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Assessment of an Integrated Weed Management System in No-Till Soybean and Corn

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The objective of this study was to evaluate weed control, crop yields, potential soil loss, and net returns to management of an integrated weed management system in no-till corn and soybean compared to an herbicide-based strategy. The integrated weed management system reduced herbicide inputs by delayed cover crop termination, herbicide banding, and high-residue cultivation (reduced herbicide [RH]), while the other system used continuous no-tillage and herbicides to control weeds (standard herbicide [SH]). Research was conducted within the Penn State Sustainable Dairy Cropping Systems Experiment, where corn and soybean are each planted once in a 6-yr crop rotation. In this 3-yr study, weed density and biomass were often greater under RH management, but weed biomass never exceeded 19 g m^{-2} in corn and 21 g m^{-2} in soybean. Corn yield and population did not differ in any year, and net returns to management were \$33.65 ha^{-1} higher in RH corn due to lower herbicide costs and slightly, though not significantly, higher yields. Soybean yield was lower in RH compared to SH in 2 of 3 yr, and was correlated with soybean population and cover crop residue. Net financial returns were \$43.69 ha^{-1} higher in SH soybean compared to RH. Predicted soil loss never exceeded T (maximum allowable soil loss) for any treatment and slope combination, though soil loss was 100% greater on a 10% slope under RH management (vs. SH) due to cultivation.

Nomenclature: cereal rye (*Secale cereale* L.); corn (*Zea mays* L.); soybean [*Glycine max* (L.) Merr.]

Key words: Cover crops, cropping systems, no-till, high-residue cultivator, partial budget, roller-crimper, soil loss.

No-till production of field crops is popular and in 2014, 66% of corn and 73% of soybean hectares were grown using no-till practices in Pennsylvania (U.S. Department of Agriculture, National Agricultural Statistics Service [USDA] 2014). The benefits of no-till cropping are widely accepted for their positive impact on soil health, and reduction in fuel use and labor (Uri 2000) and compared to tilled cropping systems, no-till management often leads to reduced potential for soil erosion, improved nutrient cycling, and increased soil organic matter (Blevins et al. 1984). No-till production, however, is associated with an increased reliance on herbicides for weed control, as herbicides are replacing tillage as the primary means to manage weeds. Concerns for herbicides in surface water (Hayes at al. 2002) and the increased occurrence of herbicide resistance in weeds (Heap 2015) provide motivation to explore management methods that reduce herbicide use in no-tillage production systems, while at the same time maintain or reducing input costs.

Glyphosate-resistant (GR) crops have reduced the production costs for both corn and soybean providing an economic benefit to farmers in the United States (Gianessi 2008). As GR crops have become more widely adopted, the diversity of herbicides and weed management tactics implemented has decreased, with many growers relying exclusively on glyphosate rather than a suite of tactics for weed control (Young 2006). The lack of cropping system diversity and repeated use of same site of action herbicides have led to the development of herbicide resistance in weeds (VanGessel 2001; Young 2006). Common across the southern and midwestern regions of the United States, GR weeds are also problematic in Pennsylvania and the mid-Atlantic Region (Heap 2015; VanGessel 2001). In these problem areas, GR weeds have led to increased herbicide use, more tillage, supplemental hand weeding, and a higher overall cost to weed management (Peterson 1999; Sosnoskie and Culpepper 2014).

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Combining greater crop diversity with less tillage can interrupt weed lifecycles and reduce weed seed production over time (Kegode et al. 1999). Including winter cover crops in a summer cash–crop production system can add temporal diversity and reduce weed populations (Smith and Gross 2007; Teasdale et al. 2004). Cereal rye residue left on the soil surface into the following soybean crop reduced weed biomass relative to no-rye plots (Mischler et al. 2010), but its effectiveness depends on achieving sufficient levels of cover crop biomass (Mirsky et al. 2011; Mohler and Teasdale 1993; Nord et al. 2011; Ryan et al. 2011). Unfortunately, high levels of cover crop biomass can also provide challenges to cash crop establishment by creating a physical barrier and altering edaphic conditions at planting (Nord et al. 2011).

Zone application or banding of herbicides rather than broadcasting over the entire field reduced herbicide active ingredient use, resulting in a reduction in the potential for pollution (Bates et al. 2012; Donald et al. 2004; Shipitalo and Owens 2006). Banding an herbicide with residual properties over a crop row can control weeds that grow in or near the row, potentially reducing or eliminating yield loss to the crop (Hooker et al. 1997; Mt. Pleasant et al. 1994; Mulder and Doll 1993). Zone herbicide applications have resulted in adequate weed control in corn and reduced the use of residual herbicide (Donald et al. 2004). Heydel et al. (1999) found that applying atrazine in bands rather than broadcasting resulted in lower levels of atrazine in soil, without impacting corn yield.

Row-crop cultivators have been used to control weeds between rows after planting (Davis et al. 2005; Liebman et al. 2001) and generally have semirigid tines or sweeps designed to scrape the soil surface or cut below the surface at different depths. Mechanical cultivation may require several passes over a field, using a significant amount of time and fuel (Mohler et al. 1997). Timely execution of mechanical weed control tactics are subject to appropriate weather and soil conditions, so systems that rely on mechanical tactics alone experience higher risk of having poor weed control and resulting yield losses (Liebman et al. 2008; Mulder and Doll 1993; Posner et al. 2008). Depending on depth, width, timing, and frequency of use, cultivation implements can meet standards for conservation tillage and even no-tillage (Natural Resources Conservation Service [NRCS] 2011). A high-residue cultivator is designed to operate in reduced- or no-tillage environments and has coulters ahead of a wide sweep that can slice the residue, reducing the amount dragged by the sweep and the amount of soil disturbance. Bates et al. (2012) observed a 50% reduction in weed biomass with high residue cultivation. While crops planted in narrow rows generally preclude mechanical cultivation, weed control in soybean planted in narrow rows is often better compared to wide-row soybean due to a more rapid canopy closure (Harder et al. 2007; Mickelson and Renner 1997; Young et al. 2001).

