the most abundant species. Seedling recruitment from the soil seedbank varied between years, but velvetleaf recruitment was consistently greater in the tilled rye than in the NT rye treatments. Weed emergence tended to peak early in the season in the tilled rye treatment, but in the NT rye treatments, the peak occurred in mid or late season. More-diverse summer annual and perennial species were associated with the NT rye treatments. Even so, weed suppression (as measured by late-season weed shoot mass) was much greater in crimped or mowed rye NT treatments than it was in the tilled treatment. Weed suppression among NT rye treatments was greater in 19- than in 76-row spacing treatments in each year and was greater for mid May than it was for early June planted soybean in 2009. The NT planting of soybean into standing rye before termination (crimping or mowing) facilitated timely planting of soybean, as well as effective, season-long weed suppression, suggesting that those approaches to rye and weed management are of less risk than those typically perceived by growers. Our results suggest that NT systems in winter rye provide effective weed-management alternatives to the typical tillage-intensive approach for organic soybean production.

Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; cereal rye, *Secale cereale* L.; soybean, *Glycine max* (L.) Merr.

Key words: Cover crop, diversified weed management, planting date, roller-crimper, row spacing.

Challenges associated with reliance on tillage for weed management in organic grain crop systems (Cavigelli et al. 2008; Porter et al. 2003; Posner et al. 2008) have spurred interest among organic growers for alternative approaches (Sooby et al. 2007; Walz 1999). Interest in using a winter rye cover crop in organic, no-tillage (NT) soybean systems has increased because of the perceived benefits of improved weed management relative to tillage, reduced fuel and labor inputs, reduced risk of soil erosion, and increased soil quality over time. A typical tillage-intensive approach to organic soybean production includes primary tillage and seedbed preparation followed by numerous in-crop tillage operations (rotary hoeing, tine weeding, interrow cultivation) (Bernstein et al. 2011; Posner et al. 2008). A typical organic NT approach eliminates preplant and postplant tillage operations with a fall-planted winter rye cover crop. For such an approach, winter rye is typically roller-crimped (flattened and crushed using a steel drum with blunt chevron blades attached to a tractor) at anthesis in early June (Bernstein et al. 2011; Davis et al. 2010), after which, soybeans are NT-planted into the rye mulch. However, several challenges are associated with this approach, including the need for a specialized roller-crimper, delayed soybean planting from mid May to early June, reduced soybean stand (Bernstein et al. 2011; De Bruin et al. 2005; Williams et al. 2000), and the potential risk of competition between rye and soybean for soil moisture and nutrients resulting in reduced yields and economic returns (Bernstein et al. 2011; De Bruin et al. 2005; Westgate et al. 2005).

Reports on the weed-suppressive ability of rye mulch have been contradictory. Several studies have reported that weed suppression increased with the amount of rye biomass at the time of killing

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(Ashford and Reeves 2003; Ryan et al. 2011; Westgate et al. 2005). Estimates of the minimum amount of rye mulch necessary for effective season-long weed suppression range from 9,000 to 15,000 kg ha^{-1} (Ryan et al. 2011; Smith et al. 2011; Teasdale and Mohler 2000). This may, in part, explain why De Bruin et al. (2005) found that rye mulch (1,000 to 4,000 kg ha^{-1}) did not suppress weeds sufficiently at sites where weed populations were high, particularly later-emerging weed species. Nord et al. (2011) found that rolled rye in organic NT soybean systems was an effective weed-management tactic at low weed seedbank densities (300 seeds m^{-2}), but at high weed seedbank densities (3,150 seeds m^{-2}), supplemental weed management was necessary. Compared with management of weeds with herbicides in NT soybean, rye mulch (3,000 to 11,000 kg ha^{-1}) provided sufficient weed suppression to eliminate the need for POST herbicides (Price et al. 2005; Davis 2010), PRE and POST herbicides (Liebl et al. 1992), and POST organic herbicides or high-residue cultivation (Smith et al. 2011).

The weed suppressive ability of NT rye mulch can be attributed to several factors. Physical factors include reduced light transmittance through the mulch (Teasdale and Mohler 1993; Wagner-Riddle et al. 1994), reduced amplitude and maximum soil-temperature fluctuations (Teasdale and Mohler 1993; Wagner-Riddle et al. 1994; Williams et al. 1998), increased soil-moisture content (Price et al. 2005; Williams II et al. 1998), and physical interference with seedling emergence (Teasdale and Mohler 2000). Additional effects may be due to a shift in the red to far-red light ratio under a green rye mulch, which may prevent weed seed germination (Teasdale and Mohler 1993), a low nitrogen environment because of the high C : N ratio of the rye mulch (Wells et al. 2013), and the release of allelopathic compounds inhibitory to weed seed germination and seedling growth (Burgos and Talbert 2000). However, allelopathy from a roller-crimped rye cover crop was not found in one study (Davis 2010). Delayed weed emergence in NT rye mulch systems also likely contributes to season-long weed suppression because weeds are less competitive than those in systems with no rye mulch (Williams et al. 1998). Reduced or delayed weed emergence or both in conventional herbicide, rye mulch, NT soybean systems, relative to no rye mulch, have been reported in several studies (Mirsky et al. 2011; Mohler and Teasdale 1993).

Rye mulch can have differential effects on seed germination and seedling growth among weed species. Mirsky et al. (2011) found that mulch from a rye cover crop that was terminated in May delayed weed emergence and lowered weed densities but not for later-emerging summer annual or perennial species, such as yellow nutsedge (*Cyperus esculentus* L.). They found that such asynchrony between cover-crop termination and the emergence of some weed species could change weed community composition. Tabaglio et al. (2013) found that redroot pigweed (*Amaranthus retroflexus* L.) and common purslane (*Portulaca oleracea* L.) were sensitive to rye allelochemicals, whereas common lambsquarters was not sensitive and velvetleaf was favored by rye mulch. The differential response among species was attributed in part to differential absorption of allelochemicals. Burgos and Talbert (2000) found that small-seeded weed species were more sensitive to rye allelochemicals than were large-seeded weed species in culture-dish bioassays. However, Mohler and Teasdale (1993) found no relationship between seed size and emergence of weed species through rye mulch in field studies. Other field research in NT corn (*Zea mays* L.) found that a rye cover-crop mulch did not affect weed community species composition compared with no rye (with herbicides) (Moonen and Bàrberi 2004).

