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Cover-Crop Roller–Crimper Contributes to Weed Management in No-Till Soybean

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Termination of cover crops prior to no-till planting of soybean is typically accomplished with burndown herbicides. Recent advances in cover-crop roller–crimper design offer the possibility of reliable physical termination of cover crops without tillage. A field study within a no-till soybean production system was conducted in Urbana, IL, from 2004 through 2007 to quantify the effects of cover crop (cereal rye, hairy vetch, or bare soil control), termination method (chemical burndown or roller–crimper), and postemergence glyphosate application rate (0, 1.1, or 2.2 kg ae ha^{-1}) on soybean yield components, weed–crop interference, and soil environmental variables. Biomass of weeds surviving management within a soybean crop following either a vetch or rye cover crop was reduced by 26 and 56%, respectively, in the rolled system compared to the burndown system. Soybean yield loss due to weed interference was unaffected by cover-crop termination method in soybean following a rye cover crop, but was higher in the rolled than burndown treatment in both hairy vetch and bare soil treatments. In soybean following a rye cover crop, regardless of termination method, yield loss to weed interference was unaffected by glyphosate rate, whereas in soybean following a vetch cover crop or bare soil, yield loss decreased with glyphosate rate. Variation in soybean yield among cover crops and cover-crop termination treatments was due largely to differences in soybean establishment, rather than differences in the soil environment. Use of a roller–crimper to terminate a cover crop preceding no-till soybean has the potential to achieve similar yields to those obtained in a chemically terminated cover crop while reducing residual weed biomass.

Nomenclature: Common waterhemp, *Amaranthus rudis* Sauer, AMARU; giant foxtail, *Setaria faberi* Herrm., SETFA; hairy vetch, *Vicia villosa* Roth.; cereal rye, *Secale cereale* L. 'FS Hi-Rye 500'; soybean, *Glycine max* (L). Merr.

Key words: Cover-crop termination, *Glycine max* establishment, weed suppression, *Secale cereale*, *Vicia villosa*, organic, low external input.

Including cover crops within cropping systems can create a variety of agronomic benefits, including improved soil structure (Villamil et al. 2008), reduced soil nutrient losses due to leaching (Drinkwater et al. 1998), and suppression of weeds (Creamer et al. 1996; Teasdale 1996). In cropping systems focused on the production of summer annual grain crops, cover crops are typically planted in late summer, provide soil cover during winter, and are terminated prior to planting of the agronomic crop. The method by which cover crops are terminated is critical to their utility because renewed growth from cover crops can interfere with growth and development of the agronomic crop, eventually causing crop yield loss (Singer et al. 2007). Moreover, the method used to terminate cover crops can influence their potential to suppress weeds in the subsequent agronomic crop.

In no-till cropping systems, cover-crop termination with a burndown herbicide is a common approach, but physical methods are also available (Creamer and Dabney 2002; Teasdale and Rosecrance 2003). Mowing can be used to kill some cover crops without soil disturbance, but this method has potential pitfalls, including cover-crop regrowth and aggregated spatial distribution of cover-crop residues (Creamer and Dabney 2002). Another tool for no-till physical termination of cover crops, the cover-crop roller–crimper, has ancient origins in draft-animal powered agriculture (Khatounian, personal communication) and has received increased attention in the past decade (Ashford and Reeves 2003). This tool is essentially a cylinder with protruding fins that rotates on a lengthwise axis as it is drawn over the soil. The implement crimps and crushes the cover crop to form a flat, uniform layer of mulch into which the agronomic crop is planted. Recent advances in cover-crop roller–crimper design have improved its operation, reducing vibrations (Kornecki et al. 2006), increasing planting efficiency (Sayre 2003), and improving efficacy in terminating cover crops (Ashford and Reeves 2003; Mirsky et al. 2009).

Successful weed management within organic and low-external-input (LEI) farming systems depends upon the partial or complete substitution of multiple sublethal tactics for the direct control offered by herbicides (Liebman and Gallandt 1997). To investigate the potential of the newly redesigned roller–crimper for weed suppression in a no-till system with minimal or no reliance upon herbicides, a field study was made with two primary objectives: (1) quantify the impact of cover-crop species, cover-crop termination method, and postemergence herbicide application rate on weed growth and interference with no-till soybean; and (2) elucidate mechanisms of weed suppression in the different treatments by characterizing concomitant changes in soil moisture, temperature, phytotoxicity, and light environment. Study objectives were framed by the following hypotheses: (1) in no-till soybean production, cover-crop termination with a roller–crimper ("Rolled") reduces weed population density, biomass production, and yield loss compared to a system using chemical cover-crop termination ("Burndown"); (2) postemergence glyphosate application rate can be reduced, or eliminated, without reducing soybean yields in a Rolled, but not a Burndown, system; and (3) enhanced weed suppression within a Rolled system, compared to a Burndown system, is associated with physical changes in the soil surface environment, rather than differences in phytotoxicity.

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Materials and Methods

Site Description and Experimental Design. A field study was conducted at the University of Illinois Crop Science

Table 1. Schedule of field operations, in Urbana, IL, from 2005 to 2007.

Field operation	Date 2005	Date 2006	Date 2007
Burndown herbicide applied to cover crop	May 13	May 12	May 11
Roller–crimper termination of cover crop	May 17	May 22	May 22
Soybean planting	May 24	June 2	May 29
Postemergence application of glyphosate	June 8	June 20	June 15
Soybean harvest	October 5	October 11	October 3

Research and Education Center (CSREC), in Urbana, IL (40.05°N, 88.24°W). The dominant soil at the study site was a Catlin silt loam (Oxyaquic Argiudoll) with 7% sand, 68% silt, 25% clay, pH 7.2, and 4.2% soil organic carbon. Prior to the initiation of the experiment, the study site was managed commercially in a corn–soybean rotation for more than 30 years. The study took place on two different fields over three successive growing seasons, starting in fall 2004, within the soybean phase of a soybean–oat (*Avena sativa* L.) crop sequence, where spring-planted oat was used simply as a placeholder to allow late-summer planting of cover crops for more reliable stand establishment than usually occurs after corn harvest at this location. Oat ('Ogle') was no-till drilled in 18-cm rows at 112 kg ha^{-1} in mid-March, and harvested in late July. Weed management in oat stubble prior to cover-crop planting in early September consisted of a single broadcast application of glyphosate made at 2.2 kg ae ha^{-1} in mid-August. Implementation of such a system under commercial production conditions would require either a means of reliably establishing a cover crop within a senescing corn crop (such as aerial cover-crop seeding) in a corn–soybean rotation, or initiating a 3-yr or longer crop sequence, in which a small grain phase precedes soybeans to allow for early cover-crop planting and establishment every third year. Because soybean often represents a weak point in the crop sequence for weed management on LEI and organic farms (Davis et al. 2005), the focus on enhancing cover-crop establishment prior to soybean planting is warranted.

