Timing of Cover-Crop Management Effects on Weed Suppression in No-Till Planted Soybean using a Roller-Crimper

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S. B. Mirsky, W. S. Curran, D. M. Mortensen, M. R. Ryan, and D. L. Shumway*

Integrated weed management tactics are necessary to develop cropping systems that enhance soil quality using conservation tillage and reduced herbicide or organic weed management. In this study, we varied planting and termination date of two cereal rye cultivars ('Aroostook' and 'Wheeler') and a rye/hairy vetch mixture to evaluate cover-crop biomass production and subsequent weed suppression in no-till planted soybean. Cover crops were killed with a burn-down herbicide and roller-crimper and the weed-suppressive effects of the remaining mulch were studied. Cover-crop biomass increased approximately 2,000 kg ha^{-1} from latest to earliest fall planting dates (August 25–October 15) and for each 10-d incremental delay in spring termination date (May 1–June 1). Biomass accumulation for cereal rye was best estimated using a thermal-based model that separated the effects of fall and spring heat units. Cultivars differed in their total biomass accumulation; however, once established, their growth rates were similar, suggesting the difference was mainly due to the earlier emergence of Aroostook rye. The earlier emergence of Aroostook rye may have explained its greater weed suppression than Wheeler, whereas the rye/hairy vetch mixture was intermediate between the two rye cultivars. Delaying cover-crop termination reduced weed density, especially for early- and late-emerging summer annual weeds in 2006. Yellow nutsedge was not influenced by cover-crop type or the timing of cover-crop management. We found that the degree of synchrony between weed species emergence and accumulated cover-crop biomass played an important role in defining the extent of weed suppression.

Nomenclature: Cereal rye, *Secale cereale* L.; hairy vetch, *Vicia villosa* Roth; yellow nutsedge, *Cyperus esculentus* L.

Key words: Cover crops, mulches, roller-crimper, planting and termination date.

Surface mulches from cover crops suppress weed growth by reducing light levels at the soil surface, thereby slowing photosynthesis and warming of soils in the spring. In return, these conditions reduce seed germination and act as a physical barrier to seedling emergence and growth (Teasdale et al. 2007). Weed suppression increases with increasing cover-crop biomass; however, historical biomass levels achieved in the mid-Atlantic region of the United States have typically been low (e.g., 3,300 kg ha^{-1}) and insufficient to provide adequate levels of weed suppression (Mohler and Teasdale 1993). More recently, increased attention to basic agronomic management of cover crops has resulted in improved performance (Teasdale et al. 2004a). In addition, uniform distribution of the cover-crop residue is needed for consistent suppression of weed emergence (Creamer et al. 1996; Teasdale and Mohler 1993). The effect of cover-crop residues on weed control is species specific, with annual species being quite susceptible to cover-crop surface mulches, whereas perennials are not (Liebman and Davis 2000; Mohler and Teasdale 1993). Weed suppression with cover-crop residues alone has been reported to be inconsistent and inadequate, often requiring integration of cover crops into a weed management program that includes additional management tactics (Williams et al. 1998).

Cereal rye and hairy vetch are cover crops that have been commonly grown throughout the United States and evaluated for their weed-suppressive potential in no-till cropping systems (Hoffman et al. 1993; Teasdale et al. 2007; Wilkins and Bellinder 1996). Both are selected for their winter hardiness and high biomass potential and their temporal compatibility with the following summer crop. Adoption of cereal rye in the mid-Atlantic region is due to its fall establishment success and persistent residue (Ruffo and Bollero 2003), whereas hairy vetch is favored for its ability to fix 150 kg ha^{-1} of nitrogen (Decker et al. 1994).

Manipulating planting date in the fall or termination date in the spring may allow growers to achieve a higher level of weed suppression (Duiker and Curran 2005; Teasdale et al. 2004a). The rate of cover accumulation in the spring is influenced by the timing of fall planting. Teasdale et al. (2004a) showed that later fall establishment of hairy vetch reduced spring biomass by 43% when terminated in the vegetative stage compared with only 20% at the flowering stage. In a Pennsylvania study, Duiker and Curran (2005) showed that average aboveground cereal rye biomass was three times greater when terminated at the late-boot stage (4,200 kg ha^{-1}) compared with the early-boot stage (1,400 kg ha^{-1}).

Fall planting and spring termination dates for cereal rye and hairy vetch cover crops are primarily determined by previous and future crops in the rotation. For example, a longer-season maize hybrid will push the date of cover-crop seeding later in the fall. Depending on the cropping system and method of cover-crop termination, timing of cover-crop establishment and termination will vary considerably. In the northeastern United States, cereal rye is typically sown over a wide range of planting dates from midsummer to late fall. Hairy vetch is planted from mid-August to no later than mid-September in the mid-Atlantic region to increase the likelihood of overwinter survival. Although much work has been conducted to quantify the effect of growing-season length on hairy vetch biomass accumulation (Teasdale et al. 2004a), less is known about the combined effects of planting and termination dates on cereal rye and rye/hairy vetch mixtures.

Research assessing the weed suppression of surface-killed cereal rye and cereal rye/hairy vetch covers has focused on herbicide-killed cover crops or control accomplished mechanically by mowing (e.g., rotary or flail mowing) or stalk chopping (Moore et al. 1994; Teasdale and Rosencrance 2003;

Yenish et al. 1995). In general, these control methods result in a suppressed cereal grain or grain–legume mix that is not uniformly distributed on the soil surface, but instead is left partially standing in the case of the herbicide-killed covers, or is unevenly distributed after mowing or stalk chopping. (Facelli and Pickett 1991; Teasdale and Mohler 1993). Roller-crimpers are a relatively new residue management tool adapted from equipment used in southern Brazil and Paraguay that lays cover crops down while crimping and damaging the vascular tissue (Figure 1) (Ashford and Reeves 2003). In contrast to mowing, cover crops managed with a roller-crimper are more uniformly distributed on the soil surface. Because the plant material is mostly left intact, residues can persist for longer periods of time (Creamer and Dabney 2002; Morse 2001). Although not fully investigated, one would expect that greater uniformity coupled with a more persistent cover should result in greater weed suppression (Ashford and Reeves 2003).