Other management practices, such as soybean planting date, soybean seeding rate, and rye termination method, may affect weed community dynamics and suppression. Increased soybean seeding rate in organic systems is associated with improved weed management and increased soybean yield and returns (Place et al. 2009). Ryan et al. (2011) found that increased rye biomass and soybean seeding rate was associated with increased weed suppression, and that the relationship was synergistic, in some cases. In contrast, Coulter et al. (2011) found no effect of soybean seeding rate on weed density; however, when soybean planting date was delayed from mid May to mid June, weed density was 51% less (Coulter et al. 2011).

Wisconsin is second in the United States in number of certified organic farms, of which, approximately one-half are organic dairies (USDA-NASS 2012). The rapid expansion of organic dairy production in Wisconsin has led to a simultaneous increase in organic pasture and grain crop production. Although interest has increased among organic grain crop producers in alternatives to tillage-intensive approaches to weed management, our

Table 1. Rye and soybean management treatments for experiments conducted at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009.

Year	Treatment	Rye management		Soybean planting date	Soybean row spacing	Soybean viable seeding rate
		Implementation	Date			
					cm	seeds ha^{-1}
2008	Tilled	Chisel-disk	April 23	May 21	76	511,500
	Mowed	Mowed	June 11	May 21	76	511,500
	Drilled-crimped	Crimped	June 11	May 21	19	625,200
	Drilled-mowed	Mowed	June 11	May 21	19	625,200
	Late crimped-drilled	Crimped	June 11	June 17	19	568,300
	Late mowed-drilled	Mowed	June 11	June 17	19	568,300
2009	Tilled	Chisel-disk	April 17	May 18	76	511,500
	Mowed	Mowed	June 6	May 18	76	511,500
	Drilled-crimped	Crimped	June 6 and June 12	May 18	19	625,200
	Drilled-mowed	Mowed	June 6	May 18	19	625,200
	Late crimped-drilled	Crimped	June 6 and June 12	June 6	19	625,200
	Late mowed-drilled	Mowed	June 6	June 6	19	625,200

understanding of cover crop and conservation tillage effects on weed community dynamics and season-long weed suppression in organic grain crop production systems is limited. Our previous research found that soybean yields were less in organically managed NT rye mulch systems than they were in tilled systems, but NT systems had fewer labor inputs and 25% greater profitability per hour (Bernstein et al. 2011). Further, predicted soil erosion was nearly 90% less in NT than in tilled systems. Much recent research has been conducted to better understand the effect of these high-residue NT systems on weed community dynamics and suppression in both organic and conventional contexts (Davis 2010; Mirsky et al. 2011; Nord et al. 2011; Smith et al. 2011), yet little is understood about these aspects between organic tilled and NT rye–soybean systems. Therefore, our objectives were to quantify the effects of winter rye cover crop management (tilling, crimping, or mowing), soybean planting date (mid May or early June), and soybean row width (19 or 76 cm) on weed recruitment, emergence patterns, season-long suppression, and late-season weed community composition in transitional organic production systems.

Materials and Methods

Field Procedures and Experimental Design. Research was conducted at the University of Wisconsin Arlington Agricultural Research Station (UWAARS) (43°18′N, 89°21′W; 315 m above sea level) near Arlington, WI, in 2008 and 2009. The soil type was a Plano silt loam, with 4.7% organic matter and pH 6.7 in 2008, and 3.6% organic matter and pH 6.0 in 2009, typical of prairie-derived soils of Wisconsin. Research sites changed each year to place the study following conventionally-managed corn silage. The experimental design was a randomized complete block with four replications of six treatments (Table 1). The tilled treatment represented a typical organic soybean production system, whereas the other five treatments were NT rye cover crop treatments with varying factors of rye management, soybean planting date, and row spacing (seeding rate). Plot size was 9 m wide by 55 m long in 2008 (0.050 ha) and 9 m wide by 50 m long in 2009 (0.045 ha).

Winter rye variety ‘Rymin’ was planted in early October (October 5, 2007, and October 10, 2008) at a rate of 180 kg ha^{-1}. Rye in the tilled treatment was disk-chiseled in mid April at the second-node growth stage (Feekes growth stage 7) (Zadoks et al. 1974) or at tillering (Feekes growth stage 4) (Table 2). The subsequent stale seedbed was lightly disked and field cultivated for weed management and seedbed preparation before soybean planting (Table 2). Organic feed-grade soybean varieties (maturity group I) ‘Viking 0.1832’ in 2008 and ‘Blue River 16A7’ in 2009 (Viking 0.1832 was not available in 2009) were treated with a liquid inoculants (Cell-Tech SCI Soybean Custom Inoculant, EMD Crop BioScience, Inc., Brookfield, WI 53005) and planted with a conservation-tillage planter (76-cm row spacing) or NT drill (19-cm row spacing). In the mowed, drilled-crimped, and drilled-mowed treatments (Table 1), soybeans were planted on the same date as in the tilled treatment, approximately 2 wk before crimping or mowing the rye. Rye in the five NT treatments was flattened using a 4.6-m-wide roller–crimper (I & J Manufacturing,

Table 2. Preplant and in-crop tillage practices for the tilled treatment in experiments conducted at the University of Wisconsin–Arlington Agricultural Research Station in 2008 and 2009.[a]

	Preplant tillage[a]				In-crop tillage	
Year	Chisel-disk	Disk	Seedbed preparation[b]	Tine weeding	Rotary hoeing	Inter-row cultivation
	date					
2008	April 23	May 2	May 21 (2×)	May 28	—[c]	June 24
	—	May 9	—	June 16 (2×)	—	July 2
	—	—	—	—	—	July 15
2009	April 17	May 12 (2×)	May 18 (3×)	May 22	June 1	June 26
	—	—	—	—	June 12	July 7
	—	—	—	—	June 18	—

[a] 2X and 3X indicate two and three passes, respectively.
[b] Soil finisher in 2008; field cultivator (×2) and cultipacker (×1) in 2009.
[c] Dash (—) indicates operation was not conducted.