The experiment was arranged in a split–split plot design with four replications of a factorial combination of cover-crop type ("Cover"), cover-crop termination method ("Kill"), and postemergence glyphosate application rate ("Rate"). Cover was the main plot factor, consisting of either hairy vetch or cereal rye no-till drilled into oat stubble in 18-cm rows at 33 and 112 kg ha^{-1}, respectively, in early September, or a bare soil control treatment in which no cover crop was planted. Kill was the subplot factor: cover-crop residues were terminated when they reached anthesis in mid- to late-May, either with a single-pass of a cover-crop roller–crimper or a chemical burndown. The cover-crop roller–crimper, custom-fabricated following design specifications developed by the Rodale Institute (Mirsky et al. 2009; Sayre 2003), was a 3-m-long by 0.45-m-diameter steel cylinder with 7-cm fins protruding at 90° from the cylinder in a chevron pattern that was oriented lengthwise 10° off of the central axis of the roller. When filled with H_2O, the roller weighs approximately 5,000 kg. The burndown herbicide application consisted of either glyphosate (used in bare and rye treatments, applied at 2.2 kg ae ha^{-1}) or a low-volatility-ester formulation of 2,4-D (used in hairy vetch cover-crop treatment, applied at 2.2 kg ai ha^{-1}). The low-volatility ester formulation of 2,4-D was used in vetch because it is effective, yet is also safe to use before soybean, provided a 2-wk interval elapses between herbicide application and planting (University of Illinois Extension 2007). Finally, *Rate* was the sub-subplot factor, with a broadcast application of glyphosate made at 0, 1.1, or 2.2 kg ae ha^{-1} in late June. Main plots were 12.1 m wide by 35 m long (0.042 ha), subplots were 6.1 m wide by 35 m long (0.021 ha), and sub-subplots were 6.1 m wide by 11.6 m long (0.007 ha).

Soybean (Pioneer 93M60, maturity group III) was planted in late spring on the same day for all treatments within a given year (Table 1). Different amounts of time elapsed between the initiation of chemical and physical termination treatments and soybean planting, due to the longer amount of time needed for cover-crop mortality in chemical than in physical treatments. At least 1 wk was allowed to elapse between physical termination and planting, to reduce oviposition on soybean seeds by the seed corn maggot [*Delia platura* (Meigen); Diptera: Anthomyiidae], which use freshly killed cover-crop residues as a cue for egg laying (Hammond and Cooper 1993). A four-row no-till planter,[1] with coulters set for maximum downward pressure, was used to plant soybean into terminated cover-crop residues in 76-cm rows at a depth of 3 cm and a target population of 419,900 plants ha^{-1}. The late soybean planting date was to accommodate use of the roller–crimper. For the cover-crop roller–crimper to work effectively, rolling must be done when cover-crop anthesis is well underway (Ashford and Reeves 2003; Mirsky et al. 2009); if rolled earlier, cover-crop residues will regrow and potentially interfere with crop growth.

Intensive weed management practices at the study location in the 30 yr of commercial farming prior to initiation of the study resulted in low initial weed seed bank population densities (< 10 seeds m^{-2}) for the study species: common waterhemp and giant foxtail. After cover crops were established, a single 1-m by 1-m quadrat centered over two soybean rows was marked in the center of each sub-subplot in late October. Each quadrat was overseeded with 100 seeds of each of the study weed species. Common waterhemp and giant foxtail were chosen for their importance to commercial field crop production in the north central region of the United States (Bensch et al. 2003; Lindquist et al. 1999). Paired 1-m by 1-m quadrats located 2 m apart were kept weed free by hand for the entire growing season. Mature seeds of common waterhemp and giant foxtail were collected within soybean fields adjacent to the study location by gently shaking inflorescences over a container. Seeds were processed on a seed cleaner[2] to remove light seeds and chaff. Initial viability of seed lots was determined prior to planting with a tetrazolium dye assay (Association of Official Seed Analysts [AOSA] 2000).

Crop, Weed, and Environmental Measurements. Cover-crop biomass was measured in mid-May, prior to termination, by clipping all plants within 0.25-m^2 quadrats and drying at 65 C to constant weight. Soybean stand was measured 14 d after planting (DAP), and again in late August, within 2 m of row in each subplot. Soybean yield was determined in mid-October by harvesting mature plants from the 2 m of row within weedy and weed-free quadrats, threshing with a stationary thresher, and measuring seed mass at 13% moisture. Soybean percent yield loss was determined within a given sub-subplot as $[(\text{yield}_{\text{weed-free}} - \text{yield}_{\text{weedy}})/\text{yield}_{\text{weed-free}}] \times 100$. Harvest areas within experimental quadrats were kept small to allow for tight spatial correspondence between plant growth and environmental measurements. Nonetheless, soybean yields in quadrats correlated strongly ($r = 0.70$, $P < 0.001$) with plot combine yields over 20 m of row in adjacent areas, taken for the purpose of verifying the utility of yield determination within quadrats (data not shown).

Densities of residual populations of common waterhemp and giant foxtail were quantified 14 d following postemergence application of glyphosate, in late June. Dry biomass of the entire weed community was recorded within each quadrat at soybean harvest. The weed community was dominated by the target species common waterhemp and giant foxtail, which accounted for over 75% of the weed biomass, but also included small amounts of marestail [*Conyza canadensis* (L.) Cronquist], prickly sida (*Sida spinosa* L.), and venice mallow (*Hibiscus trionum* L.).

Measurements of soil environmental variables were made within the 1× Rate subplot within each combination of Cover by Kill. Soil gravimetric water content was measured biweekly for a composite sample of 30 soil cores per experimental unit taken to a depth of 30 cm with a 2.5-cm-diameter soil probe. Soil temperature was measured at a depth of 2.5 cm with a Tidbit® temperature probe[3] recording at 30-min intervals. Photosynthetically active radiation (PAR) transmittance through terminated cover-crop residues to the soil surface was measured near solar noon under full sun just prior to soybean planting with a line quantum sensor[4] placed on the soil below cover-crop residues, linked to a point quantum sensor held above the residues for instantaneous calculation of PAR transmittance. The line and point sensors were both calibrated just prior to taking the readings. Inserting the line sensor beneath the terminated cover-crop residues did not result in significant disturbance, as the residues held together in a tight mat. Before each PAR reading, the line sensor was wiped with a soft cloth to remove any debris.

Phytotoxic effects of soil underlying various cover-crop treatments at the time of cover-crop termination and 1 mo afterwards on seedling germination was measured with the use of rag-doll bioassays (Dabney et al. 1996). Forty seeds of either common waterhemp or giant foxtail were placed in 100 g of soil spread between two layers of germination paper moistened with 5 ml distilled deionized H_2O (ddH_2O), rolled up, and incubated vertically in a Conviron 125L incubator[5] for 96 hr at 25 C in the light (16 h) and 20 C in the dark (8 h). Following incubation, seed-germination proportion and seedling radicle elongation were measured. Soil for the bioassays was collected at the time of cover-crop termination and 4 wk later (and used immediately afterwards in each case), when 30 2.5-cm soil cores were taken to a depth of 10 cm, bulked to form a composite sample, and passed through a 5-mm soil sieve. Gravimetric soil moisture content was determined for each sample, and based on soil characteristic curves for the site, ddH_2O was added to bring all samples to field capacity (−33 kPa).