Species-specific differences in weed suppression from cover-crop mulches are the likely result of differences in synchrony between weed germination and amount of cover-crop biomass. Changes in weed suppression can influence the composition and abundance of the weed community (Booth and Swanton 2002; Facelli and Pickett 1991; Shea et al. 2004). A weed management program that utilizes cover crops for weed suppression and relies less on tillage and herbicides must focus on integrating multiple tactics. Varying the timing of cover-crop management both in the fall and spring to increase biomass accumulation can increase weed suppression from the cover-crop mulch. Additionally, by tactically enhancing the synchrony between high cover-crop biomass and emergence of particularly troublesome weeds, significant improvements to weed suppression may be achieved.

The relationship between the amount of cereal rye and hairy vetch surface residues and weed suppression has been examined at a single termination date in the spring (Mohler and Teasdale 1993; Moore et al. 1994). The range of cover-crop biomass was achieved by clipping and adding residues from adjacent plots (Mohler and Teasdale 1993). Although this work carefully quantified the effect on weed emergence in a range of cover-crop biomass levels, it was an artificial study system in that the residue was added by hand to represent an array of biomass levels at a single point in time during the spring growing season. Winter annual cover-crop biomass accumulates during the course of the spring, with low accumulation early in the spring and accelerating biomass accumulation later in the spring. Therefore, the timing of cover-crop management influences the amount of biomass, which in turn alters soil physical and chemical properties known to directly influence weed seed germination and establishment. In this study, our objective was to evaluate the effect timing of cover-crop management has on biomass accumulation and subsequent weed suppression. We hypothesize that weed suppression is dependent on cover-crop biomass, timing of termination, the emergence periodicity of the weed community, and the response of those species to cover-crop residues.

Materials and Methods

Field experiments were conducted from 2004 to 2006 at the Russell E. Larson Agricultural Research Center near Rock

Figure 1. Photograph of a front-mounted roller-crimper constructed by Penn State University. The roller-crimper is 3.2-m long by 51-cm diam by 3.2-mm thick and weighs 1,520 kg.

Springs, PA ($40°44'$N, $77°57'$W). The study was conducted on a Hagerstown silt loam soil (Fine, mixed, mesic, Typic Hapludalfs) with a surface soil pH of 6.5 and organic carbon content of 20 g kg^{-1}. The experimental design was a modified split block with a factorial of cover-crop type (three treatment levels) and termination date (four termination dates) as the main plots, and fall establishment (six planting dates) a split plot within cover-crop type main-effect treatment. The experimental treatments were replicated four times. Therefore, planting date is a split-plot nested within a split-block design with a full factorial of all treatment factors present in this experiment. Individual subplots measured 1.5 m wide and 2.3 m in length. The experiment was initiated in the fall of 2004 and repeated again in 2005 in an adjacent field. Cover crops included two cereal rye cultivars and a cereal rye/hairy vetch mixture. 'Aroostook' rye was selected because of its winter hardiness and common use in the region. 'Wheeler' rye was included for comparison because of its reported high allelochemical content (Reberg-Horton et al. 2005), which is useful for suppressing weeds. The cereal rye/hairy vetch combination is a common mixture used in the region for its soil quality contributions, including N fixation (Clark et al. 1994). Aroostook rye was used in the seeding of the cover crop mixture; we used 'Auburn Early Cover' hairy vetch that had been reproduced for many years by a Pennsylvania farmer (Steve Groff).

In both years, the previous crop was spring-planted oats (*Avena sativa* L.), which was harvested for grain in July. Seedbed preparation for the cereal rye included disking and cultimulching to produce a uniform seedbed. Cereal rye and the rye/hairy vetch mixture were seeded on 10-d intervals from August 25 to October 15 (six equally spaced planting dates in total). Cover crops were drill-seeded in a 19-cm row spacing using a 1.8-m wide 'Great Plains (3P605NT)' small plot drill, at 135 kg ha^{-1} for cereal rye alone and 90 plus 45 kg ha^{-1} of rye and hairy vetch, respectively, for the mixture. Ammonium sulfate was broadcast-applied at a rate of 71 kg N ha^{-1} in March of each year to stimulate cover-crop growth and ensure adequate biomass production. To terminate the cover crop in the following spring, 0.84 kg ae ha^{-1} glyphosate plus 0.28 kg ae ha^{-1} 2,4-D Low Volatile Ester (LVE) was applied in 187 L ha^{-1} of water at 207 kPa using a tractor-mounted sprayer at 10-d intervals

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from May 1 to May 30 (four termination dates). The cover crops were rolled-crimped approximately 24 h after herbicide application. The herbicide was applied to ensure successful weed and cover-crop control without reliance on mechanical control alone. A no-cover-crop treatment that also received the herbicide and rolling-crimping regime at each termination date was included to compare the effects of cover-crop residue vs. no residue on weed emergence.

The roller-crimper used in this experiment was made from cylindrical steel well casing (3.2-m length by 51-cm diam by 3.2-mm thickness) with metal slats spaced 10.2 cm apart welded onto the cylinder in a chevron pattern (Ashford and Reeves 2003) (Figure 1). The roller-crimper weighed 1,520 kg and was front-mounted on a John Deere 7700 tractor operated at 7.2 km h^{-1}. The cover crops were rolled-crimped in a direction perpendicular to the direction of sowing; thereby laying the cover crop down in a unidirectional pattern. Soybean (Chemgro 3340) was no-till drilled (432,400 seeds ha^{-1}) into the cover-crop residue in a 19-cm row spacing 10 d after rolling-crimping. Soybean was planted with a Great Plains (1006NT) no-till drill in the same direction that the cover crop was rolled-crimped.

Air temperature and precipitation were recorded at a weather station located within 0.25 km of the experiment. Supplemental irrigation was provided (a single 2.5-cm application in May 2005 and two 2.5-cm applications in May and June 2006) to ensure successful soybean and weed emergence. Cover-crop biomass was harvested immediately before herbicide application in each planting date main plot by clipping all aboveground plant material from a single 0.5-m^2 quadrat in an area independent of future weed assessments. Biomass samples were dried at 50 C for 1 wk before weighing.

The effect of cover-crop surface residue and timing of residue management on weed suppression was determined by assessing weed seedling emergence at 4 and 8 wk after cover-crop termination. Weed emergence was quantified by randomly placing two 0.25-m^2 quadrats within each planting-by-termination-date subplot and counting the emerged weeds by species. Surviving weeds that appeared injured from the burn-down herbicide application were not recorded.