Gap, PA 17527) or mowed at a height of 15 cm using a 2.1-m-wide sickle-bar mower (model 350, Deere & Company, Moline, IL 61265), in early June, after the rye reached late anthesis (Feekes stage 10.5.1). The roller–crimper was filled with water, for a total mass of 1,360 kg. In 2009, the rye was crimped twice, on June 6 and 12, in part because of the unevenness of the soil surface, which reduced effectiveness of the roller–crimper. Each year, immediately after the rye was crimped or mowed, soybeans were drilled into the late-planted treatments (late crimped-drilled and late mowed-drilled) (Table 1). The drill mass was increased by 800 kg to improve seed placement, and row cleaners were removed to avoid clogging in the rye mulch. In the tilled treatment, flex-tine weeding, rotary hoeing, and interrow cultivation were used for weed management as needed, typically two to three passes each, spaced a week apart from mid May until soybean canopy closure in July (Table 2).

Data Collection. Weather data were measured at a meteorological station about 1.7 and 3.2 km from the research sites in 2008 and 2009, respectively (Wisconsin State Climatology Office, Madison, WI 53706). Growing degree days were calculated for rye using a base temperature of 1 C and an optimum temperature of 18 C (Feyereisen et al. 2006). Soybean growing degree days (GDD) were calculated using a base temperature of 10 C and an optimum temperature of 30 C (Zhang et al. 2001).

In early April of each year, 80 soil cores (10 cm deep, 1.9-cm-diam core, 0.023 m^2) were sampled from each block to characterize the viable soil weed seedbank as described by Forcella et al. (2003), with modifications. Soil samples were stored at 0 C until seed-germination tests were conducted in the greenhouse. Soil was mixed with one part sterile sand and placed in plastic trays no deeper than 5 cm. Greenhouse day/night temperatures were 15.6/15.6 C, and the photoperiod was 16 h. Trays were subirrigated as needed to keep soil moisture near field capacity. Seedlings were counted, identified, and removed shortly after emergence. After 3 wk, soil was air dried, mixed, and rewet for another germination and emergence cycle. This process was repeated once more, for three total germination cycles. After the third cycle, dormant seeds were separated by wet-sieving as described by Kovach et al. (1988). A 20-mesh screen was used to retain weed seeds from washed soil samples. Seeds were dried at 21 C, counted, and identified (Delorit 1970; Uva et al. 1997) with the aid of a table-mounted magnifying lens. During counting, seeds that withstood the pressure of a fine-tipped forceps were considered viable, representing the dormant portion of the seedbank. Seed number was expressed based on soil surface area. Weed plant density of each species was determined in four permanent 1-m^2 quadrats per plot every 7 d from June to mid July and every 14 d until September; at which time, aboveground weed mass was harvested by hand, separated by species, dried at 21 C until a constant mass was achieved, and weighed.

Data Analysis. The species-specific contribution to weed aboveground biomass (relative biomass, Equation 1) (Williams II 2009) in the late-season community was calculated using the average late-season weed mass per plot:

$$\text{Relative biomass} = M_i/M \qquad [1]$$

where M_i is the amount of aboveground biomass of the ith species (across all plots), M is the total amount of weed biomass in all plots (24 in each year).

Weed seedling recruitment was calculated from the cumulative number of emerged seedlings of a species per square meter divided by the number of seeds of that species in the seedbank per square meter (Davis and Liebman 2003). Cumulative emergence was estimated by taking the initial count of a species and adding any subsequent increase in density of that species to the initial count.

ANOVA was conducted using the PROC MIXED in SAS/STAT (SAS Institute Inc., Cary, NC 27513-2414) to test the effect of treatments on total weed density and recruitment: total, velvetleaf, common lambsquarters, redroot pigweed, and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.]. Data were analyzed within each year with the block considered a random effect. All data were tested for homogeneity of variance by examining residual versus predicted plots and for normal distribution of variance using the PROC UNIVARIATE to examine quantile–quantile plots (Littell et al. 2006; Onofri et al. 2010; Piepho 2009). Data were transformed, if needed, using the Box–Cox transformation in the PROC TRANSREG. Back-transformed data are presented for ease of interpretation (Piepho 2009). Total weed density was analyzed with repeated measures because the same quadrats were counted multiple times throughout each season, similar to the methods used by Davis and Liebman (2003). Because transformations did not adequately stabilize the heterogeneous variance of the weed-density data and the generalized mixed models (Poisson and negative binomial) in the PROC GLIMMIX of SAS/STAT failed to converge, a general, linear, mixed model with heterogeneous treatment variance was used by specifying the treatments as variance groups in the repeated statement of the PROC MIXED (Littell et al. 2006; Onofri et al. 2010). Preplanned contrasts were made to compare rye and soybean management effects within NT rye treatments and between tilled and NT rye treatments.

Nonmetric multidimensional scaling (NMDS), a multivariate ordination method, was used to examine the similarities in the weed community species composition among treatments (Clarke 1993). NMDS is considered the most robust and generally applicable ordination method for community data analysis because minimal distributional assumptions are made about the data (Clarke 1993; Kenkel et al. 2002; Minchin 1987). Years were pooled to have replication for tests, and a two-dimensional NMDS plot was created for late-season weed biomass using the default parameters in PRIMER-E (Primer-E Ltd., Ivybridge PL21 9RH, UK). Data were square root transformed to reduce the influence of very abundant species. Species occurring in less than three plots were considered rare and were omitted from the species matrix, reducing the number of species from 35 to 28. The Sørenson (Bray-Curtis) distance measure was used to create the similarity matrices for the NMDS. Each species present and its mass in each research plot were used to calculate the degree of similarity among plots (each plot was compared with every other plot). The ordination represents the dimensional relationship between communities in plots by matching the distance between points in the figure (each representing a research plot) to similarity values. Points that are closer to each other in the ordination show greater similarity in species composition and abundance.

