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Mechanical Termination of Diverse Cover Crop Mixtures for Improved Weed Suppression in Organic Cropping Systems

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Cover crops can provide many benefits in agroecosystems, including the opportunity for improved weed control. However, the weed suppressive potential of cover crops may depend on the species (or mixture of species) chosen, and the method of cover crop termination and residue management. The objective of this study was to determine the effects of cover crop mixture and mechanical termination method on weed biomass and density, and relative crop yield in an organic cropping system. A field experiment was conducted from 2009 to 2011 near Mead, NE, where spring-sown mixtures of two, four, six, and eight cover crop species were included in a sunflower–soybean–corn crop rotation. Cover crops were planted in late March, terminated in late May using a field disk or sweep plow undercutter, and main crops were planted within 1 wk of termination. Terminating cover crops with the undercutter consistently reduced early-season grass weed biomass, whereas termination with the field disk typically stimulated grass weed biomass relative to a no cover crop control (NC). The effects of cover crop mixture were not evident in 2009, but the combination of the undercutter and the eight-species mixture reduced early-season weed biomass by 48% relative to the NC treatment in 2010. Cover crops provided less weed control in 2011, where only the combination of the undercutter and the two-species mixture reduced weed biomass (by 31%) relative to the NC treatment. Termination with the undercutter resulted in relative yield increases of 16.6 and 22.7% in corn and soybean, respectively. In contrast, termination with the field disk resulted in a relative yield reduction of 13.6% in soybean. The dominant influence of termination method highlights the importance of appropriate cover crop residue management in maximizing potential agronomic benefits associated with cover crops.

Nomenclature: Common lambsquarters, *Chenopodium album* L. CHEAL; green foxtail, *Setaria viridis* (L.) Beauv. SETVI; redroot pigweed, *Amaranthus retroflexus* L. AMARE; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; confectionary sunflower, *Helianthus annuus* L.; maize, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Key words: Organic farming, allelopathy, mechanical weed control, ecological weed management, physical weed suppression, biodiversity.

Cover crops can provide many benefits to agroecosystems, and there is growing interest in cover crop use among a diverse range of agricultural stakeholders. The potential for weed suppression is one benefit of cover crops of particular interest to farmers in the corn–soybean belt of the United States. Cover crops have been shown to suppress weeds through physical interference (Teasdale et al. 1991), light interception (Teasdale et al. 2007), buffered soil temperatures (Teasdale and Mohler 1993), increased habitat for weed seed predators (Gallandt et al. 2005), delayed release of plant available nitrogen (Dyck et al. 1995), and release of allelopathic phytotoxins (Sarrantonio and Gallandt 2003). The effectiveness of cover crops as a component of a long-term weed management plan will depend on a combination of these factors, but the mechanisms of physical interference and allelopathy are often viewed as near-term weed management solutions.

Regardless of the mechanism, the success of cover crops as a weed management tool will depend on high production of biomass and resulting soil coverage (Teasdale et al. 2007). With respect to light interception, it may be necessary to achieve 97% soil coverage with cover crop residue to reduce weed density by 75% (Teasdale et al. 1991). However, many cover crops are not grown to full maturity, so achieving optimum biomass and soil coverage is difficult. Therefore, it is necessary to choose cover crop species that provide additional mechanisms of weed suppression through allelopathic activity or effects on germination (Teasdale et al. 2007). When cover crop residue is decomposed in the soil, phytotoxins may be released that can inhibit the emergence and growth of many weed species (Davis and Liebman 2003; Sarrantonio and Gallandt 2003). There are many cover crop species with demonstrated phytotoxicity such as rye (*Secale cereal* L.), crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth), and members of the Brassicaceae family (Norsworthy et al. 2007; Barnes and Putnam 1986; White et al. 1989).

All *Brassicaceae* spp. contain glucosinolates (Rosa et al. 1997), which are hydrolyzed into biologically active compounds during decomposition (e.g., isothiocyanates) that can inhibit weed seed germination (Norsworthy et al. 2007; Teasdale and Taylorson 1986). The potential of glucosinolates to suppress weed emergence and growth has been widely demonstrated in the greenhouse; thus, *Brassicaceae* spp. are increasingly popular cover crops (Al-Khatib et al. 1997; Bialy et al. 1990). Phytotoxin composition differs among and within species, and total production may depend on a variety of biotic and abiotic stresses (Branca et al. 2002; Louda and Rodman 1983). Moreover, the specific allelopathic effects of individual phytotoxic compounds may be weed species specific (Norsworthy et al. 2007). Therefore, a diverse mixture of allelopathic cover crop species may be more effective in targeting a broad range of weed species. Mixed species communities also may help to ensure stable, resilient, and productive cover crop yields that will contribute to improved soil coverage and physical mechanisms of weed suppression (Teasdale et al. 2007; Tilman et al. 2001; Wortman et al. 2012b).

Cover crop choice is important, but appropriate cover crop termination method and residue management may be the most critical factors in successfully using cover crops for weed

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suppression. Cover crops can be terminated climatically (e.g., winterkill), chemically, or through various mechanical measures (e.g., plowing, disking, mowing, roller-crimping, or undercutting). The most appropriate termination method will depend on the farm management objective. For example, full soil incorporation of cover crop residue with a plow or field disk is most commonly chosen when managing for increased soil nutrients (e.g., green manures). When managing for improved weed management, previous studies have shown that termination methods resulting in maximum surface residue and minimal soil disturbance have the greatest potential to inhibit weed germination and growth (Teasdale et al. 1991, 2007). However, it is possible that allelopathic phytotoxins are most effective when residues are incorporated into the soil (Rice et al. 2012); thus, multiple methods of cover crop termination may be effective depending on the targeted mechanism of weed suppression (e.g., physical suppression or allelopathy).

When managing cover crops for maximum surface residue and minimal soil disturbance, a sweep plow undercutter may have great potential, especially in organic cropping systems where chemical termination is prohibited. Creamer et al. (1995) demonstrated that cover crop termination with a sweep plow undercutter created a thick and uniform cover crop mulch, and subsequent weed suppression was greater than when cover crops were terminated via mowing (which finely shredded the cover crop). While other mechanical termination methods such as the roller-crimper have shown great promise for weed control (Davis 2010), the sweep plow undercutter may be more effective in killing cover crops at younger growth stages (Creamer et al. 1995; Mirsky et al. 2009). Moreover, the sweep plow undercutter is a traditional tillage implement in the US Great Plains that may be more easily accessible compared to newer implements not yet widely distributed, such as the roller-crimper.