Statistical Analyses. Residual weed populations, weed biomass, soybean yield, and soybean yield loss were analyzed with mixed-effects models fit by REML (restricted maximum likelihood) in the *nlme* package of R 2.7.1 (Pinheiro and Bates 2004; R Development Core Team 2006). Soybean yield loss was $\sin^{-1}(x)^{0.5}$-transformed to meet assumptions of normally distributed residuals and constant residual variance (Crawley 2007). Models included Cover, Kill, and Rate as fixed effects and replication and year as random effects. Percent transmittance of PAR [$\sin^{-1}(x)^{0.5}$ transformed] and phytotoxicity bioassay data were also analyzed with mixed-effects models, with Cover and Kill as fixed effects and replication and year as random effects. Rather than presenting means for all factorial treatment combinations, means associated with the highest-order significant interaction terms for each variable are shown in figures to facilitate understanding of the many interactions between treatments in this study.

Soil moisture and soil temperature were analyzed with mixed-effects ARMA (autoregressive moving average) repeated-measures models with lags of 5 and 7 d, respectively, in the *nlme* package of R 2.7.1 (R Development Core Team 2006). Use of ARMA models helps account for temporal autocorrelation between repeated measures data, amplifying signals from treatment effects in relation to noise associated with sampling structure (Crawley 2007). These models included Cover and Kill as fixed effects and replication and year as random effects.

Pearson correlations were estimated, within levels of Cover, between soybean yield, soybean yield loss or weed biomass and abiotic and biotic environmental variables, including cover-crop biomass, PAR transmittance, soil gravimetric water content, soil temperature, common waterhemp, and giant foxtail radicle length in rag-doll bioassays, soybean stand, residual population density of common waterhemp and giant foxtail, and weed biomass. Correlation coefficients and Bonferroni-corrected P values were calculated using the *MASS* package of R 2.7.1. Correlations were used to identify potential mechanisms underlying treatment effects as a means of guiding future controlled studies.

Results and Discussion

Cover-Crop Biomass and Weed-Free Soybean Yields. To provide a context for understanding the effects of Cover, Rate, and Kill on weed and crop performance in following sections, an overview of cover-crop biomass and weed-free soybean yields is presented here.

Rye dry biomass at the time of termination was 7,100 kg ha^{-1} in 2005, and 6,000 kg ha^{-1} in both 2006 and 2007. Hairy vetch dry biomass at the time of termination was 3,500, 6,200, and 6,300 kg ha^{-1}, respectively, in 2005, 2006, and 2007. Cover-crop biomass did not differ significantly between subplots for Rate or Kill.

Weed-free yield of soybean varied substantially among treatments and years. In the bare soil control, soybean yield ranged from 3,400 to 4,000 kg ha^{-1} in the Burndown treatment, and from 2,700 to 3,800 kg ha^{-1} in the Rolled treatment. In soybean following a rye cover crop, yields ranged from 2,400 to 3,700 kg ha^{-1} in the Burndown treatment, and from 2,200 to 3,200 kg ha^{-1} in the Rolled treatment. In soybean following a vetch cover crop, yields ranged from 2,700 to 3,500 kg ha^{-1} in the Burndown treatment, and from 640 to 3,300 kg ha^{-1} in the Rolled treatment. Weed-free soybean yields were lower in the Rolled treatment than the Burndown treatment for all levels of Cover ($F_{1,33}$ = 11.4, P < 0.01). Negative effects of the Rolled treatment on weed-free soybean yield may have included continued water use by cover crops that died more slowly in the Rolled than Burndown treatment (supported by a positive correlation between soil moisture posttermination and soybean yield in the Rolled rye treatment: r = 0.74, P < 0.01, but not in the Burndown rye treatment: r = 0.22, P = 0.25) and soil compaction from the heavy roller–crimper (supported by lower weed-free yields in the Rolled treatment than the Burndown treatment in the bare soil control).

Late planting date of soybean in this study limited soybean yield potential, compared to conventional planting practices, in 2 out of 3 yr. The typical soybean planting date in central Illinois is early May (Nafziger 2002), but soybeans were planted during late May or early June in this study (Table 1) (1) to allow the cover crops to reach anthesis and thus achieve better roller–crimper efficacy (Ashford and Reeves 2003; Mirsky et al. 2009), and (2) to plant all treatments at the same time to understand effects of cover-crop termination method without the confounding influence of variable planting date. Had the bare soil control and Burndown cover-crop treatments been planted in early May, the yield differences between these treatments and the Rolled cover-crop treatments would likely have been larger. Yield of weedy soybeans within the Burndown treatment in the bare soil control, followed by a postemergence glyphosate application made at 2.2 kg ae ha^{-1} (the set of treatments in this study closest to commercial production conditions), was 17 and 30% lower than the Champaign County average of 3,700 kg ha^{-1} in 2005 and 2007, respectively. In 2006, mean soybean yield for this treatment was 3,650 kg ha^{-1}, as was the county soybean yield average, indicating no loss of yield potential due to late planting of soybean in this year. The 2006 growing season started off with ample moisture in April (18% higher precipitation than 20-yr average), followed by an extremely dry May and June (precipitation 48 and 85% below 20-yr average). This temporal pattern of moisture availability could have reduced the relative loss of soybean yield potential in the study, compared to the county average, by hindering the early growth of soybeans in commercial production fields planted in May.

Weed Populations and Biomass. Residual population densities of common waterhemp were lowest in rye, intermediate in vetch, and greatest in the bare fallow treatment (Figure 1; Table 2). There was a significant Cover by Year interaction for this variable, such that residual populations of waterhemp remained low in rye throughout the study, but increased greatly in the vetch and bare treatments in 2007. Residual populations of giant foxtail were subject to a Year by Cover by Kill by Rate interaction (Table 2). This interaction is broken down in Figure 2 to facilitate interpretation. Giant foxtail residual populations remained low in rye from 2005 through 2007, but increased greatly in the vetch and bare treatments in 2007 (Figure 2a). Cover-crop termination method also interacted with Cover to affect giant foxtail residual populations (Figure 2b): Giant foxtail population density remained low in rye regardless of

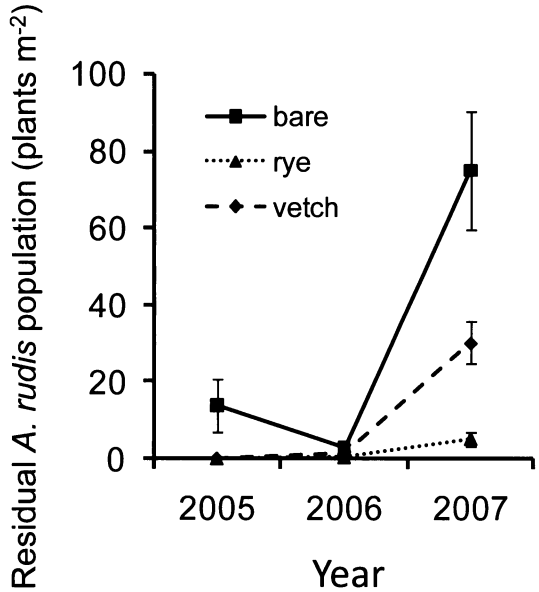

Figure 1. Interaction of study year with residual population density of common waterhemp in soybean grown following bare fallow, hairy vetch, or rye cover crops.

termination method, increased slightly in vetch in the Rolled treatment compared to the Burndown treatment, and decreased in the bare soil control in the Rolled treatment compared the to the Burndown treatment. Residual giant foxtail population density was unaffected by postemergence application rate of glyphosate in rye and vetch, but was lower in the 1.1 and 2.2 kg ae ha^{-1} treatments than in the unsprayed control (Figure 2c).