A nonparametric permutation procedure (analysis of similarity [ANOSIM]) in PRIMER-E was conducted to determine relative effects among treatment factors on late-season weed biomass (Clarke 1993; Clarke and Warwick 2001). Research plots were classified as tilled or NT and were classified by the NT rye treatment factors of soybean row-spacing, soybean planting date, and rye management method. Two-way, crossed ANOSIM, with treatment and years as factors and blocks as replications, was conducted. A test statistic (R) equaled 1 if data values among replicates within a treatment showed greater similarity to each other than they did to the data of the other treatments. Conversely, if R equaled -1, data values among replicates within a treatment showed greater similarity to the data of other treatments than they did to each other. If R was near 0, data values among replicates within and between treatments were the same, indicating no treatment effect (the null hypothesis).

Two-way contribution of species to similarity (similarity percentages, SIMPER), with year and tillage as crossed factors, was conducted in PRIMER-E to determine which species were contributing to the dissimilarity between the tilled and NT plots and which species contributed to similarity within the tilled and NT plots. Similarity values are restricted to values between 0 and 100%; a value of 0% indicates that the same species did not occur in each plot, and a value of 100% indicates that the same species-specific contribution to biomass occurred in each plot. In contrast, a dissimilarity value of 0% indicates that the same species-specific contribution to biomass occurred in each plot, and a value of 100% indicates that the same species did not occur in each plot.

Results and Discussion

Year and Site Characterization. Growing seasons in each year for rye and soybean were characterized by temperatures below the long-term average (1978 to 2007) and variable precipitation (data not shown). During the rye growing season, from October to May, precipitation was similar to the long-term average in the 2007 to 2008 season and was above average in the 2008 to 2009 season, whereas accumulation of growing degree days for rye was below average in each year. Rye shoot biomass was greater in 2008 than it was in 2009, reaching 10,800 and 4,300 kg ha^{-1} at late anthesis, respectively. Greater rye biomass in 2008 was attributed in part to more timely precipitation, slightly warmer spring temperatures, and greater soil fertility than in 2009 (data not shown). During the soybean growing season, from May to October, precipitation was above average in 2008 and below average in 2009. Precipitation was threefold above average in June 2008. However, several dry periods occurred in May, August, and September 2008 and in July and September 2009, with precipitation about 50% of average.

Total density of the viable weed seedbank in the upper 10 cm of soil was lower in 2008 than it was in 2009. In 2008, the mean $\pm$ SE viable seedbank density was 2,300 $\pm$ 300 seeds m^{-2}, 21% of which were nondormant (480 seeds m^{-2}). The most abundant species in the viable seedbank were common lambsquarters (1,160 $\pm$ 200 seeds m^{-2}), ladysthumb (*Polygonum persicaria* L.; 540 $\pm$ 120 seeds m^{-2}), woolly cupgrass [*Eriochloa villosa* (Thunb.) Kunth; 110 $\pm$ 46 seeds m^{-2}], and yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes; 120 $\pm$ 120 seeds m^{-2}]. In 2009, the viable seedbank density was 11,300 $\pm$ 1,070 seeds m^{-2}, 11% of which were nondormant (1,300 seeds m^{-2}). The most-abundant species were common lambsquarters (8,120 $\pm$ 670 seeds m^{-2}), prostrate knotweed (*Polygonum aviculare* L.; 790 $\pm$ 120 seeds m^{-2}), redroot pigweed (420 $\pm$ 70 seeds m^{-2}), and ladysthumb (450 $\pm$ 260 seeds m^{-2}). These viable seedbank densities in our research were within the range of total seedbank densities measured across the U.S. Corn Belt (600 to 162,000 seeds m^{-2}) (Forcella et al. 1992).

The late-season weed plant community consisted largely of summer annual species in each year (Table 3). In 2008, velvetleaf was the most abundant species (59% of total aboveground biomass) in the weed community, followed by common lambsquarters (18%), barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.] (7%), , redroot pigweed (6%), and prostrate knotweed (3%). In 2009, common lambsquarters was the most-abundant species (71% of biomass), followed by ladysthumb (7%), redroot pigweed (4%), prostrate knotweed (4%), and velvetleaf (3%).

Seedling Recruitment. Seedling recruitment was consistently low in the NT rye treatments across years but varied between years in the tilled treatment (Table 4). In 2008, total seedling recruitment of the viable seedbank was greater in the tilled treatment (2.7%) than it was in the NT rye treatments ($\leq$ 0.3%). Velvetleaf recruitment (58%) was more than 100 times greater in the tilled treatment than it was in the NT rye treatments ($\leq$ 0.5%). Similarly, common lambsquarters, redroot pigweed, and shepherd's-purse recruitment was greater in the tilled treatment than it was in the NT rye treatments. Among the NT rye treatments, total seedling recruitment was greater in mowed than the crimped treatments but was not affected by other treatment factors. Common lambsquarters recruitment was greater in mowed than the crimped treatments and in treatments with wide, compared with narrow, soybean row spacing.

In contrast to 2008, seedling recruitment in 2009 was greater in NT rye treatments (0.3 to 0.6%) than it was in the tilled treatment (0.2%) (Table 4). Shepherd's-purse recruitment was greater in NT rye treatments (1.5 to 2.6%) than it was in the tilled treatment (0.6%). However, similar to 2008, velvetleaf recruitment was greater in the tilled treatment (9.8%) than it was in the NT rye treatments ($\leq$ 5.6%). Among NT rye treatments, velvetleaf recruitment was greater in the mowed than the crimped treatments, and common lambsquarters recruitment was greater in the late-planted than it was in the early planted treatments. These results are consistent with Mirsky et al. (2010) in that velvetleaf recruitment was greatest in high-disturbance cropping systems, and that common lambsquarters was less responsive to disturbance.