Thermal time, using growing degree days (GDD), was used to evaluate cereal rye biomass accumulation. GDD were calculated using the following equation:

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \quad [1]$$

where T_{max} is the maximum daily temperature, T_{min} the minimum daily temperature, and T_{base} the base temperature (base temperature where physiological activity and growth occur) set at 4.4 C (Nuttonson 1958). Cumulative GDD is the summation of daily GDD between a planting date and termination date. For mean temperatures less than T_{base}, GDD were assumed to be zero.

Three thermal-based growth models were used to characterize cereal rye biomass: one driven solely by spring temperature (spring$_{GDD}$), one based on cumulative heat units from the fall and spring (total$_{GDD}$), and the final model based on separate effects of fall and spring heat units (fall$_{GDD}$ and spring$_{GDD}$). The spring$_{GDD}$ and total$_{GDD}$ models have been used previously to evaluate crop growth and development (Nuttonson 1958; Teasdale et al. 2004a). The fall$_{GDD}$ and

spring$_{GDD}$ model was included because timing of fall cereal rye planting can influence the growth of cereal rye (Fowler 1983; Mirsky et al. 2009). Spring GDD estimates were initiated on March 1 (Nuttonson 1958). Biomass data collected in the subplots from the experiment described herein were fitted with linear regression using the following thermal-based growth models:

$$Biomass = \beta_0 + \beta_1(spring_{GDD}) \quad [2]$$

$$Biomass = \beta_0 + \beta_1(total_{GDD}) \quad [3]$$

$$Biomass = \beta_0 + \beta_1(fall_{GDD}) + \beta_2(spring_{GDD}) \quad [4]$$

where biomass is the cover-crop residue dry weight sampled before rolling-crimping, and β_0 the intercept and β_1 are parameter coefficients defining the slope of the equation in relation to fall$_{GDD}$ and spring$_{GDD}$.

Data Analysis. Analysis of variance (ANOVA) was conducted to test the effects of year, cultivar, and planting and termination dates on cover-crop biomass accumulation using a proc-mixed procedure in SAS v. 9.1 (SAS Institute Inc. 2004). Linear regression was used to determine the relationship between growth stage and GDD using a linear mixed-models package (lm) in R 2.4 (R Development Core Team 2006). The adjusted coefficient of determination (R^2) was used as an indication of goodness of fit and the Akaike information criterion (AIC) was used for model selection (Johnson and Omland 2004). Analysis of covariance (ANCOVA) was applied to evaluate the effect of cereal rye cultivar on cover-crop biomass with fall and spring GDD as covariates. ANOVA was used to examine differences in weed density among the residue treatments.

Weed community associations were examined using redundancy analysis (RDA) with CANOCO 4.5 (ter Braak and Smilauer 2002). RDA is well-suited for evaluating weed community data as it reveals associations between systems attributes and weed communities (Reberg-Horton et al. 2006). A constrained form of principle component analysis, RDA identifies optimal linear models describing community structure and predicts species response. The regression coefficients in RDA are constrained by factors in the experimental design as well as environmental gradients, which allows for hypothesis testing by partitioning treatment effects into individual factors (Reberg-Horton et al. 2006). The influence of cover crops on broad changes in the weed community was evaluated by grouping weedy species into one of the following three life history classes: summer annual broadleaves, summer annual grasses, and perennials. An RDA was performed where weed community was constrained by the following explanatory variables: field site, termination date, cover-crop biomass, and spring GDD gradients. A Monte Carlo permutation was used to test for significant community gradients using 500 permutations. The significance of the community gradients was determined by calculating the proportion of F statistics generated from the permutated environmental matrices that were greater than the F statistic calculated from the empirical species–environmental matrix. Environmental variables that significantly influenced species response were then determined by using a forward selection procedure on the environmental variables. Weed species count data were Hellinger-transformed (Le-

gendre and Gallagher 2001) before analysis to standardize data by sample.

The RDA was considered a partial RDA because blocks were treated as covariables to remove the block effect. The degree of association of weed species groups and explanatory variables were visualized with biplots, developed in CanoDraw (bundled with CANOCO 4.5), in which the species and explanatory variables were plotted along the orthogonal primary and secondary community gradients. Proximity or an acute angle between weed group vectors and explanatory variables is indicative of a high degree of association, whereas vectors perpendicular to the weed species group are not correlated and those at 180° of the weed species group are negatively correlated.

Weed community response to the cover-crop treatments was further tested with permutational multivariate analysis of variance (PERMANOVA; Anderson 2005). Using permutation methods, PERMANOVA simultaneously tests for the effects of multiple treatment factors on multiple response variables on the basis of distance measures, retaining the structure of the experimental design (Anderson 2001; McArdle and Anderson 2001). A single distance measure is computed from community associations and compared between samples to calculate an F statistic. The Bray–Curtis distance measure (Beals 1984) was used and data were permutated 500 times.

Homogeneity of weed community structure (dominance distribution) among cover-crop residue treatments across the termination dates was determined by performing a frequency analysis in contingency tables on the weed community composition contingency table (PROC FREQ, SAS v. 9.1). Differences were tested using Pearson's chi-square test (Zar 1999). A change in the frequency distribution of weed counts resulting in a significant Pearson's chi square would indicate a change in dominance structure. Preliminary analysis showed differences ($P < 0.05$) between residue treatments for both field sites; therefore the analysis was conducted by residue treatment across the termination dates by field site. When differences in community structure were found, species contributing most to the shift in dominance structure were identified as those with the highest cell chi-square values. Where a high proportion of the test statistic was skewed to a few weed species, the proportion of the total test statistic that these species represent was reported. ANOVA was also used to examine differences in weed emergence and suppression between the no-residue and residue treatments. A log (weed density +1) transformation was completed on individual weed species emergence data when variances were not homogeneous. All means comparisons were performed using the Tukey–Kramer method ($P < 0.05$) in SAS v. 9.1.