A 3-yr field experiment was conducted to determine the capacity of cover crop mixtures to contribute to weed management in organic cropping systems. The specific objectives of this study were to (1) quantify the weed suppressive potential of four cover crop mixtures of different levels of species richness and two cover crop termination methods; and (2) quantify the effects of cover crop mixture and termination method on crop yields relative to a traditional organic cropping system with no cover crops. We hypothesized that the most diverse cover crop mixtures coupled with the undercutter for termination would be most effective in reducing weed density and biomass resulting in increased crop yield.

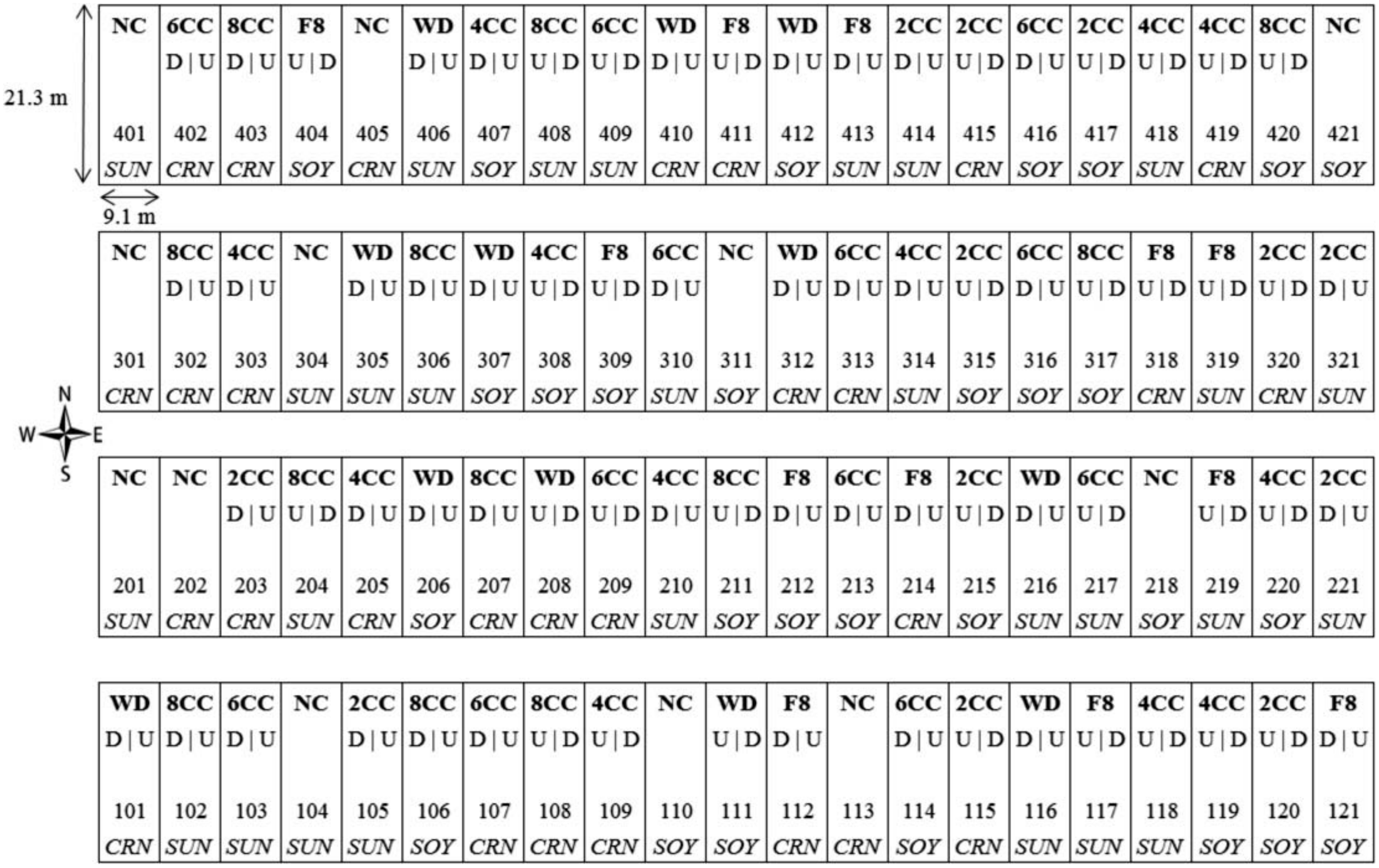
Materials and Methods

Experimental Site and Treatment Design. A field experiment was conducted in 2009, 2010, and 2011 at the University of Nebraska–Lincoln Agricultural Research and Development Center near Mead, NE. The dominant soil type at the site is a Sharpsburg silty clay loam (fine, smectitic, mesic typic Argiudoll) with 0 to 5% slopes. The experimental 2.8 ha field is certified for organic production (OCIA International, Lincoln, NE) and is managed without irrigation. This field was in organic alfalfa hay production for the five seasons prior to 2009. In the fall of 2008, the experimental area was amended with 50 Mg ha^{-1} of liquid beef feedlot manure that was incorporated via field disk. On March 15, 2009, the entire field (excluding a no cover control treatment) was seeded with historically abundant weed species of eastern Nebraska including: 8.1 kg ha^{-1} of velvetleaf seed, 2.6 kg ha^{-1} of common lambsquarters seed, 1.2 kg ha^{-1} of redroot pigweed seed, and 3.7 kg ha^{-1} of green foxtail seed to establish a common weed seedbank throughout the field.

The experiment was designed as a split-plot randomized complete block design with four replications nested within a 3-yr crop rotation. Experimental units were maintained at the same location within the field for the entire study. The rotation sequence consisted of confectionery sunflower ('Seeds 2000 Jaguar')–soybean ('Blue River Hybrids 2A71')–corn ('Blue River Hybrids 57H36'). Whole-plots (9.1 by 21.3 m; 12 crop rows spaced 0.76 m apart) were defined as main crop by cover crop mixture combinations, while split-plots (4.6 by 21.3 m; six crop rows spaced 0.76 m apart) were defined by cover crop termination method (Figure 1). Each "crop by cover crop mixture by termination method" treatment combination was replicated within each block so that each phase of the 3-yr crop sequence was present each year within each block. There were six whole-plot cover crop treatments including: (1) two-species cover crop mixture (2CC), (2) four-species cover crop mixture (4CC), (3) six-species cover crop mixture (6CC), (4) eight-species cover crop mixture (8CC), (5) weedy but cover crop-free (prior to main crop planting) (WD), and (6) weed-free and cover crop-free (prior to main crop planting) control (NC). The NC whole-plots were field disked and hand-hoed twice prior to main crop planting, while the WD whole-plots were left unmanaged until cover crop termination.