Weed Emergence and Density. In both years, weed density peaked early in the season in the tilled treatment and then declined (Figure 1). In contrast, weed density in the NT rye treatments peaked in the late season in 2008 and in the mid and late season in 2009. In 2008, weed densities were greater

Table 3. Relative aboveground biomass among species in the late-season weed community in 2008 and 2009. Data were pooled over treatments.

Weed species		Relative biomass[a]		
Common name	Latin binomial	Bayer code	2008	2009
			% of total biomass	
Velvetleaf	*Abutilon theophrasti* Medik.	ABUTH	0.59	0.03
Redroot pigweed	*Amaranthus retroflexus* L.	AMARE	0.06	0.04
Common lambsquarters	*Chenopodium album* L.	CHEAL	0.18	0.71
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv.	ECHCG	0.07	—
Prostrate knotweed	*Polygonum aviculare* L.	POLAV	0.03	0.04
Ladysthumb	*Polygonum persicaria* L.	POLPE	< 0.01	0.07
Giant foxtail	*Setaria faberi* Herrm.	SETFA	0.01	0.02
Yellow foxtail	*Setaria pumila* (Poir.) Roemer & J.A. Schultes	SETLU	0.01	0.01
Green foxtail	*Setaria viridis* (L.) Beauv.	SETVI	0.01	—
Dandelion	*Taraxacum officinale* G.H. Weber ex Wiggers	TAROF	0.01	0.01
White clover	*Trifolium repens* L.	TRFRE	< 0.01	0.05
Other species[b]			< 0.03	0.02

[a] Dash (—) indicates species was not present.

[b] Boxelder, *Acer negundo* L. ACRNE; shepherd's-purse, *Capsella bursa-pastoris* (L.) Medik. CAPBP; Canada thistle, *Cirsium arvense* (L.) Scop. CIRAR; smooth crabgrass, *Digitaria ischaemum* (Schreb.) Schreb. ex Muhl. DIGIS; large crabgrass, *Digitaria sanguinalis* (L.) Scop. DIGSA; quackgrass, *Elymus repens* (L.) Gould AGRRE; woolly cupgrass, *Eriochloa villosa* (Thunb.) Kunth ERBVI; common sunflower, *Helianthus annuus* L. HELAN; Venice mallow, *Hibiscus trionum* L. HIBTR; meadow hawkweed, *Hieracium caespitosum* Dumort. HIECA; black medic, *Medicago lupulina* L. MEDLU; yellow woodsorrel, *Oxalis stricta* L. OXAST; fall panicum, *Panicum dichotomiflorum* Michx. PANDI; wild-proso millet, *Panicum miliaceum* L. PANMI; broadleaf plantain, *Plantago major* L. PLAMA; wild buckwheat, *Polygonum convolvulus* L. POLCO; white poplar, *Populus alba* L. POPAL; common purslane, *Portulaca oleracea* L. POROL; wild radish, *Raphanus raphanistrum* L. RAPRA; hedge mustard, *Sisymbrium officinale* (L.) Scop. SSYOF; eastern black nightshade, *Solanum ptychanthum* Dunal SOLPT; red clover, *Trifolium pratense* L. TRFPR; common blue violet, *Viola sororia* Willd. VIOPP; riverbank grape, *Vitis riparia* Michx. VITRI.

in the tilled than the NT rye treatments early in the season, from mid June to early July (370 to 490 GDD) (Table 5). Weed density in the tilled system peaked at 44 plants m^{-2} by mid June (370 GDD, V2 soybean) and declined thereafter to 4.5 plants m^{-2} by late August (980 GDD). In the NT rye treatments, weed densities were low early in the season, averaging 0.2 plants m^{-2} by mid June

Table 4. Effects of tillage and rye cover crop, rye termination method, soybean planting date, and soybean row spacing on seedling recruitment as percent of viable seeds in the upper 10 cm of the soil for total species, velvetleaf (ABUTH), common lambsquarters (CHEAL), redroot pigweed (AMARE), and shepherd's-purse (CAPBP) in 2008 and 2009.

	Recruitment									
	Total		ABUTH		CHEAL		AMARE		CAPBP	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
	%									
Treatment										
Tilled	2.7	0.2	57.9	9.8	0.3	0.1	6.1	0.7	15.3	0.6
Mowed	0.3	0.3	0.5	4.4	0.2	0.1	< 0.1	0.4	0.2	2.3
Drilled-crimped	0.1	0.4	< 0.1	1.3	< 0.1	0.2	< 0.1	0.2	<0.1	1.8
Drilled-mowed	0.2	0.4	0.1	4.5	< 0.1	0.2	0.1	0.1	0.2	2.6
Late crimped-drilled	< 0.1	0.3	< 0.1	2.8	< 0.1	0.2	< 0.1	0.3	<0.1	1.5
Late mowed-drilled	0.2	0.6	0.3	5.6	0.1	0.2	0.4	1.2	0.3	2.1
Contrasts[a]	P values									
Tilled vs. NT rye	****	†	****	**	***	NS	****	NS	****	*
NT: wide vs. narrow spacing	NS	NS	NS	NS	*	NS	NS	NS	NS	NS
NT: early vs. late PD	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
NT: mowed vs. crimped rye	*	NS	NS	*	†	NS	NS	NS	NS	NS
NT: PD × crimped/mowed rye[b]	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Abbreviations: NT, no-tillage; PD, planting date; NS, nonsignificant at $P > 0.10$.

[b] Second-level interaction of planting date and rye management.

† $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; **** $P < 0.0001$.