The weed community was evaluated in three ways: (1) total weed density, (2) three life history classes (i.e., annual broadleaves, annual grasses, and perennials), and (3) individual species. Univariate analysis was performed on total weed density; univariate and multivariate analyses were performed on annual broadleaves, annual grasses, and perennial weed density. Species with a relative abundance $\geq 3\%$ for at least one field site were included in the life history class analysis. Relative abundance is defined as the proportion of an individual species density of the total weed species density. The species-specific univariate analysis was performed when an individual species made up more than 3% of total weed abundance.

Table 1. Analysis of variance for biomass as influenced by year, cover crop, termination date, and planting date.

Effect		Biomass	
	df	F value	P > F
Cover crop (CC)	2	11.02	0.0049
Termination date (TD)	3	460.49	< 0.0001
CC × TD	6	0.46	0.8370
Planting date (PD)	5	65.35	< 0.0001
CC × PD	10	1.53	0.1265
TD × PD	15	1.32	0.1860
CC × TD × PD	30	0.81	0.7569
Year	–	–	0.2403

Results and Discussion

Cover-Crop Biomass. Cover crop, planting date, and termination date significantly influenced biomass accumulation. Year was not a significant source of variation and there were no significant interaction terms (Table 1). Aroostook growing in monoculture produced greater biomass than Wheeler rye, and biomass of the cereal rye/hairy vetch mixture was intermediate between the two (Table 2). Cover-crop biomass increased when planted earlier in the fall and terminated later in the spring (Table 2). Cover-crop biomass was largest for the early-planted cover crop; a 65% increase over late-seeded cover-crop plantings. Biomass accumulation was 7,880 kg ha^{-1} at the earliest planting date and 5,070 kg ha^{-1} at the latest planting date (crop and termination date pooled). The loss in cover-crop biomass from one planting date to the next grew larger the later the cover crop was planted, 12% between August 25 and September 25 compared with 24% between October 5 and 15. Across spring termination dates, cover-crop biomass ranged from 4,050 up to 10,000 kg ha^{-1}, averaging a 37% increase in biomass with each 10-d incremental delay in cover-crop termination. The sensitivity of cover-crop biomass accumulation in the spring observed in this study is in the range reported by others for hairy vetch (Teasdale et al. 2004a; Clark et al. 1994). Teasdale et al. (2004a) reported a 76 and 24% increase in hairy vetch biomass with delay in termination in a study pooled over three experimental sites in Maryland and New York comparing spring cover-crop termination at the vegetative and flowering stages, respectively. Ashford and Reeves (2003) found that cereal rye produced 10,500 kg ha^{-1} of biomass when terminated at the soft dough stage (a growth stage also represented in this study), and Vaughan and Evanylo (1998) reported 10,370 and 9,985 kg ha^{-1} for cereal rye and rye/hairy vetch biomass, respectively, in a study that delayed termination until late May. The wide range of cover-crop dry matter production observed in this study is a result of broad planting and termination windows in the fall and spring, respectively.

Simple thermal models of cereal rye growth and development were fitted to cereal rye (year and cultivar pooled) (Table 3). Cultivar and year were pooled because an ANCOVA of cereal rye biomass accumulation with fall$_{GDD}$ and spring$_{GDD}$ as covariates revealed no year, cultivar-by-fall$_{GDD}$, or cultivar-by-spring$_{GDD}$ interactions (Table 4). The fall$_{GDD}$ plus spring$_{GDD}$ model was the best predictor, accounting for the greatest variation in rye biomass accumulation and also had the lowest AIC values. This result demonstrates that cultivar did not influence the slope of the regression between biomass and fall$_{GDD}$ or spring$_{GDD}$; that is,

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Table 2. Mean cover-crop biomass as influenced by cultivar, planting date, and termination date main effects, pooled across years. Mean comparison was performed by crop (planting and termination date pooled), planting date (crop and termination date pooled), and termination date (crop and planting date pooled) independently, with different lowercase letters indicating significant differences ($P < 0.05$) using the Tukey–Kramer method.

Treatment	Biomass
	kg ha^{-1}
Crop	
Aroostook	7,259a
Wheeler	6,508b
Rye/hairy vetch	6,876ab
Planting date	
August 25	7,880a
September 5	7,904a
September 15	7,161b
September 25	7,016b
October 5	6,260c
October 15	5,066d
Termination date	
May 1	4,051a
May 10	5,809b
May 20	7,599c
May 30	10,066d

Table 4. Analysis of covariance (ANCOVA) of biomass as influenced by year and cover crop (Crop) with fall and spring growing degree days (GDD) as covariates. The effects of cover crop on the slope of the response of cover-crop biomass to fall growing degree days (fall$_{GDD}$ × crop) and spring growing degree days (spring$_{GDD}$ × crop) is assessed by the associated P value provided by the ANCOVA.

	Biomass
Effect	$P > F$
Crop	0.4323
Fall$_{GDD}$	< 0.0001
Fall$_{GDD}$ × crop	0.9522
Spring$_{GDD}$	< 0.0001
Spring$_{GDD}$ × crop	0.1265
Year	0.2554

and could help infer the results of these place-based studies to other sites in the study region. To extend the results of these findings to other sites, models used for forecasting are needed. Those models would also need to address regional variation in photoperiod, precipitation, and soil fertility (Malhi et al. 2006; Ruffo et al. 2004).

Weed Response to Residue Management. The 8-wk emergence data was used for the weed community analysis because few differences in emergence patterns were observed between the 4- and 8-wk sampling dates and because the 8-wk assessment integrated a longer period for weed emergence. The weed species included in the analysis of the life history classes represented 88 and 93% of the total weed community emerging in residue treatments and 88 and 91% emerging in the no-residue control in 2005 and 2006, respectively. These species included the following annual broadleaf weeds: redroot pigweed (*Amaranthus retroflexus* L.), common ragweed (*Ambrosia artemisiifolia* L.), common lambsquarters (*Chenopodium album* L.), and wild buckwheat (*Polygonum convolvulus* L.). Annual grass species included fall panicum (*Panicum dichotomiflorum* Michx.) and giant and yellow foxtail (*Setaria faberi* Herrm. and *S. glauca* L.). Perennial weeds included yellow nutsedge and dandelion (*Taraxacum officinale* Weber in Wiggers).