Cover crop mixtures consisted of equal contributions of cover crop species in the Brassicaceae and Fabaceae families (with the exception of 2009 when buckwheat [*Fagopyrum sagittatum* Gilib.], of the Polygonaceae family, was included in all mixtures). Species in the Brassicaceae family were chosen due to their demonstrated capacity for allelopathic weed suppression (Norsworthy et al. 2007). While members of the Fabaceae family were primarily included in mixtures to add the potential for biological N_2-fixation, individual species were chosen based on previous evidence of allelopathic weed suppression (White et al. 1989). Details on the individual species and seeding rates included in each cover crop treatment whole-plot are included in Table 1. In general, seeding rates (by mass) for individual species within a mixture were determined by dividing the recommended seeding rate for that species (obtained from a variety of extension and industry sources) by the number of species in mixture. This seeding strategy—typically defined as a substitutive seeding approach—results in variable seeding rates among mixtures, but the contribution of individual species within mixtures remains proportional among mixtures (Joliffe et al. 2000).

Split-plot cover crop termination methods included either disking or undercutting. Termination method was randomized within vertical strips, where experimental units in the first block (southernmost) were randomized and duplicated across the remaining three blocks (north of the first block) to facilitate adequate speed for effective tillage operations driving north-south through the field. Thus, a "strip" consisted of four vertically oriented whole-plot experimental units (e.g., 101, 201, 301, and 401; Figure 1). Disking was conducted with a 4.6 m wide Sunflower 3300 (Sunflower Mfg., Beloit, KS) disk to an approximate depth of 15 cm. Undercutting



NC	**6CC**	**8CC**	**F8**	**NC**	**WD**	**4CC**	**8CC**	**6CC**	**WD**	**F8**	**WD**	**F8**	**2CC**	**2CC**	**6CC**	**2CC**	**4CC**	**4CC**	**8CC**	**NC**
	D | U	D | U	U | D		D | U	D | U	U | D	U | D	D | U	U | D	D | U	D | U	D | U	U | D	D | U	U | D	U | D	U | D	U | D	
401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421
SUN	*CRN*	*CRN*	*SOY*	*CRN*	*SUN*	*SOY*	*SUN*	*SUN*	*CRN*	*CRN*	*SOY*	*SUN*	*SUN*	*CRN*	*SOY*	*SOY*	*SUN*	*CRN*	*SOY*	*SOY*

NC	**8CC**	**4CC**	**NC**	**WD**	**8CC**	**WD**	**4CC**	**F8**	**6CC**	**NC**	**WD**	**6CC**	**4CC**	**2CC**	**6CC**	**8CC**	**F8**	**F8**	**2CC**	**2CC**
	D | U	D | U		D | U	D | U	D | U	U | D	U | D	D | U		D | U	D | U	D | U	U | D	D | U	U | D	U | D	U | D	U | D	D | U
301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321
CRN	*CRN*	*CRN*	*SUN*	*SUN*	*SUN*	*SOY*	*SOY*	*SOY*	*SUN*	*SOY*	*CRN*	*CRN*	*SUN*	*SOY*	*SOY*	*SOY*	*CRN*	*SUN*	*CRN*	*SUN*

NC	**NC**	**2CC**	**8CC**	**4CC**	**WD**	**8CC**	**WD**	**6CC**	**4CC**	**8CC**	**F8**	**6CC**	**F8**	**2CC**	**WD**	**6CC**	**NC**	**F8**	**4CC**	**2CC**
		D | U	U | D	D | U	D | U	D | U	U | D	U | D	D | U	U | D	D | U	D | U	D | U	U | D	D | U	U | D		U | D	U | D	D | U
201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221
SUN	*CRN*	*CRN*	*SUN*	*CRN*	*SOY*	*CRN*	*CRN*	*CRN*	*SUN*	*SOY*	*SOY*	*SOY*	*CRN*	*SOY*	*SUN*	*SUN*	*SOY*	*SUN*	*SOY*	*SUN*

WD	**8CC**	**6CC**	**NC**	**2CC**	**8CC**	**6CC**	**8CC**	**4CC**	**NC**	**WD**	**F8**	**NC**	**6CC**	**2CC**	**WD**	**F8**	**4CC**	**4CC**	**2CC**	**F8**
D | U	D | U	D | U		D | U	D | U	D | U	U | D	U | D		U | D	D | U		D | U	U | D	D | U	U | D	U | D	U | D	U | D	D | U
101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121
CRN	*SUN*	*SUN*	*SUN*	*SUN*	*SOY*	*CRN*	*CRN*	*CRN*	*SOY*	*SOY*	*CRN*	*CRN*	*SOY*	*CRN*	*SUN*	*SUN*	*SUN*	*SOY*	*SOY*	*SOY*

Figure 1. Experimental layout displaying the 2011 crop by cover crop mixture treatment structure. Cover crop mixture is identified (**bold**) in the top row of each box (e.g., 2CC; F8 is an experimental treatment not included in this study), and the termination method for each split-plot experimental unit and subsequent strip is labeled below the cover crop mixture (i.e., D = disk; U = undercutter). The main crop is identified (*italics*) at the bottom of each box (i.e., CRN = corn; SOY = soybean; SUN = sunflower), and above the crop designation is the experimental unit number. The final two digits of the experimental unit number (i.e., 01 through 21) indicate the strip number. Only main crop rotated among years, whereas cover crop mixture and termination method combinations were maintained in the same experimental unit throughout the experiment.

was conducted with either a Buffalo 6000 (Buffalo Equipment, Columbus, NE) cultivator (modified for undercutting) with seven overlapping 0.75-m wide sweep blades (2009) or a Miller Flex-Blade sweep plow undercutter (2010 and 2011) with three overlapping 1.5 m sweep blades. The undercutter sweeps are designed to cut a level plane through the soil at an approximate depth of 10 cm, severing plant roots and minimizing soil inversion, resulting in a layer of intact surface residue. Details on the design of the undercutter can be found in Creamer et al. (1995).