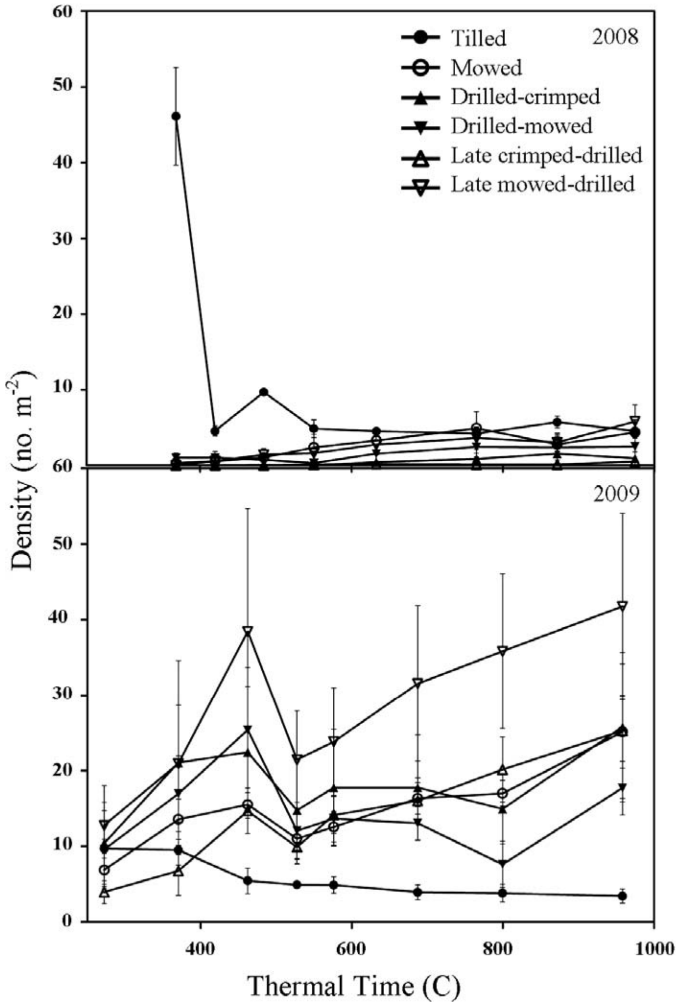

Figure 1. Effect of tillage, rye cover crop, rye termination method, soybean planting date, and soybean row spacing on mean total weed density in 2008 and 2009. Refer to Table 1 for treatment descriptions. Bars represent ± 1 SE.

(370 GDD, VE to V2 soybean). By late August, densities were 1.8 plants m^{-2} (980 GDD). Weed densities were not affected by soybean row spacing or planting date. However, weed densities were greater in the mowed than they were in the crimped NT rye treatments from mid July to late August (640 to 980 GDD).

In 2009, weed density in the tilled treatment peaked in mid June at 9.5 plants m^{-2} (270 GDD, VC soybean) and declined to 3.2 plants m^{-2} by early September (960 GDD) (Figure 1; Table 5). In contrast, weed emergence in the NT rye treatments showed two peak periods, with peak densities of 20 plants m^{-2} in late June (460 GDD, V1 to V5 soybean) and 24 plants m^{-2} in early September (960 GDD). The peak in late June was attributed mostly to winter annual species and common lambsquarters (data not shown). In contrast to 2008, weed densities were lower in the

Table 5. Contrast tests of the effects of tillage and rye cover crop, rye termination method, soybean planting date, and soybean row spacing on total weed density in the 2008 and 2009 soybean growing seasons.

	Total weed density															
	2008 Thermal time (10 C)								2009 Thermal time (10 C)							
Contrasts[a]	370	420	480	550	630	770	870	980	270	370	460	530	580	690	800	960
	P values															
Tilled vs. NT rye	****	NS	**	NS	NS	NS	NS	NS	NS	†	****	*	**	***	***	****
NT: wide vs. narrow spacing	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	†	NS	NS	NS	†	NS
NT: early vs. late PD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
NT: mowed vs. crimped rye	NS	NS	NS	NS	†	*	†	**	NS	NS	†	NS	NS	NS	NS	NS
NT: PD × crimped/mowed rye[b]	NS	NS	NS	NS	NS	NS	NS	†	NS	NS	NS	NS	NS	NS	NS	NS

[a] Abbreviations: NT, no-tillage; PD, planting date; NS, nonsignificant at P > 0.10.
[b] Second-level interaction of planting date and rye management.
† P < 0.10; * P < 0.05; ** P < 0.01; *** P < 0.001; **** P < 0.0001.

Table 6. Effects of tillage and rye cover crop, rye management method, soybean planting date, and soybean row spacing on total late-season aboveground weed biomass.

	Weed biomass[a]	
	2008	2009
	—— $kg\ ha^{-1}$ ——	
Treatment		
Tilled	164	410
Mowed	28	122
Drilled-crimped	3	52
Drilled-mowed	6	32
Late crimped-drilled	5	229
Late mowed-drilled	24	119
	—— P values ——	
Contrasts		
Tilled vs. NT rye	****	**
NT: wide vs. narrow spacing	†	*
NT: early vs. late PD	NS	**
NT: mowed vs. crimped rye	NS	NS
NT: PD × crimped/mowed rye[c]	NS	NS

[a] Abbreviations: NT, no-tillage; PD, planting date; NS, nonsignificant at $P > 0.10$.

[b] Second-level interaction of planting date and rye management.

† $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; **** $P < 0.0001$.

tilled treatment than they were in the NT rye treatments at each sampling date, except in mid June (270 GDD) (Table 6). Other treatment factors (rye management, soybean planting date, and soybean row spacing) did not affect weed densities, except in late June (460 GDD) and in mid August (960 GDD).

Later peak emergence of weeds in the NT rye treatments was similar to the results of Moore et al. (1994) and Williams et al. (1998) who observed delayed emergence of annual weed species in NT rye mulch treatments. Both Coulter et al. (2011) and Mirsky et al. (2011) found that delaying soybean planting into June (compared with May planting dates) was associated with delayed weed emergence and densities. In our study, treatment effects on weed density varied between years (Figure 1; Table 5). In 2008, weed densities were greater or no different in the tilled than they were in the NT rye treatments, consistent with Coulter et al. (2011) and Mirsky et al. (2011), whereas in 2009, weed densities were typically greater in the NT rye treatments. The difference between years could be due, in part, to differences in weed seedbank densities. In 2008, total viable nondormant seedbank density was 480 seeds m^{-2}, similar to the low seedbank density in Nord et al. (2011) where a rye mulch was a sufficient weed management tool, whereas in 2009, the viable nondormant seedbank density was 1,300 seeds m^{-2}, closer to the medium seedbank density in Nord et al. (2011), at which, supplemental weed management was necessary beyond the rye mulch. Less rye biomass accumulation, and potentially less suppressive ability, may have contributed to greater weed densities in 2009 than in 2008.