Cover-crop type, planting date, and termination date were all significant sources of variation in total weed density (Table 5). Although differences were relatively small, total weed density was lowest under Aroostook cereal rye mulches (Table 6), the cultivar with greater biomass accumulation (Table 2) compared with Wheeler and rye/hairy vetch mixtures. Although Wheeler is known to produce larger amounts of known allelochemicals such as 2,4-dihydroxy-1,4-(2H)benzoxazine-3-one than some other rye cultivars (Reberg-Horton et al. 2005), physical impedance is likely the primary mechanism suppressing weeds. Teasdale and Mohler (2000) reported that quantity of residue was more important than the type of residue and found that weed suppression was similar under varying mulch types that included both allelopathic and highly weathered residues.

the rate of biomass accumulation was similar for both rye cultivars. In the case of both cover-crop cultivars, heat units accumulated in the spring had a more pronounced effect on cover-crop biomass accumulation than fall heat units. This pattern is borne out in the ANCOVA that revealed similar slopes for biomass accumulation for the fall$_{GDD}$ and spring$_{GDD}$ for each cultivar. Although biomass differences were observed between cereal rye cultivars, when GDD was used as a covariate, differences between cultivars were observed (Table 1). The rye/hairy vetch mixture was not fit to a thermal model since biomass accumulation for the two-species mixture is dependent on the proportion of each in the mixture, which was not quantified in this experiment.

Previous attempts at estimating cereal rye development have centered on the accumulation of springtime GDD (Nuttonson 1958). The wide range of planting dates included in this study provides insight into the extent to which cover-crop biomass is influenced by altering fall and spring GDD. Incorporating the separate effects of fall and spring heat units in the model significantly improved our ability to predict biomass accumulation. Late August and early September cereal rye planting dates have generally not been investigated in row-crop production because timing of fall-planted covers is limited to when the cash crop can be removed (Westgate et al. 2005). However, cover crops are being used increasingly in a broad array of fruit, vegetable, grain, and forage crops, which enables a wider range of fall sowing dates (Curran et al. 2007; Veenstra et al. 2006). The thermal-based growth model was a useful approach for quantifying the variation in biomass accumulation associated with planting and termination dates

Table 3. Thermal-based biomass models predicting cover-crop biomass accumulation (year and cultivar pooled). The parameter estimates characterize the effects of growing degree days (GDD) on cereal rye biomass accumulation. Included are adjusted R^2 values and Akaike information criteria (AIC) for goodness of fit and model selection, respectively.

Thermal models	β_0	Total β_1	Fall β_1	Spring β_2	Adj. R^2	AIC
Total$_{GDD}$	1,068.6	4.1	–	–	0.375	10,581
Spring$_{GDD}$	−1,060.9	–	–	13.7	0.683	10,191
Fall$_{GDD}$ vs. spring$_{GDD}$	−2,885.6	–	2.2	13.7	0.772	10,000

Table 5. Analysis of variance for weed species as influenced by year, cover crop, termination date, and planting date. Selection of weed species was based on relative abundance (> 3% of total abundance) and economic importance.

Effect	df	Total weed density P > F	Broadleaf P > F	Grass P > F	Perennial P > F	Common lambsquarters P > F	Foxtail species P > F	Common ragweed P > F	Yellow nutsedge P > F	Dandelion P > F
Cover crop (CC)	2	**	0.5532	0.321	0.0657	0.4705	0.2945	0.8002	0.1135	0.6156
Planting date (PD)	5	***	**	0.1468	0.1688	***	0.2690	0.1830	0.2077	0.1412
CC × PD	10	0.5412	0.4100	0.7830	0.0999	0.1085	0.8377	0.6096	0.0801	0.6656
Termination date (TD)	3	***	***	***	0.9710	**	*	***	0.2017	***
PD × TD	15	0.9266	0.4246	0.1188	0.2901	0.1776	0.1028	0.9907	0.7451	0.8301
Crop × TD	6	0.7289	0.3452	0.5165	0.9206	0.3861	0.1078	0.0628	0.8238	0.5266
CC × TD × PD	30	0.8905	0.6511	0.6742	0.9546	0.5866	0.4399	0.7904	0.8474	0.4470
Year	1	0.2403	0.2410	***	0.2409	0.2453	0.3160	***	0.2403	***

* Significant effect of treatment factor at P ≤ 0.05.
** Significant effect of treatment factor at P ≤ 0.01.
*** Significant effect of treatment factor at P ≤ 0.001.

Earlier fall planting and delay in spring cover-crop termination reduced weed densities. Suppression of annual broadleaves did not vary by cover crop, but was influenced by time of fall planting and spring termination. Annual grass density was reduced only in the late termination treatments in 2006 (Table 6). Perennial weeds were not influenced by cover-crop type or the timing of cover-crop management. For individual weed species, cover-crop type did not affect weed emergence, whereas planting date effects were observed only for common lambsquarters (Table 5). In contrast, termination date influenced the density of several species including common lambsquarters, foxtail species, dandelion, and common ragweed (Table 5). In general, the influence of cover-crop planting and termination date resulted in lower weed population densities at earlier planting and later termination dates. Since planting and termination dates define the growing season length for the cover crop, they directly influence cover-crop biomass, which in turn influences weed density. Earlier cover-crop establishment resulted in greater cover-crop biomass in the spring and moderate reductions in annual broadleaf weed density across the planting date gradient (Table 6). Common lambsquarters was the only annual broadleaf influenced by planting date, with a small reduction in density as timing of cover-crop planting was delayed. Delayed cover-crop termination in spring had the greatest suppressive effect from cover-crop biomass on weed density (Tables 2 and 6). However, the degree of synchrony between weed species emergence periodicity and cover-crop biomass accumulation may also play an important role in defining the extent of weed suppression.

Ordination biplots from the RDA were used to interpret weed community associations with treatment factors and environmental gradients (Figure 2). Planting date was not included in the RDA since there was no planting date by termination date interaction. The RDA identified significant primary and secondary community gradients depicted in the biplots as the horizontal and vertical axes, respectively (Figure 2; first axis: $F = 31.25$, $P = 0.002$; second axis: $F = 15.89$, $P = 0.002$). Using forward selection, the primary axis was associated with year ($F = 58.41$, $P = 0.002$), whereas the secondary axis was associated with the cover-crop biomass gradient ($F = 20.46$, $P = 0.002$), which was also strongly associated with increasing spring GDD and timing of cover-crop termination. Therefore, the greatest amount of variation in weed communities was attributed to field site followed by the gradient in cover-crop biomass. Rye cultivars and rye/hairy vetch mixture grouped at the centroid (intersection of

Table 6. Mean weed population density as influenced by cultivar, planting date, and termination date main effects, pooled across years unless otherwise presented. Mean comparison was performed by planting date and termination date independently, with different lowercase letters indicating significant differences (P < 0.05) using the Tukey–Kramer method. A dash (–) indicates a lack of significance in the data.