Cover crop mixtures were planted via hand-crank broadcast seeding followed by light incorporation (to a depth less than 3 cm) with a John Deere 950 cultipacker (Deere and Company, Moline, IL). Generally, cover crops were planted in late March, terminated in late May, and the main crop was planted within 1 wk of termination. Specific dates for field operations across all years are detailed in Table 2. While fall-sown cover crops are more commonly used in the US Corn Belt, there is increasing interest among farmers in spring-sown species (e.g., increasingly diverse cropping systems will require a broader range of cover crop strategies). A spring-seeded cover crop will not provide fall and winter soil coverage but may still offer improved soil fertility and weed control in the subsequent cash crop. Seeding rates for confectionery

Table 1. Cover crop species and seeding rates used in individual cover crop mixtures for 2009 and 2010–2011 (2CC = two-species mixture; 4CC = four-species mixture; 6CC = six-species mixture; 8CC = eight-species mixture).

		Cover crop seeding rate			
Common name	Scientific name	2CC	4CC	6CC	8CC
		kg ha^{-1}			
Hairy vetch	*Vicia villosa* Roth	22.4	11.2	7.5	5.6
Buckwheat (2009)	*Fagopyrum sagittatum* Moench	28.0	14.0	9.3	7.0
Idagold mustard (2010–2011)	*Sinapis alba* L.	6.7	3.4	2.2	1.7
Field pea	*Pisum sativum* L.	—	28.0	18.7	14.0
Pacific Gold mustard	*Brassica juncea* (L.) Czern.	—	2.2	1.7	1.1
Oilseed radish	*Raphanus sativus* L.	—	—	2.8	2.1
Crimson clover	*Trifolium incarnatum* L.	—	—	4.7	3.5
Dwarf essex rape	*Brassica napus* L.	—	—	—	1.7
Chickling vetch	*Lathyrus sativus* L.	—	—	—	8.4

Table 2. Timing of field operations and data collection for each year of the study.

Operation	2009	2010	2011
Cover crop planting	20 March	30 March	21 March
Cover crop termination	22 May	28 May	3 June
Main crop planting	28 May	1–3 June	6 June
Weed sampling	29–30 June	24–25 June	12–13 July
1st inter-row cultivation	1 July	28 June	30 June
2nd inter-row cultivation	—	1 July	8 July

sunflower, soybean, and corn were 62,000, 556,000, and 86,000 seeds ha^{-1}, respectively. All crops were inter-row cultivated once approximately 30 d after planting (DAP) the main crop. A second inter-row cultivation was performed within 10 d of the first cultivation in 2010 and 2011; the second cultivation served to ''throw'' soil near the base of crop plants and cover emerged weed seedlings in the intra-row area. Seeds of all legume cover crop and crop species were inoculated with appropriate rhizobia bacterial species prior to planting in 2009 and 2010.

Data Collection. Three (2009) or four (2010 and 2011) aboveground plant samples were taken from each whole-plot experimental unit prior to cover crop termination to determine productivity of the cover crop mixtures and weed communities. Samples were combined within each experimental unit, dried at 60 C to constant mass, and weighed. Three (2009) or four (2010 and 2011) aboveground plant samples were taken from each split-plot experimental unit approximately 30 DAP the main crop to quantify weed species density and aboveground biomass. Actual sampling date depended on environmental conditions (e.g., precipitation events) and the timing of inter-row cultivations. Samples were combined within each split-plot experimental unit, sorted by species, and each component was counted. In 2010 and 2011, the samples were then divided into broadleaved and grass weeds, dried at 60 C to constant mass, and weighed. The 2009 samples were divided into broadleaved and grass weeds, fresh weights were recorded, and one composite sample (containing all weeds) was dried to constant mass and weighed. The sampling quadrat area in 2009 consisted of three 0.3 by 0.3 m samples per experimental unit. The sampling quadrat area in 2010 and 2011 was increased to four 0.3 by 0.6 m samples per experimental unit. Quadrats were placed at random locations between (2009 and 2010) or within (2011) crop rows of each split-plot. Sample quadrats were placed within crop rows in 2011 to avoid the inter-row area that was previously cultivated. Sampling occurred prior to inter-row cultivation in 2009 and 2010 but not in 2011. The undercutting operation in 2011 was less effective than in previous years (it is believed the undercutter sweeps were traveling too deep in the soil profile), which required an earlier inter-row cultivation to manage escaped weeds and cover crops. While it meant a deviation from the original protocol, it was decided that sampling the intra-row area following cultivation would be more informative (with regard to the effects of cover crop mixtures) than sampling the inter-row area before cultivation in 2011.

Crop yield was determined for each main crop by harvesting seed from the middle three (corn) or four (soybean and sunflower) rows of each split-plot experimental unit. Seed yield was weighed using a Weigh-Tronix 400 combine scale (Avery Weigh-Tronix, Fairmont, MN) and adjusted for moisture level in the lab. Corn yields were adjusted to 0.155, soybean to 0.130, and sunflower to 0.10 g kg^{-1} moisture. Relative yield for each experimental unit was calculated as:

$$\text{Relative Yield} = ((\text{CCE} - \text{NC})/(\text{NC})) * 100\%$$

where CCE is the yield from one split-plot cover crop experimental unit, and NC is the yield from the NC experimental units averaged across all replications within a given year.

Data Analysis. The experimental design resulted in 132 split-plot experimental units per year (Figure 1; 18 main crop by cover crop mixture whole-plot experimental units per block and 33 main crop by cover crop mixture by termination method split-plot experimental units per block [the 3 NC control treatments per block were not split by termination method]).Weed biomass data were either log- or square root-transformed prior to statistical analysis to improve normality and homogeneity of variances when necessary. After transformation (if necessary), values for weed biomass and relative yield were compared among treatments using a linear mixed model analysis of variance in the GLIMMIX procedure of SAS 9.2 (SAS Institute Inc., Cary, NC). Fixed effects in the model included main crop, cover crop mixture, termination method, and all possible interactions of these effects. The random effects included block, strip, the interaction of block by main crop by cover crop mixture, and the interaction of strip by termination method. Main crop by cover crop mixture whole-plots were randomized within individual complete blocks, while termination method split-plots were randomized within individual strips (Figure 1). Effects were tested within individual years due to experimental changes in the cover crop mixtures (buckwheat was replaced in all mixtures with Idagold mustard after 2009 due to poor growth of buckwheat) and interactions with year when initially included as a fixed effect. Least square (LS) means and standard errors were calculated for all significant fixed effects at an alpha level of 0.05. LS means obtained from these analyses were back-transformed for presentation in all tables and figures. However, transformation of data does not allow for back-transformation of error terms; thus, differences among transformed LS means are indicated in tables and figures with different letters. Lastly, a linear regression of cover crop biomass and early-season weed biomass between 2009 and 2011 for both termination methods was conducted using the REG procedure in SAS 9.2 (SAS Institute Inc.) to quantify the potential role of physical interference in the weed suppressive capacity of cover crop residue. To aid in the visualization of statistical interactions, some of the data have been plotted with cover crop mixture on the x-axis and the cover crop mixtures arranged in order (left-to-right) of increasing species richness (from zero in the NC treatment to eight species in the 8CC treatment) along the x-axis (Sosnoskie et al. 2006; Tilman et al. 2001).