Weed biomass at soybean harvest showed significant two-way interactions of Cover with Kill and Rate (Table 2). Within both the rye and vetch cover-crop treatments, weed biomass was lower in the Rolled treatment than in the Burndown treatment (Figure 3a). In contrast, weed biomass was greater in the Rolled treatment than in the Burndown treatment within the bare soil control, indicating that the crimper did not damage weeds as it passed over them, and could have even stimulated weed seedling emergence through greater seed-soil contact (Jurik and Zhang 1999). Alternatively, this relationship may have been due to the indirect influence of termination treatments on soybean stand, which was negatively correlated with final weed biomass (Table 2; see below). Increasing postemergence application rates of glyphosate decreased weed biomass in the bare and vetch treatments, but were unrelated to weed biomass in the rye treatment (Figure 3b).

An objective of this investigation was to test the hypothesis that cover-crop termination with a roller–crimper reduces weed population density and biomass production compared to a system using chemical cover-crop termination. Results support this hypothesis for biomass of residual weed populations, but not for population density. Use of a cover-crop roller–crimper resulted in 26 and 56% reductions in residual weed biomass within the vetch and rye systems, respectively, compared to the Burndown treatment (Figure 3a). In contrast, Teasdale and Rosecrance (2003) found that physical termination of hairy vetch cover crops via chopping and mowing resulted in greater weed growth and interference in no-till corn, compared to chemical termina-

Table 2. Mixed-model analysis of variance of soybean yield, soybean yield loss due to weed interference, residual weed populations, and weed biomass at harvest.

Fixed effects[a]	Soybean yield[b]	Soybean yield loss[c]	Residual weed population: Common waterhemp	Residual weed population: Giant foxtail	Weed biomass
	$F_{(dfn,dfd)}$				
(Intercept)	$12.4_{(1,139)}$***	$21.8_{(1,139)}$***	$2.5_{(1,139)}$	$3.1_{(1,132)}$	$14.7_{(1,139)}$***
Cover	$12.8_{(2,20)}$***	$20.2_{(2,20)}$***	$7.1_{(2,20)}$**	$3.9_{(2,20)}$*	$16.1_{(2,20)}$***
Kill	$29.0_{(1,32)}$***	$7.3_{(1,32)}$*	$0.1_{(1,32)}$	$1.2_{(1,30)}$	$0.1_{(1,32)}$
Rate	$81.0_{(1,139)}$***	$70.7_{(1,139)}$***	$0.1_{(1,139)}$	$8.2_{(1,132)}$**	$66.4_{(1,139)}$***
Year	$0.1_{(1,1)}$	$0.2_{(1,1)}$	$2.1_{(1,1)}$	$3.9_{(1,1)}$	$0.12_{(1,1)}$
Cover × Kill	$4.7_{(2,32)}$*	$6.5_{(2,32)}$**	$0.6_{(2,32)}$	$2.4_{(2,30)}$	$7.9_{(2,32)}$***
Cover × Rate	$21.7_{(2,139)}$***	$12.3_{(2,139)}$***	$2.6_{(2,139)}$	$7.4_{(2,132)}$***	$12.6_{(2,139)}$***
Cover × Year	$5.8_{(2,20)}$*	$0.2_{(2,20)}$	$4.3_{(2,20)}$*	$2.6_{(1,132)}$	$1.8_{(2,20)}$
Kill × Rate	$2.2_{(1,139)}$	$1.3_{(1,139)}$	$0.9_{(1,32)}$	$5.6_{(2,20)}$*	$4.0_{(1,139)}$*
Kill × Year	$0.7_{(1,32)}$	$4.8_{(1,32)}$*	$1.9_{(1,32)}$	$2.0_{(1,30)}$	$0.1_{(1,32)}$
Rate × Year	$0.6_{(1,139)}$	$1.1_{(1,139)}$	$0.1_{(1,139)}$	$11.0_{(1,132)}$***	$0.1_{(1,139)}$
Cover × Kill × Rate					$2.5_{(2,132)}$
Cover × Kill × Year					$3.8_{(2,30)}$*
Cover × Rate × Year					$11.1_{(2,132)}$***
Kill × Rate × Year					$3.9_{(1,132)}$
Cover × Kill × Rate × Year					$3.9_{(2,132)}$*

[a] Maximum-likelihood comparisons guided model simplification. Only fixed effects retained in the most parsimonious models are shown.
[b] ANOVA was performed on soybean yield in weedy quadrats.
[c] Soybean yield loss data were $\sin^{-1}(x)^{0.5}$ transformed to meet ANOVA assumptions.
*, **, and *** represent significance of F tests at $\alpha = 0.05$, 0.01, and 0.001, respectively.

tion. The discrepancy in results between the two studies may have arisen due to the tight packing of, and low light transmission through, rolled cover-crop residues compared to more loosely distributed residues in a chopped–mowed system (Teasdale and Mohler 2000).

Soybean Yield under Weed Competition. There were significant two-way interactions for soybean yield in weedy plots between Cover and Year, Kill, and Rate (Table 2). Soybean yield was greatest in the rye treatment in 2005 through 2007 (Figure 4a). In 2006 and 2007, soybean yield was similar in the vetch and bare treatments, but in 2005, it was lower in vetch. Cover-crop termination method did not affect soybean yield within rye, but soybean yield was 25 and 42% lower in the Rolled treatment than in the Burndown treatment for vetch and the bare soil control, respectively (Figure 4b). For the bare soil control, the reason for the negative impact of cover-crop termination method on soybean yield is clear: The cover-crop roller–crimper did not damage weeds (Figure 3a). For the vetch system, the reduction in soybean yield in the Rolled system appeared to be due to low efficacy of the roller in killing vetch within this study. Biomass estimates of live cover-crop residues in mid June, prior to postemergence application of glyphosate, indicated that 222, 289, and 56 g m^{-2} of hairy vetch remained alive in the Rolled treatment in 2005, 2006, and 2007, respectively, whereas no vetch remained alive in the Burndown treatment and no rye remained alive in either termination treatment. Others have reported better success in terminating hairy vetch with physical methods (Dabney et al. 1991), so there may be much room for improvement in hairy vetch termination with the cover-crop roller. A final interaction for soybean yield, between Cover and Rate, is presented in Figure 4c. Soybean yield increased with increasing glyphosate rate in both the bare soil control and vetch treatments, but was unaffected by Rate in the rye treatment.