Treatment	Total weed density	Broadleaves	Grasses 2005	Grasses 2006	Perennials	Common lambsquarters	Foxtail species	Common ragweed 2005	Common ragweed 2006	Yellow nutsedge	Dandelion 2005	Dandelion 2006
						plants m^{-2}						
Cover crop												
Aroostook	26a	–	–	–	–	–	–	–	–	–	–	–
Wheeler	33b	–	–	–	–	–	–	–	–	–	–	–
Rye/hairy vetch	31ab	–	–	–	–	–	–	–	–	–	–	–
Planting date												
August 25	27a	11ab	–	–	–	6ab	–	–	–	–	–	–
September 5	27a	10a	–	–	–	5a	–	–	–	–	–	–
September 15	30b	12ab	–	–	–	6a	–	–	–	–	–	–
September 25	30b	13ab	–	–	–	7ab	–	–	–	–	–	–
October 5	36c	14b	–	–	–	7ab	–	–	–	–	–	–
October 15	36c	16b	–	–	–	9b	–	–	–	–	–	–
Termination date												
May 1	36a	16a	7a	13a	–	10a	9a	–	2a	–	4a	7a
May 10	33b	15ab	6a	9b	–	9ab	6ab	–	2a	–	5a	5ab
May 20	26c	12b	6a	2c	–	5bc	4b	–	2a	–	3ab	3bc
May 30	24d	6c	4a	1c	–	2c	2c	–	0b	–	1c	1c

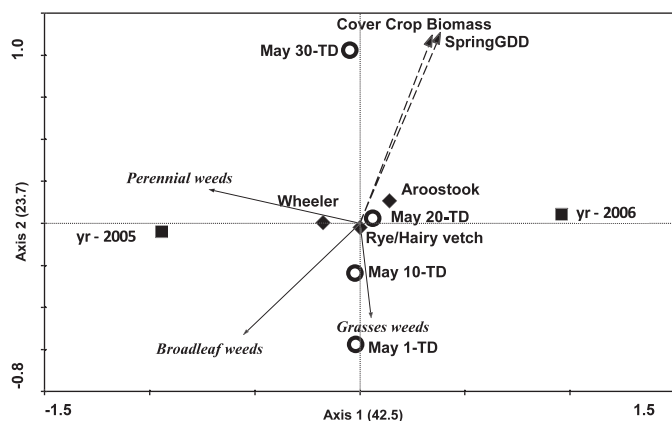Mirsky et al.: Cover-crop management effects on weed suppression • 385

Figure 2. Biplot ordinations from a redundancy analysis displaying the associative relationships between weed communities categorized by grass, broadleaf, and perennial species and the explanatory variables: year (yr; ■), cover crop (◆), termination date (TD; ○), biomass accumulation (---), and spring heat units (GDD) (---). The percentage of variation explained by the primary and secondary axis is included in parentheses. Weed community data were Hellinger-transformed before analysis.

the axes) indicating weed life history classes were equally affected by each of the three cover crops, a result consistent with the univariate analysis (Table 5).

Annual grass and broadleaf weed species were negatively associated with cover-crop biomass as indicated by the weed species vectors pointing in an opposing direction of the cover-crop biomass vector (Figure 2). Annual grasses were not correlated with field site (i.e., year) as indicated by the perpendicular angle between the grass vector and the year axis. Annual broadleaf weeds were associated more with the 2005 field site and both annual broadleaves and grasses were correlated with earlier cover-crop termination dates. Perennial weeds were strongly associated with the 2005 field site, but not correlated to the biomass gradient, and were weakly associated with the last termination date. The significant field site effect reflected the unique broadleaf and perennial weed communities at the two sites. This suggests that perennial weeds in this study were unaffected by increasing amounts of cover-crop residue.

PERMANOVA, used to examine treatment factor effects on the selected weed life history classes, indicated that the weed community was significantly influenced by field site and interaction between field site and termination date (Table 7). This corresponded to the significant community gradient observed in the biplot with the two field sites between years where perennial and annual broadleaf species were more strongly associated with 2005 than 2006 (Figure 2). The field site-by-termination interaction can be explained by the association between increasing perennial and annual broadleaf weeds within the 2005 field site. Clearly the effects of cover-crop biomass varied by weed species life history class and field site. However, field site variations and species-specific emergence patterns and their interaction with varying cover-crop biomass cannot be distinguished in the multivariate analysis (ordination and PERMANOVA). These questions were addressed in greater detail by evaluating weed populations in the following section.

Weed Species Dominance and Suppression. Termination date significantly influenced dominance structure in both cover-crop residue and no-residue treatments and in both field

Table 7. Multivariate analysis of variance table using permutational multivariate analysis of variance (PERMANOVA) of treatment factors.

Effect	Weed Community		
	df	F value	P (perm)
Field site	1	69.39	0.002
Cover crop (CC)	2	1.30	0.618
Termination date (TD)	3	1.72	0.240
Field site × CC	2	1.49	0.174
Field site × TD	3	5.79	0.002
CC × TD	6	0.83	0.634
Field site × CC × TD	6	0.73	0.810

sites (Figures 3 and 4; 2005 plus residue: P < 0.001; no residue: P < 0.0001; 2006 plus residue: P = 0.0106; no residue: P = 0.0149). Those species accounting for the greatest proportion of the chi-square test statistic most strongly influence the community. For the no-residue treatment, these were yellow nutsedge, common lambsquarters, and wild buckwheat in 2005, and common lambsquarters, foxtail species, and common ragweed in 2006. These species accounted for greater than 75 and 80% of these differences in 2005 and 2006, respectively. For the residue treatment, differences in the dominance structure were most influenced by yellow nutsedge and common lambsquarters (> 65%) in 2005. The dominance structure was more evenly distributed among the different species in the residue treatment in 2006.