Table 3. *F*-values from linear mixed model analyses of variance for fixed effects and all possible interactions of cover crop mixture, termination method, and main crop on grass, broadleaved, and total weed biomass, and total broadleaved weed density at 32, 23, and 36 d after planting (DAP) for the years 2009, 2010, and 2011, respectively. Significance of *F*-values is designated as * = $P < 0.05$, ** = $P < 0.01$, and *** = $P < 0.001$.

Source	df[a]	Grass biomass	Broadleaved biomass	Total biomass	Broadleaved density
2009					
Mixture	4	0.8	1.2	0.8	1.4
Termination	1	3.8	0.8	4.1	24.8***
Crop	2	4.2*	0.1	1.5	0.1
Mixture × termination	4	1.7	1.2	2.5	0.6
Mixture × crop	8	1.1	0.7	1.1	0.7
Termination × crop	2	1.2	3.5*	0.7	3.8*
Mixture × termination × crop	8	1.6	2.1	1.6	1.3
2010					
Mixture	4	2.7*	5.6**	2.2	1.2
Termination	1	91.4***	0.4	95.0***	17.7***
Crop	2	0.2	5.3**	0.4	9.7***
Mixture × termination	4	3.1*	0.7	4.1**	1.4
Mixture × crop	8	0.4	0.8	0.6	0.6
Termination × crop	2	2.1	0.4	2.0	0.6
Mixture × termination × crop	8	1.5	0.3	1.5	1.5
2011					
Mixture	4	3.3*	2.0	0.6	1.4
Termination	1	69.5***	0.6	16.8***	10.0**
Crop	2	3.2*	4.7*	5.0**	20.0***
Mixture × termination	4	< 0.1	3.6*	4.6**	1.0
Mixture × crop	8	1.0	0.5	0.7	0.9
Termination × crop	2	3.7*	1.7	4.3*	2.4
Mixture × termination × crop	8	0.9	1.3	1.5	1.2

[a] Abbreviation: df, degrees of freedom.

Results and Discussion

Early-Season Weed Suppression. Grass weed biomass (fresh shoot weight) was only influenced by the effect of main crop at 32 DAP in 2009 (Table 3). Grass weed biomass was lowest in sunflower (1,115 g m^{-2}) and greatest in corn (1,288 g m^{-2}). Sunflower may be a competitive crop choice, especially in organic systems, due to its capacity for early light interception (Geier et al. 1996) and allelopathic effects on weed seed germination and growth (Leather 1983). Overall, the amount of grass biomass observed here (> 1 kg m^{-2}) is exceptionally high, highlighting the need for supplemental weed management tools (e.g., inter-row cultivation) in this cover crop system.

In 2010 at 23 DAP, grass weed biomass was influenced by the interaction of mixture and termination method (Table 3). Termination with the undercutter in the 4CC and 8CC mixtures reduced biomass by 39 and 45%, respectively, relative to the NC control (Figure 2a). In contrast, termination with the disk in the 6CC and 8CC mixtures stimulated a grass weed biomass increase of 56 and 32%, respectively, relative to the NC control (Figure 2a). While grass weed biomass was generally not influenced by the number of species in a mixture, the differences among mixtures within termination methods suggests there may be unique characteristics associated with each mixture (e.g., biomass quantity, quality, biochemical composition, or phytotoxins) driving this variable response.

Grass weed biomass was influenced by the effects of mixture and the interaction of termination method by crop at 36 DAP in 2011 (Table 3). In general, grass weed biomass was stimulated by the presence of cover crops (but not by weeds in the WD treatment) regardless of termination method (data not shown). However, the termination method by crop interaction indicated that disk termination stimulated grass weed biomass in all crops, while termination with the undercutter reduced grass weed biomass only in soybean (data not shown). The results in 2011 highlight the challenges of using high quality (low C : N ratio) residue (which decompose more rapidly) to suppress weeds regardless of termination strategy. As cover crops increase nutrient availability, both crops and weeds are likely to respond with greater growth if the weeds are not managed properly (Liebman and Davis 2000). Moreover, small quantities of legume cover crop residue (perhaps similar to levels found in a diverse mixture) have been shown to stimulate weed seed germination and radicle elongation (Teasdale and Pillai 2005).

Broadleaved weed biomass was not affected by any main effects at 32 DAP in 2009 but was influenced by the interaction of crop by termination method (Table 3). Broadleaved biomass in the undercutter treatment (25.0 g m^{-2}) was less than biomass in the disk (60.6 g m^{-2}) and NC treatments (106.7 g m^{-2}) in corn, but this relationship was not consistent in soybean or sunflower. In 2010, broadleaved biomass was influenced by the effects of cover crop mixture and main crop. The effect of cover crop mixture was largely due to exceptionally high levels of broadleaved biomass in the NC control compared to cover-cropped and weedy treatments, and not the result of differences among mixtures. Broadleaved weed biomass in sunflower was reduced by 53 and 44% relative to corn and soybean, respectively; this is consistent with grass weed response and provides further support for the assumed competitiveness of the sunflower crop. In 2011 (at 36 DAP), broadleaved weed biomass was again influenced by the effect of crop but also by the interaction of mixture by termination method (Table 3). Differing from the 2010 results, broadleaved weed biomass in 2011 was lowest in soybean (13.5 g m^{-2}) and greatest in corn and sunflower (26.2 and 22.2 g m^{-2}, respectively). This may be related to