Soybean yield loss due to weed interference was affected by significant two-way interactions of Cover with Kill and Rate (Table 2). In the rye treatment, soybean yield loss was unaffected by Kill, whereas yield loss was 15 and 42% greater in the Rolled than in the Burndown treatment for vetch and the bare soil control, respectively (Figure 5a). Likewise, soybean yield loss in the rye treatment was unaffected by Rate, whereas increasing POST rate in both vetch and the bare soil control increased soybean yield and reduced yield losses to weed interference (Figure 5b). There was also a significant two-way interaction for soybean yield loss between Kill and Year, in which yield loss was 40% greater in the Rolled than in the Burndown treatment in 2005, but similar for the two treatments in 2006 and 2007 (data not shown).

Initial hypotheses 1 and 2 were not supported by the data presented here. Soybean yield loss due to weed interference was either unaffected by Kill (as in the rye system) or was greater in the Rolled than the Burndown treatment (for vetch and the bare soil control). Soybean yield losses were unaffected by postemergence glyphosate application rate in rye, but this result applied to both the Rolled and Burndown treatments, and did not appear to vary with differences in termination method. This is consistent with other reports of partial or complete substitution of weed suppression by cover-crop residues for chemical weed control (Liebl et al. 1992; Williams et al. 2000).

Influence of Soil Environment on Soybean Yield and Weed Growth. Rag-doll bioassays did not show any indication that soil beneath cover crops at the time of termination or one month thereafter (data not shown) had phytotoxic effects on weed growth. There were no significant main effects or interactions of Cover or Kill for bioassays of soil effects on either common waterhemp or giant foxtail. In studies where this method has detected phytotoxic inhibition of weed radicle elongation by cover crops (Conklin et al. 2002; Dabney et al. 1996; Davis et al. 2003), crop residues were thoroughly physically incorporated into the soil as a green manure. In the present study, cover-crop residues remained on the soil surface, and appeared not to cause chemical inhibition of weed growth. On the contrary, for soil collected at the time of cover-crop termination, bioassay

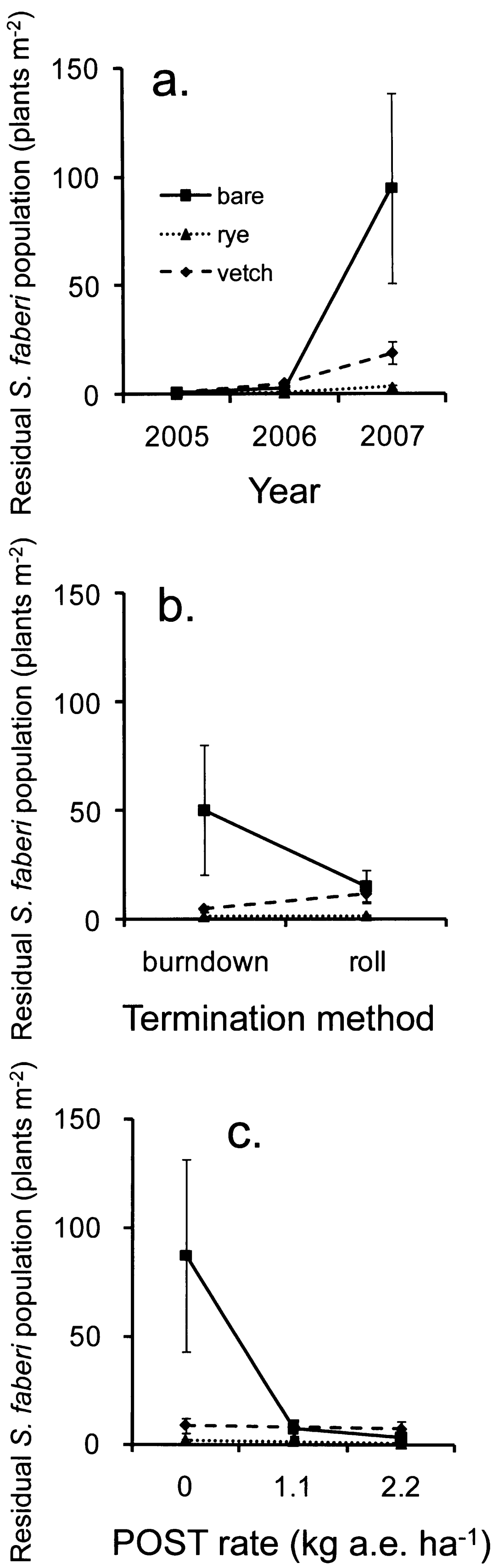

Figure 2. Interaction of (a) study year, (b) cover-crop termination method, and (c) postemergence application rate of glyphosate with residual population density of giant foxtail. Giant foxtail was measured in soybean grown following bare fallow, hairy vetch, or rye cover crops.

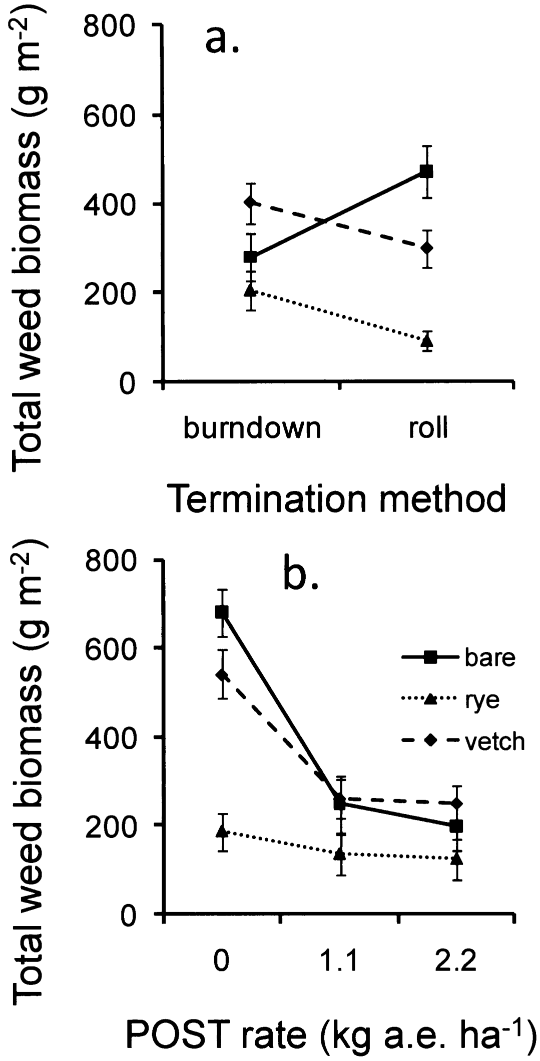

Figure 3. Interaction of (a) cover-crop termination method and (b) postemergence application rate of glyphosate with total weed biomass at time of soybean harvest. Weed biomass was measured in soybean grown following bare fallow, hairy vetch, or rye cover crops.

results under controlled conditions were positively correlated with soybean growth in the field for selected treatments. Common waterhemp radicle length in the bioassay was positively associated with soybean stand in the bare and rye treatments, and soybean yield in the rye treatment (Table 3). This result may have been due to a positive influence of cover-crop residues on some soil factor beneficial for plant growth, but it is beyond the scope of this study to identify the mechanism.