Changes in the dominance structure across termination dates can be explained by the weed emergence patterns in the no-residue treatment, and the suppressive effects of the cover-
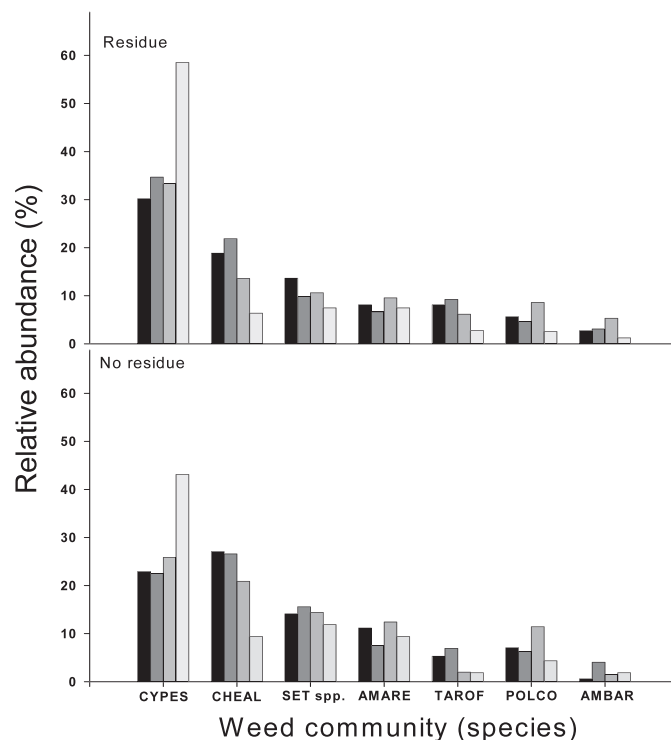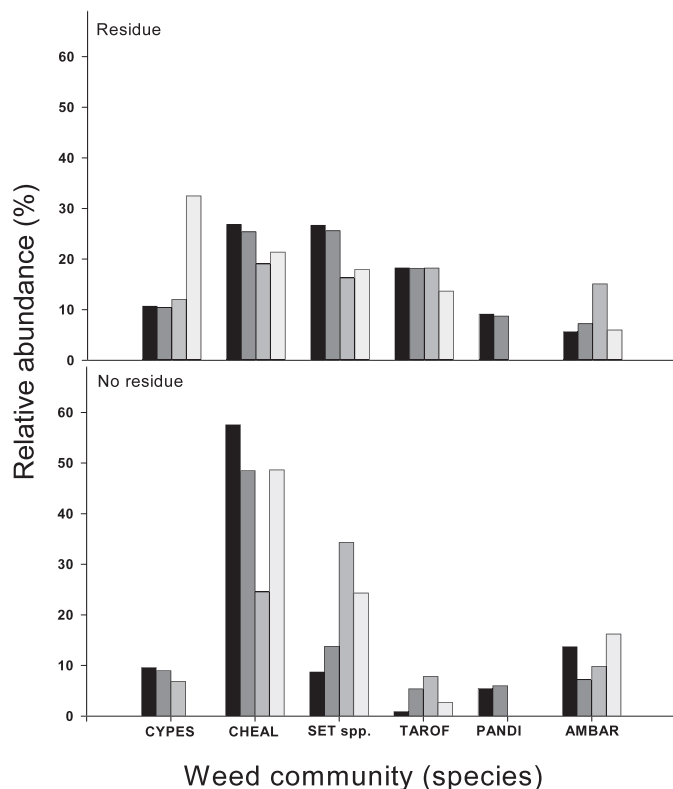

Figure 3. Relative weed species abundance characterizing the species (CYPES, yellow nutsedge; CHEAL, common lambsquarters; SET species, foxtail species; AMARE, redroot pigweed; TAROF, dandelion; POLCO, wild buckwheat; AMBAR, common ragweed) dominance structure within the 2005 field site across the spring termination dates (black = May 1, dark gray = May 10, light gray = May 20, white gray = May 30) for the residue and no-residue treatments.

Figure 4. Relative weed species abundance characterizing the species (CYPES, yellow nutsedge; CHEAL, common lambsquarters; SET species, foxtail species; TAROF, dandelion; PANDI, fall panicum; AMBAR, common ragweed) dominance structure within the 2006 field site across the spring termination dates (black = May 1, dark gray = May 10, light gray = May 20, white = May 30) for the residue and no-residue treatments.
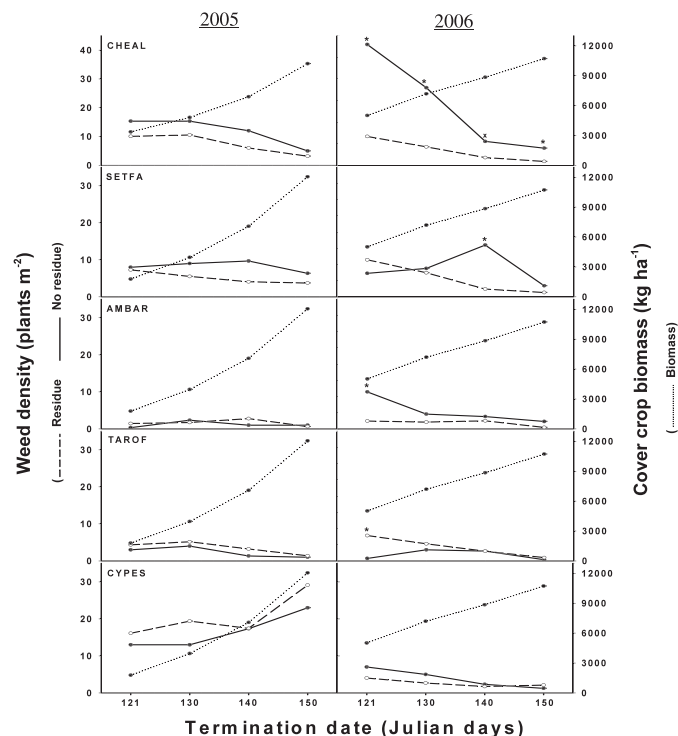

Figure 5. Weed population as a function of cover-crop termination date in the 2005 and 2006 field sites (cover crop and planting date pooled) for the residue and no-residue treatments. An analysis of variance and mean comparison was conducted on selected weed species (CHEAL, common lambsquarters; SETFA, giant foxtail; AMBEL, common ragweed; TAROF, dandelion; CYPES, yellow nutsedge) at each termination date, with * indicating significant difference (P < 0.05; x = P < 0.1) between control and residue plots using the Tukey–Kramer method. Weed population data were overlaid with biomass accumulation for relating weed emergence with cover-crop biomass.

crop mulch in the residue treatment (Figure 5). Delay in cover-crop termination selected for later-emerging annual weeds (e.g., foxtail species and wild buckwheat) and the perennial, yellow nutsedge, which has an extended emergence period. In the residue treatments, we attribute differences in the dominance structure across termination dates to increased control of summer annual weeds as cover-crop biomass increased, whereas the perennials were not substantially influenced by this gradient.