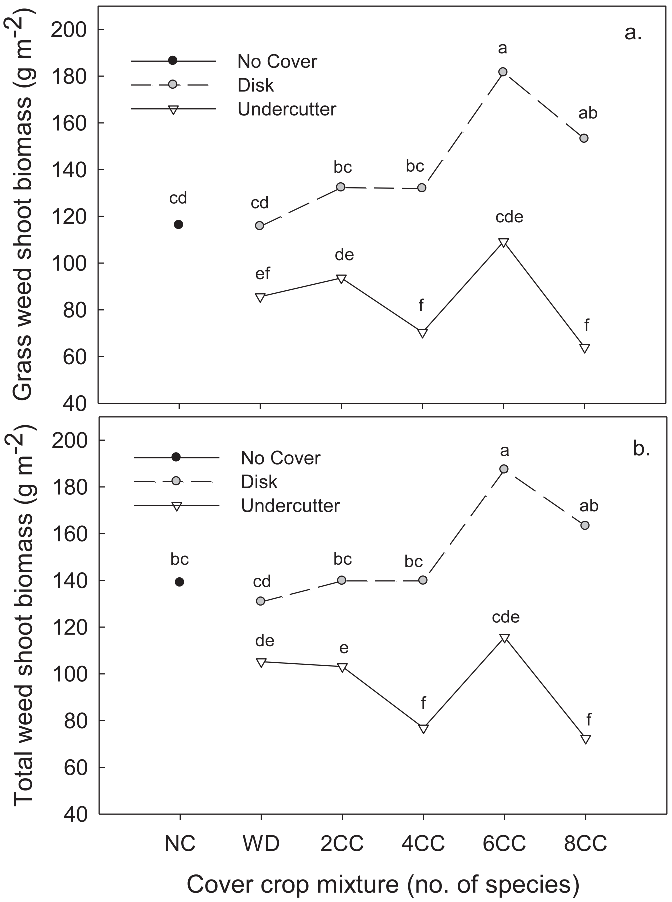


Figure 2. Grass (a) and total (b) weed shoot biomass (g m^{-2}) as influenced by the interaction of cover crop mixture and termination method at 23 d after planting (DAP) in 2010. Data shown are back-transformed least square (LS) means and differences ($\alpha = 0.05$) among all transformed LS means, which are indicated by different letters above back-transformed data points. NC = no cover control; WD = weedy mixture; 2-, 4-, 6-, and 8CC = two, four, six, and eight cover crop species mixtures, respectively (Table 1).

the low level of weed biomass seen in the 2010 sunflower crop (relative to corn and soybean crops in 2010), which preceded soybean in the rotation. This conclusion is based on the assumption that lower biomass at 23 DAP observed in the 2010 sunflower crop resulted in lower fecundity of broadleaved weeds and reduced emergence the following year in the soybean crop (Aarssen and Taylor 1992). Managing weed populations for reduced biomass and seed production is an essential component of integrated weed management strategies in low-external-input cropping systems, especially when growing less competitive crops like soybean (Kegode et al. 1999).

The interaction of mixture by termination method for broadleaved weed biomass in 2011 was the result of exceptionally high broadleaved weed biomass (51.8 g m^{-2}) in the WD/undercutter treatment combination, relative to the average of all other treatments combined (18.8 g m^{-2}; Table 3). The large amount of broadleaved weed biomass in the WD/undercutter treatment combination was likely related to the ineffectiveness of the undercutter in terminating small weed seedlings. Creamer et al. (1995) also found that plants were difficult to terminate with the undercutter if they had not yet reached the mid- to late-bloom stage of maturity. The continuous and unmanaged emergence of weed seedlings throughout the spring in the WD treatment resulted in a weed community composed of various growth stages (e.g., multiple cohorts). The undercutter sweeps travel at a depth of 10 cm beneath the soil surface; thus, it is probable that recently emerged weed seedlings with shallow root systems were not effectively killed by the undercutting operation. Presumably, this was not an issue in the cover crop mixtures as there were fewer weeds growing in the mixtures, and those that were established were likely mature enough to compete with the mixtures; thus, the root systems would be mature enough to be effectively terminated by the undercutter.

Broadleaved weed density was influenced by crop and termination method (2010 and 2011) or the interaction of termination by crop (2009; Table 3). With regard to termination method, broadleaved weed density following termination with the undercutter was always at least 36% less than the densities observed following termination with the disk or the NC control (Table 4). Broadleaved weed density spiked upward in 2010, where 115.2 plants m^{-2} were observed in the NC control compared to 38.6 and 24.7 plants m^{-2} following termination with the disk and undercutter, respectively (Table 4). The interaction effect in 2009 was due to the lack of a termination effect in sunflower, whereas trends in corn and soybean were consistent with those observed across all other years and crops (e.g., reduced weed biomass following termination with the undercutter). It is possible that the competitive effects of sunflower masked the weed suppressive potential of termination with the undercutter. With regard to the influence of crop, broadleaved weed density was greatest in corn in 2010 and 2011 and lowest in either sunflower (2010) or soybean (2011; Table 4). Consistent with the response of broadleaved biomass, reduced broadleaved weed density in 2011 soybean may be related to the stronger competitive effects and reduced weed biomass and density observed in sunflower in 2010 (Geier et al. 1996). While trends for broadleaved biomass and density were often consistent, there were occasionally contradictions within years (Table 3). The differing outcomes between these two measures of weed suppression highlight the challenge of using weed density as a proxy for biomass (and vice versa). Indeed, a dense broadleaved weed population (especially early in the growing season) may consist of many small individuals resulting in low overall biomass; similarly, a sparse weed population may contain only a few large individuals resulting in high biomass.

When pooling grass and broadleaved weed biomass into a measure of total weed biomass, results were similar to those for grass weed biomass in 2009 and 2010, as these weeds dominated the community (Table 3; Figure 2b). However, a more even distribution of grass and broadleaved weeds led to unique results for total weed biomass in 2011. Total weed biomass was influenced by the interactions of termination by main crop and also termination by cover crop mixture at 36 DAP in 2011 (Table 3; Figure 3). Undercutting cover crop mixtures for weed suppression was most effective in soybean, which led to the termination by crop interaction. Overall, the undercutter was less effective in suppressing weeds in 2011 as only the 2CC/undercutter treatment combination successfully reduced total weed biomass relative to the NC control (Figure 3). While the undercutter was less beneficial in 2011, using the field disk for termination was largely detrimental as total weed biomass was stimulated by 58, 52, and 51% in the 2CC, 6CC, and 8CC mixtures, respectively (Figure 3). Total weed biomass in the WD/undercutter treatment combination

Table 4. Total broadleaved weed density (plants m^{-2}) in response to main crop and cover crop termination method at 32, 23, and 36 d after planting (DAP) for the years 2009, 2010, and 2011, respectively. Data shown are back-transformed least square (LS) means and differences ($\alpha = 0.05$) among transformed LS means, which are indicated by different letters adjacent to the back-transformed value within a given year and effect.