Transmittance of PAR through cover-crop residues to the soil surface was lowest for rye, intermediate in vetch, and greatest in the bare soil control in all study years both prior to cover-crop termination ($F_{2,20}$ = 145, P < 0.0001) and following termination ($F_{2,20}$ = 193, P < 0.0001). Termination method affected PAR transmittance in all cover-crop treatments, with greater PAR transmittance following cover-crop termination in the Burndown than Rolled treatment ($F_{1,35}$ = 8.6, P < 0.01). Cover-crop residue placement has been found by others to influence light transmittance and weed germination (Teasdale and Mohler 2000). In this study, dead cover-crop residues in the Burndown treatment remained standing, whereas cover-crop residues in the Rolled

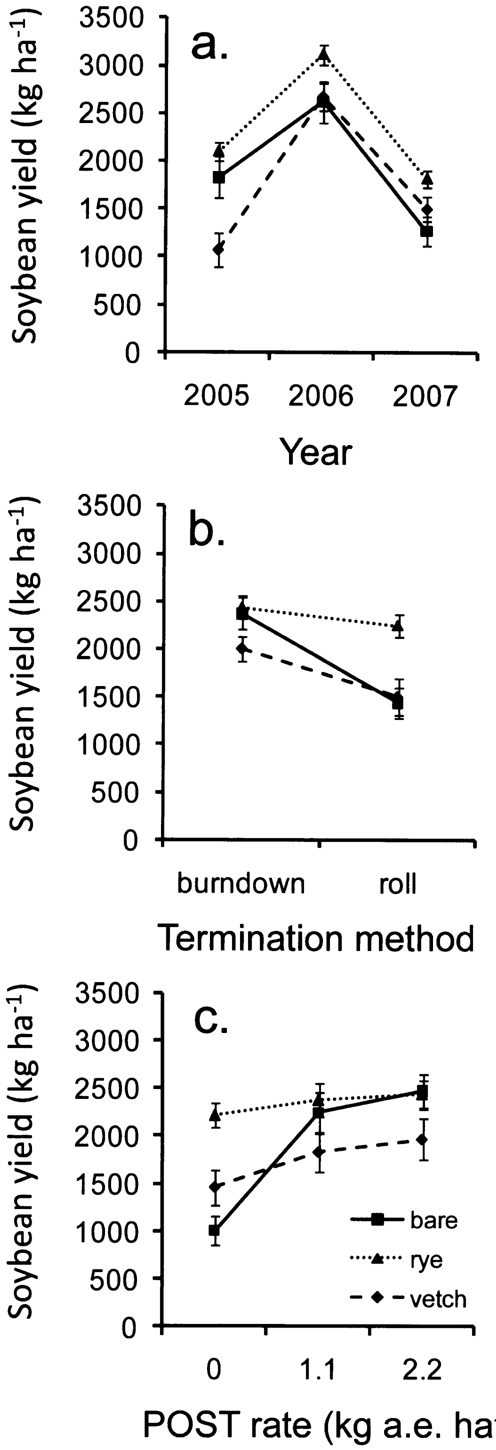

Figure 4. Interaction of (a) study year, (b) cover crop termination method, and (c) postemergence application rate of glyphosate with soybean yield. Soybean was grown following bare fallow, hairy vetch, or rye cover crops.

treatment formed a tightly compressed layer thoroughly covering the soil surface. Despite differences in PAR transmittance due to cover-crop termination method, this variable was not significantly correlated with soybean yield components or weed biomass (Table 3), nor was it correlated with residual weed populations in any of the treatments (P > 0.25, data not shown). Variation in cover-crop biomass was also not significantly correlated with soybean or weed growth, nor was it correlated with PAR transmittance.

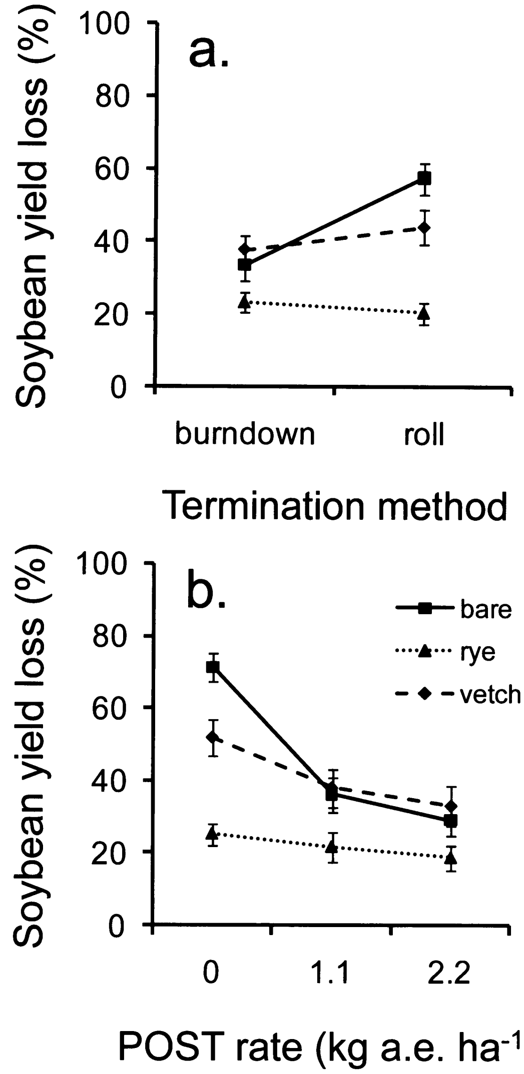

Figure 5. Interaction of (a) cover-crop termination method and (b) postemergence application rate of glyphosate with soybean yield loss [$\sin^{-1}(x)^{0.5}$] (transformed data used in analysis, but untransformed data presented here for ease of interpretation). Soybean was grown following bare fallow, hairy vetch, or rye cover crops.

Soybean yield was positively associated with soil gravimetric moisture content during the growing season, and soybean yield loss due to weed interference was negatively associated with this variable (Table 3). There was a Year by Cover by Kill interaction ($F_{4,476}$ = 2.4, P < 0.05) for soil moisture during the period following cover-crop termination through soybean harvest. Single-degree-of-freedom contrasts within the Cover treatments helped clarify this interaction. Soil moisture in soybean following rye or the bare soil cover was unaffected by termination method in any of the study years. Soil moisture in vetch was unaffected by termination method in 2005, but was lower in the Burndown than the Rolled treatment in 2006 (mean values in Burndown and Rolled were 22.23 and 23.76 g H_2O 100 g dry soil^{-1}, respectively) and 2007 (mean values in Burndown and Rolled were 15.46 and 17.59, respectively; P < 0.01).

Soil temperature was negatively associated with soybean yield for both rye and vetch and positively associated with weed biomass for vetch (Table 3). This relationship was not explained by variation in cover-crop residue biomass, which was not significantly related to posttermination soil temper-

Table 3. Pearson correlations between soybean yield components, weed biomass, and abiotic and biotic environmental variables in different cover crops.