Cover-crop residues did not affect weed density in 2005 (Figure 5); lower weed abundance across the experiment was likely the result of a drier summer (Figure 6). Moore et al. (1994) found weeds emerged 10 d after rainfall events of 10 mm or more when the rains followed a dry period. In 2006, the study site received greater than 10 cm of rainfall and irrigation in June, whereas only 3 cm fell during the same period in 2005. Common lambsquarters density was reduced 67 to 77% in the residue vs. no-residue treatments across termination dates in 2006 (Figure 5). Cover-crop residue reduced foxtail species by 85% at the May 20 termination date and common ragweed by 79% at the first termination date (May 1). Higher dandelion densities were observed at the low cover-crop biomass levels in 2006. Yellow nutsedge was not affected by cover-crop biomass in either year.

The success of weeds like yellow nutsedge underscores the need to study the entire weed community when assessing a change in management practice. In contrast to summer annual weeds, yellow nutsedge emerges from energy-rich

vegetative structures over a prolonged time period and appears to be well-adapted to high-residue cover-cropping practices. Yellow nutsedge continued to emerge even in the May 30 termination treatments and was not influenced by increasing cover-crop biomass. This is consistent with other studies that found that perennials are less influenced by surface residues
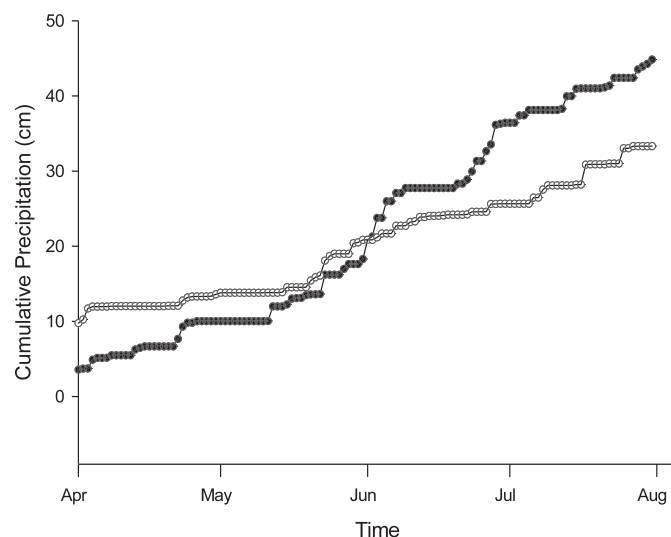

Figure 6. Cumulative daily precipitation ○ = 2005 and ● = 2006 in Rock Springs, PA.

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(Facelli and Picket 1991). In contrast, the annual broadleaves were strongly influenced by increasing cover-crop biomass. Previous research has demonstrated that small-seeded summer annual weeds are more strongly affected by cover-crop residues than are large-seeded annuals (Bhowmik and Inderjit 2003; Mohler and Teasdale 1993; Putnam and DeFrank 1983; Teasdale and Mohler 2000). Early-emerging summer annuals are more competitive at earlier termination dates when cover-crop residue levels are lower, particularly at higher weed densities as was the case for common lambsquarters in 2006. In this study, the delay in termination and subsequent increase in cover-crop biomass decreased summer annual weed populations regardless of species. However, larger-seeded summer annual weeds such as velvetleaf (*Abutilon theophrasti* Medik.), a species not common across our study site, are less sensitive to surface mulches (Mohler and Teasdale 1993) and could still be problematic.

Differences in timing of weed emergence and sensitivity to cover-crop surface residues can influence weed species dominance in a given field season; these effects can result in longer-term population influences. The lower densities observed in the residue treatments may have been the result of fatal germination or of the altered light and temperature soil environment, which may have influenced seed germination (e.g., foxtail species at May 20, 2006; Figure 5). This can be distinguished from inherent lower proportional emergence at the end of a species emergence period (e.g., foxtail species at May 30, 2006; Figure 5). The timing of cover-crop termination control directly influences environmental cues required for the initiation of weed germination. Manipulating the nature and timing of cultural practices such as delaying cover-crop management could selectively affect weed populations by shifting the community structure to less competitive weed species. Characteristics of a positive weed management shift include: less competitive species; lower weed densities; and later weed emergence and growth both due to deliberate asynchrony between management timing and weed emergence periodicity. A shift in weed community structure was identified as one potential mechanism contributing to a shift in crop tolerance to weed biomass (Ryan et al. 2010). However, our results underscore the importance of the pre-existing weed community. Where yellow nutsedge was present at the outset of the experiment, its abundance was unaffected by cover-crop management alone. Multitactical weed management strategies including rotational tillage, diverse crop rotations, and strategies for enhancing competitiveness of the cash crop may play an important role in countering the success of perennial weeds in reduced tillage systems (Buhler et al. 1994; Gill and Arshad 1995; Tørresen et al. 2003).

The weed management implications of this research largely highlight the benefit of delaying cover-crop termination but this must be tempered with concerns about how such delays affect the following crop. Shorter-season cash crops and cultivars will be needed. Alternatively, the cover crop could be sown into the growing cash crop late in the summer or in spring, or the cash crop could be sown into the living cover crop and then suppress the cover crop 1 to 3 wk later (Drinkwater et al. 2000). In the end, the optimum practice will depend on a series of trade-offs involving growing-season length for the cash crop, weed suppression, soil quality protection and enhancement, and if the cash crop is grown organically, the higher market value of organic crops.

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