	Total broadleaved weed density		
Effect	2009	2010	2011
		plants m^{-2}	
Crop			
Corn	21.8 a	53.6 a	24.1 a
Soybean	19.2 a	36.7 b	8.8 b
Sunflower	18.5 a	21.8 c	22.8 a
Termination			
No cover	25.4 a	101.5 a	23.1 a
Disk	24.0 a	39.3 b	20.6 a
Undercutter	10.1 b	25.2 c	13.1 b

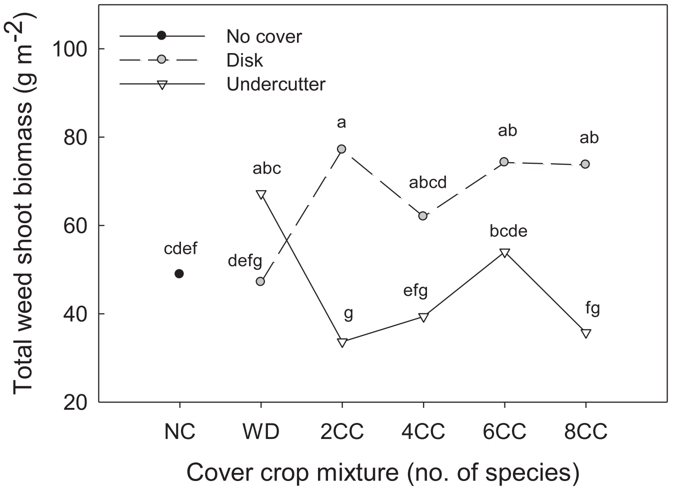


Figure 3. Total weed shoot biomass (g m^{-2}) as influenced by the interaction of cover crop mixture and termination method at 36 d after planting (DAP) in 2011. Data shown are back-transformed least square (LS) means and differences ($\alpha = 0.05$) among all transformed LS means, which are indicated by different letters above back-transformed data points. NC = no cover control; WD = weedy mixture; 2-, 4-, 6-, and 8CC = two, four, six, and eight cover crop species mixtures, respectively (Table 1).

was greater than that in the WD/disk treatment combination, which was consistent with the results for broadleaved weed biomass (data not shown). As observed in 2010, total weed biomass was greater in the 6CC mixture regardless of termination method. Given the consistency of this result across two consecutive years, it appears likely that the composition of species in the 6CC mixture (Table 1) is uniquely beneficial to early season weed growth. While increasing the number of species in a cover crop mixture did not predictably decrease weed biomass and density as we hypothesized, we did observe variable levels of weed suppression or stimulation across the four mixtures of cover crops. The consistency of these trends (i.e., weed stimulation following the 6CC mixture) may indicate unanticipated but reproducible effects of some mixtures. There may be species interactions between/among cover crops in mixtures or between/among cover crop mixtures and main crops that we could not detect in this experimental design.

Variability in the weed suppressive capacity of cover crops is most often related to cover crop biomass and productivity, especially when the residue is managed on the soil surface to promote physical interference with weed seed emergence and growth (Teasdale et al. 1991, 2007). Therefore, the hypothesis that the observed variability in early season weed suppression among cover crop mixtures was related to variability in the biomass productivity of the mixtures was tested using regression analysis. However, no relationship was observed between these two factors in any year of this study for either termination method ($P > 0.10$ for all regressions; Figure 4). This suggests that the variability in early season weed suppression observed among mixtures was driven by a mechanism (or combination of mechanisms) other than physical interference with weed seed germination and growth. Given the lack of relationship between cover crop and subsequent weed biomass, it is possible that weed biomass was driven by differences in the biochemical composition (e.g., allelopathic chemical concentration) and quality (e.g., nutrient content) of the mixture residue.

The composition and concentration of individual allelopathic plant compounds is often dependent on species and variety (Branca et al. 2002), as well as phenology (Reberg-Horton et al. 2005); thus, it is possible that a diversity of allelopathic interactions between cover crops and the numerous target weed species resulted in lower weed emergence and growth for certain mixtures in this study (Norsworthy et al. 2007). Though often documented in greenhouse studies, allelopathic effects of cover crop residue on weed seed emergence and growth has been difficult to observe in field studies (Haramoto and Gallandt 2005). While we do not have the biochemical analyses to directly support an allelopathic mechanism of weed suppression, elimination of the physical interference hypothesis (including light interference and buffered soil temperatures) serves to narrow the scope of potential mechanisms.

In addition to the "allelopathy hypothesis," differences in early-season weed biomass among cover crop mixture treatments may have been caused by a variety of factors including: changes in soil nitrogen availability (Dyck et al. 1995), increased habitat for weed seed predators (Gallandt et al. 2005), or negative soil microbial feedback effects (Klironomos 2002). However, there were no differences in early- or late-season soil nitrate availability observed among mixture treatments in this study, which seems to eliminate the "soil nitrogen hypothesis" (Wortman et al. 2012a). It is possible that differences were due in part to varying levels of weed seed predation, but weed seed predation is typically elevated in any cover-cropped field (relative to bare fallow) and differences among the mixtures seems unlikely (Shearin et al. 2008). Increased weed seed predation is undoubtedly a benefit of cover crop use but is more likely to contribute to long-term weed management success instead of short-term weed suppression observed in this study (Liebman and Davis 2000). The "negative soil feedback hypothesis" suggests that changes in the soil microbial community during cover crop growth create a soil environment less suitable for germination and growth of certain weed species, and this possibility is currently under further investigation. Successful ecological weed management will depend on diverse and complex mechanisms of weed suppression, and it is likely that cover crop mixtures contribute biological (e.g., seed predation and negative soil microbial feedback), chemical (e.g., delayed N release and allelopathic effects), and physical (e.g., increased