Environmental variable	Soybean stand			Soybean yield			Soybean yield loss[b]			Weed biomass		
	Bare[a]	Rye	Vetch	Bare	Rye	Vetch	Bare	Rye	Vetch	Bare	Rye	Vetch
	r											
Cover-crop biomass	–	−0.28	0.31	–	−0.16	0.29	–	0.14	−0.09	–	0.16	−0.14
PAR_{pre}[c]	−0.47	0.35	−0.49	0.02	0.34	−0.32	0.04	−0.09	0.15	0.23	0.01	0.32
PAR_{post}	−0.33	0.32	−0.12	0.16	0.13	−0.21	−0.08	−0.09	0.39	0.10	−0.29	0.05
Soil H_2O	−0.19	0.55*	0.27	0.28	0.70**	0.40	−0.27	−0.48	−0.47	0.05	−0.25	0.04
Soil T	−0.78***	−0.51*	−0.66**	−0.38	−0.58*	−0.63*	0.29	0.22	0.36	0.34	0.34	0.53*
Common waterhemp bioassay	0.61*	0.58*	0.35	0.28	0.65**	0.43	−0.25	−0.44	−0.34	−0.38	−0.36	−0.44
Giant foxtail bioassay	−0.14	0.12	−0.16	0.03	0.16	−0.03	−0.20	−0.37	−0.06	0.01	−0.13	0.01
Soybean stand	–	–	–	0.68**	0.69**	0.80**	−0.55*	−0.36	−0.39	−0.50*	−0.55*	−0.56*
Residual common waterhemp	−0.25	−0.29	−0.01	−0.43	−0.40	−0.13	0.40	0.35	0.32	0.44	0.01	−0.19
Residual giant foxtail	0.03	−0.26	0.02	−0.10	−0.40	−0.02	0.06	0.40	0.08	−0.10	0.08	0.02
Weed biomass	−0.50*	−0.55*	−0.56*	−0.46	−0.28	−0.49	0.46	0.18	0.14	–	–	–

[a] Correlations are for measurements made within a no-till soybean crop following either a bare-soil control or hairy vetch or rye cover crops.

[b] Soybean yield loss due to weed interference was $\sin^{-1}(x)^{0.5}$ transformed prior to estimating correlation coefficients.

[c] Explanation of variable names: PAR_{pre} and PAR_{post} = % transmittance of photosynthetically active radiation prior to, and following, cover-crop termination; soil H_2O and soil T = soil gravimetric moisture content (%) and soil temperature (C) following cover-crop termination; common waterhemp and giant foxtail bioassay = common waterhemp and giant foxtail radicle length in rag-doll phytotoxicity bioassays; soybean stand = soybean plants m^{-2} 14 d after planting; residual common waterhemp and giant foxtail = common waterhemp and giant foxtail plants m^{-2} 14 d after postemergence application of glyphosate; weed biomass = aggregated biomass of entire weed community at the time of soybean harvest.

*, **, and *** represent significant Pearson correlations at α = 0.05, 0.01, and 0.001, respectively, with Bonferroni corrections made within cover-crop types.

atures in any of the treatments. Instead, it was strongly related to variation in soybean population, which was negatively associated with soil temperature in the rye, vetch, and bare soil treatments, and positively associated with soybean yield in these treatments.

Variation in soybean establishment in this study was primarily driven by main effects of Cover ($F_{2,22}$ = 13.4, P < 0.001) and Kill ($F_{1,35}$ = 5.9, P < 0.05). Soybean stand was 30 and 17% lower in the rye and vetch treatments, respectively, compared to the bare soil control, and 10% lower in the Rolled treatment compared to the Burndown treatment. The influence of Cover ($F_{2,22}$ = 12.4, P < 0.001) and Kill ($F_{1,35}$ = 6.0, P < 0.05) on soybean stand were still evident in August (data not shown). Planting through heavy rye residue in the Rolled treatment was a challenge in this study, as has been noted by other investigators (Liebl et al. 1992). Further work is needed to determine optimum planting methods for planting into physically terminated, untilled cover-crop residues. Biomass of residual weed populations was negatively correlated with soybean stand at 14 DAP (Table 3) but not with soybean stand in August. This may indicate that variation in soybean populations soon after planting influenced the crop's ability to interfere with early weed growth (Jordan 1993).

These results do not support hypothesis 3, that cover-crop termination method influences soybean yield, weed growth, and weed interference with soybean yield through changes in physical characteristics of the soil environment. Rather, they indicate that cover-crop type and termination method had a direct effect on soybean establishment, which in turn affected the ability of the soybean crop to suppress early weed growth. The work of Liebl et al. (1992) strongly corroborates this finding: Cover-crop termination method can influence soybean stand, leading to variability in yield.

The numerous correlations between soil environmental variables and soybean yield and weed growth presented here indicate an opportunity to use a complementary statistical approach to understanding internal structure within these associations in the future. Structural equation modeling (SEM) (Grace 2006) is an appropriate statistical method for examining such relationships. In this approach, putative causal relationships between correlated variables are made explicit and compared with alternate hypothetical relationships between the variables. An important benefit of this statistical approach is reduced bias and more robust estimations of model parameters than found with multiple regression models. However, a limiting factor in constructing SEM models is the very high data requirement (6 to 10 experimental units for every parameter in the model), far exceeding the number of experimental units for which environmental data were obtained in the present study. Future studies of cropping system impacts on weed management should be designed to move beyond multiple regression and path analysis (Davis and Williams 2007) to make full use of variability across differently managed systems with structural equation models.

Management Implications. The minimum loss of soybean yield due to weed interference in the rye and vetch treatments was 20%, an unacceptable value in conventional commercial grain production systems, although not considerably greater than levels of weed interference observed in organic and low-external input production systems (Cavigelli et al. 2008; Davis et al. 2005). To make the practice of cover cropping economically viable, additional management tactics may need to be layered onto this system (Liebman and Gallandt 1997). Such tactics could include, but are certainly not limited to, modifying crop row spacing and plant population (Teasdale 1995), choosing competitive crop cultivars (So et al. 2009), including a high-residue cultivation system (Teasdale and Rosecrance 2003), and decreasing the weed seedbank through intensive weed management in other crop sequence phases (Gallandt 2006). Determining ways of ameliorating soybean yield losses associated with the cover-crop roller–crimper in the absence of weed interference could also substantially improve yields when using this termination method.

The Rolled treatment was not superior to the Burndown treatment in rye, with respect to soybean yield under weedy conditions, but neither was it inferior—an important result for those wishing to eliminate a chemical burndown in soybeans planted into a rye cover crop. In production systems where herbicide use is an option, chemical termination of the cover crop earlier in the spring clearly reduces the risk of losing soybean yield potential, relative to physical termination. However, physical termination of cover crops with a roller–crimper could be an important option for organic growers seeking a way to minimize labor and fuel costs for weed management while decreasing tillage in their production system to ameliorate potential negative effects on soil quality (Liebman and Davis 2000). The agronomic benefits of cover-crop termination with a roller–crimper are contingent on the species of cover crop, as soybeans following hairy vetch performed decidedly worse in the Rolled than in the Burndown treatment.