Weed Suppression. Late-season weed shoot biomass was consistently greater in the tilled treatment than it was in the NT rye treatments both years (Table 6). By the end of August, weed shoot mass was 12-fold greater in the tilled treatment than it was in the NT rye treatments in 2008 and fourfold greater in 2009. Weed mass among NT rye treatments was less for narrow- than wide-row soybean spacing in each year and was less for early than late-planted soybean in 2009. Weed mass did not differ between crimped and mowed rye treatments in either year. Although rye was crimped or mowed during late anthesis, some regrowth occurred, but shoot mass of the regrowth did not differ between crimping and mowing treatments (Bernstein et al. 2011). We have shown previously (Bernstein et al. 2011) that rye regrowth, soybean yield, and profitability did not differ between crimped and mowed rye treatments. Further, our capital costs for the sickle-bar mower were about half those for the crimper–roller (data not shown), which could be an important consideration for some growers. These results indicate that sickle-bar mowers are a viable alternative to roller–crimpers, providing an additional option for rye management in NT systems. Although sickle-bar mowers appear to be much less common on farms than are flail or rotary mowers (E. R. Bernstein, personal observation), sickle-bar mowers are considered more effective for management of some cover-crop types because mulch remains more intact and uniformly distributed (Creamer and Dabney 2002). However, limited availability of sickle-bar mowers may be an important constraint to their wider use by growers for rye management.

These results indicate that the rye cover crop, NT, early soybean planting date, and narrow soybean row spacing each played a role in contributing to effective season-long weed suppression and, together, comprise a diversified approach to weed management. Weed biomass was consistently less in NT treatments than it was in the tilled treatment in each year (Table 6), even though weed densities were similar among treatments in 2008 and greater in NT rye treatments in 2009 (Table 5). Davis (2010) also found that a rolled-rye mulch reduced weed biomass but not density. Weed biomass was much less in drilled-crimped and

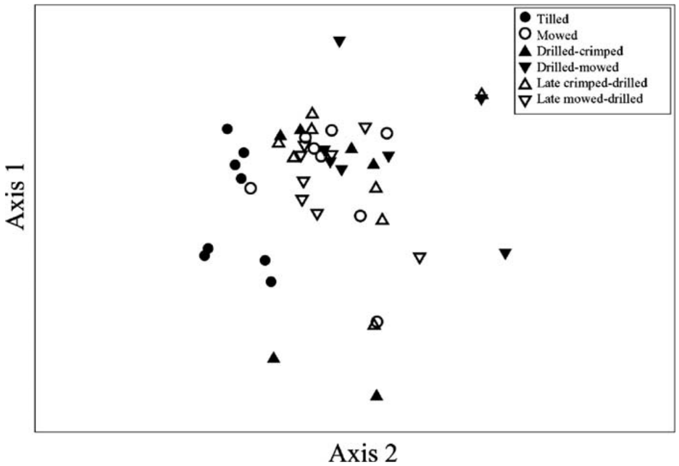

Figure 2. Ordination plot from nonmetric multidimensional scaling of late-season weed biomass in 2008 and 2009. Each point represents a single plot. Stress = 0.15.

drilled-mowed treatments than it was in the tilled treatment in each year (Table 6). In contrast to our results, De Bruin et al. (2005) found that 1,000 to 4,000 kg ha^{-1} of rye mulch did not provide adequate season-long weed suppression with high populations of later-emerging weed species. Most of these species were not present in our study, and in addition, the rye cover crop in our study was terminated at a later growth stage and had accumulated more biomass (10,800 kg ha^{-1} in 2008 and 4,300 kg ha^{-1} in 2009). Our results are consistent with those of Ryan et al. (2011), Smith et al. (2011), and Teasdale and Mohler (2000), suggesting that higher levels of rye biomass/mulch (9,000 to 15,000 kg ha^{-1}) can suppress weeds sufficiently to be used as a stand-alone weed management tool. In our research, weed suppression in the NT rye mulch treatments was greater than in the tilled treatment both years but more so in 2008 when rye biomass was 10,800 kg ha^{-1}. In 2009, with lower rye biomass and higher weed seedbank density, the combination of NT rye mulch, narrow soybean row-spacing, and earlier soybean planting date resulted in the most effective weed suppression (Table 6). Considering such variability between years, a diversified approach will likely provide the most consistently effective weed suppression year to year. These results are consistent with Ryan et al. (2011) and Nord et al. (2011), who found that supplemental weed management tactics were necessary and possibly synergistic, especially at low rye biomass levels.

Late-Season Weed Community Composition. Tillage and rye cover crop affected weed community composition, as shown by the ordination of late-season weed biomass in 2008 and 2009 (Figure 2). The points representing the eight tilled plots appear in two groups (four replicate plots in each of 2 yr) and are separate from those of the NT rye plots. The stress of the two-dimensional ordination was 0.15, which indicates that the ordination in this instance is useful but not conclusive for assessing the multidimensional relationship among research plots. The ANOSIM test on the similarity values between research plots showed that treatments significantly affected the weed community (R = 0.382; P = 0.001) as did tillage as a contrast factor (R = 0.439, P = 0.001). These results indicate that the weed communities in the tilled plots were different from the weed communities of the NT rye plots. Other factors in the NT rye treatments, soybean row spacing, planting date, and rye management method did not affect the weed community composition.

Similarity percentages indicated that the weed communities diverged between the tilled and NT rye treatments (Table 7). Summer annual weed species dominated the weed community in the tilled treatment. In contrast, perennials and *Polygonum* species, which are typically associated with less soil disturbance, were common in the NT rye treatment in addition to summer annual species. The similarity of the weed communities in the tilled plots was 61%, with common lambsquarters and velvetleaf contributing the most to the similarity across plots. In contrast, the similarity of the weed communities in the NT rye plots was only 36%, with common lambsquarters and prostrate knotweed contributing the most to the similarity. The dissimilarity of the tilled plots compared with the NT rye plots was 79%, with velvetleaf contributing the most to dissimilarity.