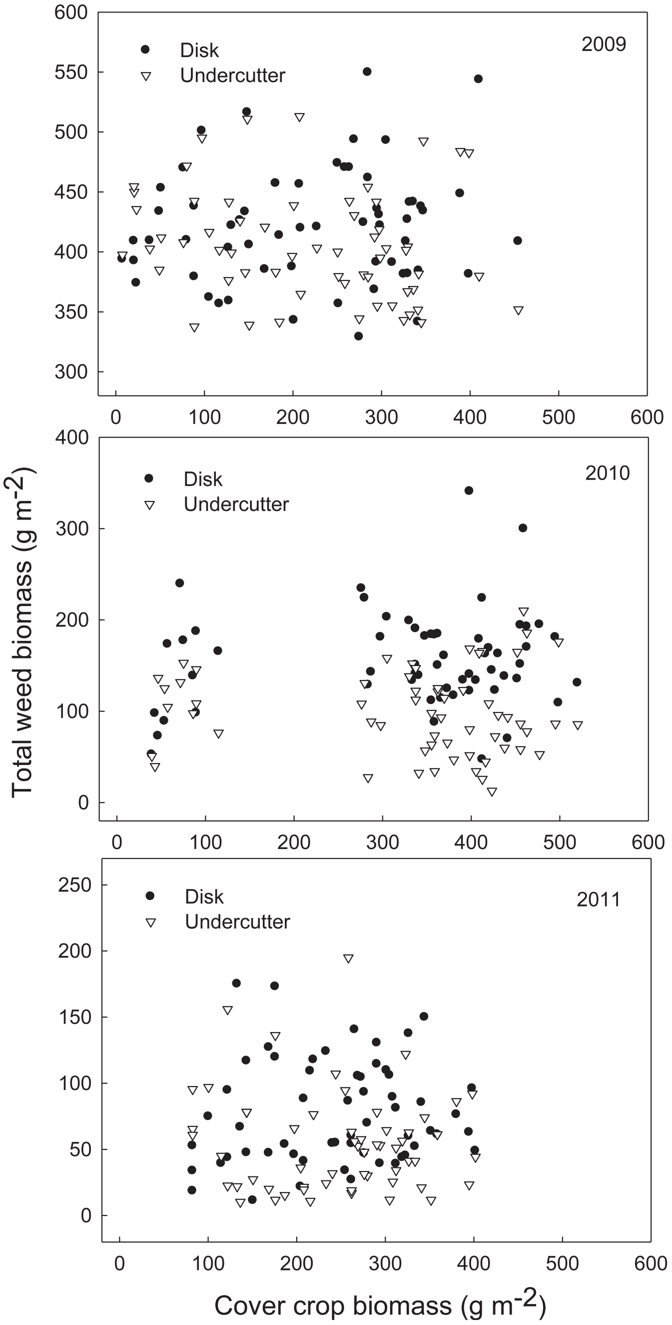


Figure 4. Relationship between cover crop biomass (g m^{-2}) and early season total weed biomass (g m^{-2}) within each mechanical termination method for the years 2009, 2010, and 2011.

light interception) mechanisms of weed suppression. The degree to which each mechanism contributes to increased weed suppression will depend on the cover crop species chosen, termination method, and subsequent residue management.

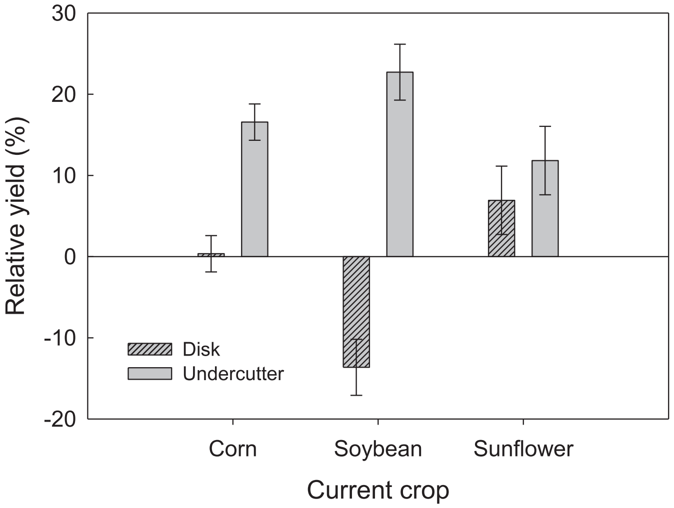


Figure 5. The effect of cover crop termination method (disk or undercutter) on crop yield relative to the no cover crop control treatment. Data were pooled across cover crop mixtures and years for each crop. Error bars indicate ± one standard error of the least square (LS) means.

Relative Crop Yield. Despite the effect of cover crop mixtures on weed biomass early in the growing season in 2010 and 2011, relative crop yield (pooled across years due to lack of interactions) was only influenced by termination method in this study. The lack of relative yield differences in response to cover crop mixture confirms the modest effects of cover crop mixture on weed biomass and density compared to the more prominent influence of termination method. Relative to an organic cropping system dependent on mechanical weed management (NC control), cover crop termination with the undercutter increased corn yield by 16.6%, while termination with the disk did not alter yield (Figure 5). In soybean, the effect of cover crop termination method was more pronounced. Termination with the undercutter increased yield by 22.7%, while termination with the disk reduced yield by 13.6% relative to the NC control (Figure 5). Reduced soybean yields in the disk treatment were likely due to increased weed biomass (relative to both the NC and undercutter treatments), in addition to reduced soil nitrate and moisture availability (Wortman et al. 2012a). Despite an apparent yield benefit following the disk and undercutter for termination in sunflower, the increase was not statistically different from the NC control due to substantial variation in relative yield within and among years (as indicated by large standard errors relative to the mean; Figure 5).

Many studies have demonstrated peripheral benefits of including cover crops in agroecosystems, but yield gains are often difficult to detect (Haramoto and Gallandt 2005; Reddy et al. 2003). However, recent studies have demonstrated the potential for cover crop mulches to increase or maintain crop yield relative to a no cover crop control (Mischler et al. 2010). Many of these systems have depended on herbicides for termination of cover crops and weeds (Shrestha et al. 2002; Teasdale et al. 2007), which has limited their applicability for organic farmers. The results of this study demonstrate the potential of cover crop mixtures to increase crop yield in organic cropping systems when combined with a sweep plow undercutter for termination.

Conclusions. Changes in weed biomass and density were largely driven by the main crop (current or prior) and differences in cover crop termination strategies. Reduced weed biomass and density following termination with the undercutter observed here is congruent with the results of Creamer et al. (1995), who found reduced weed biomass following cover crop termination with an undercutter compared to a flail mower. Moreover, the stimulation of weed growth commonly observed following termination with the disk and in the no cover control is consistent with previous work demonstrating the risks of using intensive tillage for early-season weed management and seedbed preparation (Liebl et al. 1992; Yenish et al. 1992). Use of the undercutter for weed management has historically been limited to sandier soils of the western US Great Plains. However, these results demonstrate potential for this conservation tillage implement in the silty clay loam soils of eastern Nebraska to aid in profitable cover crop and weed management for increased crop yields in organic systems.

The influence of the various cover crop mixtures in this study was far more subtle than the impacts of main crop and termination method. However, differences in weed biomass among cover crop mixtures were detectable early in the growing season in 2 of 3 yr. The lack of a relationship between cover crop biomass and early-season weed biomass suggests an alternative mechanism of weed suppression (other than physical interference) occurred. One potential explanation for these differences may be related to the allelopathic potential of species within the mixtures. While allelopathic mechanisms of weed suppression are well understood for individual cover crop species (e.g., Norsworthy et al. 2007), future studies should focus on the potentially complex interactions occurring at the plant-soil interface between diverse cover crop communities and weed seed germination and growth.

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