Finally, although the Rolled system did not result in lower weed interference than the Burndown system, it did contribute to weed management by reducing weed biomass. Fecundity of weeds was not directly measured in this study; however, mature weed biomass has been shown to be strongly related to fecundity for both giant foxtail and common waterhemp (Bensch et al. 2003; Forcella et al. 2000). Management tactics that limit weed seed return are an important component of integrated weed management systems, because large inputs to the weed seedbank have negative effects on weed management and crop yield in the following growing season (Davis and Williams 2007; Taylor and Hartzler 2000).

Sources of Materials

[1] Four-row no-till planter, MaxEmerge Planter, John Deere & Co., One John Deere Place, Moline, IL 61265.

[2] Seed cleaner, Seedburo Equipment Co., 2293 South Mount Prospect Road, Des Plaines, IL 60018.

[3] Tidbit® temperature probe, Onset Corporation, 470 MacArthur Boulevard, Bourne, MA 02532.

[4] Line quantum sensor, Delta-T Devices Ltd, 130 Low Road, Burwell, Cambridge, CB25 0EJ, England.

[5] Incubator, Conviron Ltd., 590 Berry Street, Winnipeg, Manitoba, Canada R3H 0R9.

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Literature Cited

Ashford, D. L. and D. W. Reeves. 2003. Use of a mechanical roller–crimper as an alternative kill method for cover crops. Am. J. Altern. Agric. 18:37–45.

[AOSA] Association of Official Seed Analysts. 2000. Tetrazolium testing handbook. Contribution No. 29 to the Handbook on Seed Testing. Ithaca, NY: AOSA. 302 p.

Bensch, C. N., M. J. Horak, and D. Peterson. 2003. Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci. 51:37–43.

Cavigelli, M. A., J. R. Teasdale, and A. E. Conklin. 2008. Long-term agronomic performance of organic and conventional field crops in the mid-Atlantic region. Agron. J. 100:785–794.

Conklin, A. E., M. S. Erich, M. Liebman, D. Lambert, E. R. Gallandt, and W. A. Halteman. 2002. Effects of red clover (*Trifolium pratense*) green manure and compost soil amendments on wild mustard (*Brassica kaber*) growth and incidence of disease. Plant Soil 238:245–256.

Crawley, M. J. 2007. The R Book. West Sussex, England: John Wiley and Sons. 942 p.

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.

Dabney, S. M., M. W. Buehring, and D. B. Reginelli. 1991. Mechanical control of legume cover crops. Pages 146–147 *in* W. L. Hargrove, ed. Cover Crops for Clean Water. Ankeny, IA: Soil and Water Conservation Society.

Dabney, S. M., J. D. Schreiber, C. S. Rothrock, and J. R. Johnson. 1996. Cover crops affect sorghum seedling growth. Agron. J. 88:961–970.

Davis, A. S., P. M. Dixon, and M. Liebman. 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography: II. retrospective perturbation analysis. Weed Sci. 51:930–939.

Davis, A. S., K. A. Renner, and K. L. Gross. 2005. Weed seedbank and community shifts in a long-term cropping systems experiment. Weed Sci. 53:296–306.

Davis, A. S. and M. M. Williams, II. 2007. Variation in wild proso millet (*Panicum miliaceum*) fecundity in sweet corn has residual effects in snap bean. Weed Sci. 55:502–507.

Drinkwater, L. E., P. Wagoner, and M. Sarrontonio. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396:262–264.

Forcella, F., N. Colbach, and G. O. Kegode. 2000. Estimating seed production of three *Setaria* species in row crops. Weed Sci. 48:436–444.

Gallandt, E. R. 2006. How can we target the weed seedbank? Weed Sci. 54:588–596.

Grace, J. B. 2006. Structural equation modeling and natural systems. Cambridge, UK: Cambridge University Press. 365 p.

Hammond, R. B. and R. L. Cooper. 1993. Interaction of planting times following the incorporation of a living green cover crop and control measures on seedcorn maggot populations in soybean. Crop Prot. 12:539–542.

Jordan, N. 1993. Prospects of weed control through crop interference. Ecol. Appl. 3:84–91.

Jurik, T. W. and S. Zhang. 1999. Tractor wheel traffic effects on weed emergence in central Iowa. Weed Technol. 13:741–746.

Kornecki, T. S., A. J. Price, and R. L. Raper. 2006. Performance of different roller designs in terminating rye cover crop and reducing vibration. Appl. Eng. Agric. 22:633–641.

Liebl, R., F. W. Simmons, L. M. Wax, and E. W. Stoller. 1992. Effect of rye (*Secale cereale*) mulch on weed-control and soil-moisture in soybean (*Glycine max*). Weed Technol. 6:838–846.

Liebman, M. and A. S. Davis. 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40:27–47.

Liebman, M. and E. R. Gallandt. 1997. Many little hammers: ecological approaches for management of crop-weed interactions. Pages 291–343 *in* L. E. Jackson, ed. Ecology in Agriculture. San Diego, CA: Academic Press.

Lindquist, J. L., D. A. Mortensen, P. Westra, et al. 1999. Stability of corn (*Zea mays*)–foxtail (*Setaria* spp.) interference relationships. Weed Sci. 47:195–200.

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

Nafziger, E. D. 2002. Soybeans. Pages 35–43 *in* Illinois Agronomy Handbook. Urbana, IL: University of Illinois Extension.

Pinheiro, J. C. and D. M. Bates. 2004. Mixed-effects models in S and S-PLUS. New York: Springer. 528 p.

R Development Core Team. 2006. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org. Accessed: May 3, 2010.

Sayre, L. 2003. Introducing a Cover Crop Roller without All the Drawbacks of a Stalk Chopper. Rodale Institute. http://www.newfarm.org/depts/NFfield_trials/1103/notillroller_print.shtml. Accessed: Sepember 3, 2009.

Singer, J. W., K. A. Kohler, and P. B. McDonald. 2007. Self-seeding winter cereal cover crops in soybean. Agron. J. 99:73–79.

So, Y. F., M. M. Williams, and J. K. Pataky. 2009. Wild-proso millet differentially affects canopy architecture and yield components of 25 sweet corn hybrids. Hortscience 44:408–412.

Taylor, K. L. and R. G. Hartzler. 2000. Effect of seed bank augmentation on herbicide efficacy. Weed Technol. 14:261–267.

Teasdale, J. R. 1995. Influence of narrow row/high population corn (*Zea mays* L.) on weed control and light transmittance. Weed Technol. 9:113–118.

Teasdale, J. R. 1996. Contribution of cover crops to weed management in sustainable agricultural systems. J. Prod. Agric. 9:475–479.
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.
Teasdale, J. R. and R. C. Rosecrance. 2003. Mechanical versus herbicidal strategies for killing a hairy vetch cover crop and controlling weeds in minimum-tillage corn production. Am. J. Altern. Agric. 18:95–102.
University of Illinois Extension. 2007. Illinois Agricultural Pest Management Handbook. Urbana: University of Illinois. 357 p.
Villamil, M. B., F. E. Miguez, and G. A. Bollero. 2008. Multivariate analysis and visualization of soil quality data for no-till systems. J. Environ. Qual. 37:2063–2069.
Williams, M. M., D. A. Mortensen, and J. W. Doran. 2000. No-tillage soybean performance in cover crops for weed management in the western Corn Belt. J. Soil Water Conserv. 55:79–84.

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