Mirsky et al. (2011) also found that perennial weeds were selected for by a high-residue rye mulch system along with later emerging annuals. A delay in rye mulch termination and soybean planting was identified as one of the factors that shifted the weed community in that study. In contrast, Moonen and Barberi (2004), found no effect of NT rye mulch on weed community composition. In our study, summer annual weed species, such as common lambsquarters and velvetleaf, were highly abundant (Tables 3 and 7), accounting for a high level of similarity of weed communities among tilled plots, whereas the NT rye plots were associated with more-diverse annual and perennial species. Previous research has also shown a strong association of perennials with NT systems (Buhler et al. 1994; Murphy et al. 2006). White clover (*Trifolium repens*

Table 7. Contribution of species to the similarity and dissimilarity of tilled and no-tillage (NT) treatments based on late-season weed biomass in 2008 and 2009. Data were pooled over years.[a]

Similarity of tilled treatments			Similarity of NT treatments			Dissimilarity of tilled and NT treatments			
							Shoot mass		
Species	Shoot biomass	Contribution	Species	Shoot biomass	Contribution	Species	Tilled	NT	Contribution
	$g\ m^{-2}$	%		$g\ m^{-2}$	%		$g\ m^{-2}$		%
CHEAL	30.1	52.1	CHEAL	4.1	38.3	ABUTH	16.2	0.1	31.7
ABUTH	16.2	39.0	POLAV	0.7	15.7	CHEAL	30.1	4.1	27.5
AMARE	1.0	4.4	TRFPR	0.5	8.5	AMARE	1.0	0.1	7.7
SETFA	0.1	1.6	POLPE	0.4	7.6	POLAV	0.0	0.7	5.1
POLPE	0.3	1.3	TAROF	0.1	6.2	ECHCG	0.1	0.0	4.5

[a] Abbreviations: CHEAL, common lambsquarters; ABUTH, velvetleaf; POLAV, prostrate knotweed; AMARE, redroot pigweed; TRFRE, white clover; SETFA, giant foxtail; POLPE, ladysthumb; ECHCG, barnyardgrass; TAROF, dandelion.

L.) and dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers) were the perennial species most strongly associated with the NT rye treatments in our study. These species may become problematic in the long-term if not effectively managed. However, of greater concern long-term may be the highly competitive and aggressive perennial species Canada thistle [*Cirsium arvense* (L.) Scop.] and quackgrass [*Elymus repens* (L.) Gould], both of which were present in our study, but in low abundance. If these species were to become established, the viability of a NT approach would be severely threatened.

Velvetleaf was the largest contributor to the dissimilarity of tilled and NT rye plots (Table 7). The high velvetleaf seedling recruitment in both years (Table 4) suggests that velvetleaf germination was stimulated by the frequent disturbance in the tilled system, similar to what was found by Mirsky et al. (2010). The high abundance (Tables 3 and 7) of summer annuals, particularly velvetleaf, indicates a potential for a long-term weed management problem in the tilled treatment because of the high fecundity of velvetleaf and the longevity of its seeds in the soil seedbank (Bauer and Mortensen 1992; Lueschen and Anderson 1980). However, velvetleaf fecundity is reduced if emergence is delayed (Lindquist et al. 1995), and seed survival is reduced because of greater seed predation in reduced tillage systems (Heggenstaller and Liebman 2006; Westerman et al. 2005), both characteristics of the NT rye treatments in our research.

Differences in selection intensity or opportunities for colonization between treatments may have led to the observed differences in weed communities. Higher selection intensity in tilled systems, as indicated by the greater similarity of the tilled plots to each other, will tend to result in weed communities that consist of weeds adapted to that tillage system (Jordan and Jannink 1997). This may render tillage ineffective as a weed management practice if it is not integrated with other practices. In addition, the tilled system, being associated exclusively with summer annuals, indicates that the summer annual cash crop would experience greater competition from that weed community.

Our research addressed weed community dynamics and suppression in winter rye cover crop in NT soybean production systems relative to the widely adopted tillage-intensive approach. An important caveat to this research is that, in each year, rye–soybean systems followed conventional corn silage production (typical of dairy forge–livestock systems), with low to moderate weed population densities, i.e., our first-year organic transitional treatments were imposed in that context. As such, the results may be interpreted as an indication of initial changes in weed community composition and effectiveness of weed suppression, both of which would likely change as weed community composition approaches equilibrium over time. It is also important to consider that this research was conducted over 2 site–yr, limiting the inferences that can be drawn from the results. However, despite variability in weather, rye biomass production, and weed seedbank and plant community composition between site–years, our results showed that weed emergence tended to peak early in the season in the tilled treatment, whereas in NT rye treatments, peak occurred in mid or late season. Although more-diverse summer annual and perennial species were associated with the NT rye treatments across years, weed suppression was much greater across NT rye treatments than it was in the tilled treatment. Late-season weed biomass was lowest in the drilled-crimped and drilled-mowed treatments, suggesting that earlier soybean planting and narrow row spacing were important management factors contributing to effective season-long weed suppression. Similarly, effective weed suppression by both roller-crimping and sickle-bar mowing suggests more options for rye management than commonly perceived by growers.

Our previous research (Bernstein et al. 2011) showed additional benefits associated with NT rye compared with tilled rye, including less soil loss, greater soil organic matter, and less labor and fuel inputs. These potentially long-term benefits were offset by 24% less soybean yield and 27% less profit per hectare; however, with fewer labor inputs, profitability per hour was 25% greater than in the tilled system. These rye mulch, NT soybean systems appear to be economically viable alternatives to the tillage-intensive approach. They are particularly attractive to organic growers because of reduced labor inputs, reduced need for additional organic matter inputs (e.g., manure) over time to maintain long-term soil quality, and highly effective season-long weed suppression compared with the typical tillage-intensive approach.

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