Several studies have demonstrated that different combinations of chemical and mechanical control tactics can successfully suppress weeds in corn without affecting yield (Bates et al. 2012; Hooker et al. 1997; Mt. Pleasant et al. 1994). Banded herbicide in combination with nonchemical weed control tactics, such as subsequent row-cultivation, can reduce soil residual active ingredient use by at least 50% with comparable economic returns in corn (Bates et al. 2012; Mulder and Doll 1993). Combining herbicide banding with cultivation reduced the risk of corn yield loss from weed competition in contrast to mechanical control alone (Mulder and Doll 1993). Banding herbicide over the crop row followed by cultivation reduced off-site herbicide transport due to lower herbicide use with banding and because between row weeds present before cultivation inhibited herbicide movement (Hansen et al. 2001).

This research was designed to investigate reduced herbicide use in corn and soybean production, while preserving the benefits of no-till, when practiced as part of a diverse 6-yr grain and forage cropping system suitable to the Mid-Atlantic region. Our objective was to compare a standard herbicide (SH)-based strategy to a more diverse weed management strategy that included additional mechanical and cultural tactics to suppress weeds, maintain competitive crop yields, minimize soil loss, and preserve economic viability of the cropping system.

Materials and Methods

The Sustainable Dairy Cropping Systems Project at Penn State is an interdisciplinary experiment consisting of two diverse, 6-yr crop rotations designed to produce all feed, forage, and on-farm tractor fuel (Malcolm et al. 2015) to sustain an average-sized Pennsylvania dairy herd (65 milking cow; USDA 2012). The experiment was initiated in 2010 at the Russell E. Larson Agricultural Research Station in Pennsylvania Furnace, PA (40.72°N,

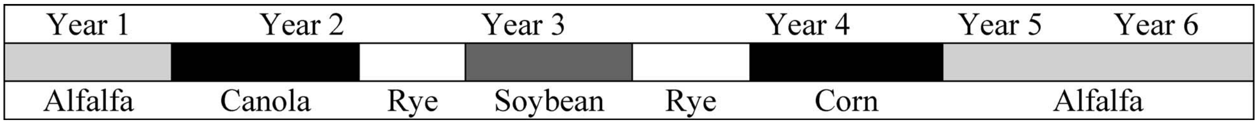

Figure 1. Penn State Sustainable Dairy Cropping Systems crop rotation.

77.92°W), and is designed to mimic production of a 97-ha farm, one-twentieth of farm scale in research plots. The soils are primarily a Murrill channery silt loam (fine-loamy, mixed, mesic Typic Hapludalts) with small areas of Buchanan channery silt loam (fine-loamy, mixed, semiactive, mesic Aquic Fraguidults) and average annual precipitation of 94 cm. The crop rotation of interest (Figure 1) compared two weed management strategies in the production of winter canola (*Brassica napus* L.), soybean, corn, and alfalfa (*Medicago sativa* L.). The experiment was a split-split-plot design in a randomized complete block design with four replications, and each crop entry present each year. This analysis examines only the rye, soybean, rye, corn portion of the rotation, where crop was the main plot factor, and weed management (SH or RH) was the subplot factor. Each main plot was 27 m by 37 m, and subplots were 18 m by 27 m. Soybean preceded corn and a cereal rye cover crop preceded both soybean and corn.

The SH treatment in these crops employs a regionally representative herbicide-based program to manage weeds, while the RH treatment uses less total herbicide by banding herbicide over the crop row, and using high-residue interrow cultivation for POST weed control. Rye cover crops were grown in both SH and RH, and broadcast burndown herbicides were used to control emerged weeds and to terminate cover crops prior to crop establishment.

Soybean Management. Prior to planting SH soybeans, 'Aroostook' rye (Tallmann Family Farms, Tower City, PA) was terminated on May 19, 2010, May 6, 2011, and April 21, 2012, when it was less than 30 cm tall with a broadcast preplant (PP) herbicide application (Table 1). Rye in the RH treatment in 2010 was also controlled on May 19, but in 2011 and 2012, rye termination was delayed until late boot or early head stage (about 45 cm tall, on May 12 in both years) to allow more cover crop growth and potentially better weed suppression. In the RH treatment, the rye was rolled to place the residue on the soil within 5 d of herbicide application with a front-mounted 3-m-wide cover crop roller-crimper as described by Mischler et al. (2010). Recommendations from the Penn State Agricultural Analytical Laboratory determined that no fertilizer was needed for soybeans in 2010 or 2011; in 2012, 34 kg K_2O ha^{-1} (0–0–60) was applied to soybean plots on May 31. Fertility management was the same in SH and RH plots each season.

RH and SH soybean were planted on May 25 and May 27, 2010, and on May 14 and May 31 in 2011, respectively. In 2012, both treatments were planted on May 31, as frequent rainfall in May of 2012 (18 cm during the month) delayed planting of the SH soybean. Growmark 'HiSoy 2766' GR soybean (maturity group 2.7; Growmark, Inc., Bloomington, IL) were seeded at a rate of 494,000 seeds ha^{-1} in 19-cm rows with a Great Plains 1005 solid-stand no-till drill (Great Plains Manufacturing, Inc., Salina, KS) in SH management and in 76 cm rows (RH) with a John Deere 1780 no-till planter (Deere & Company, Moline, IL), equipped with no-till coulters and Dawn Trashwheel row cleaners (Dawn Equipment, Sycamore, IL). Due to poor establishment with the no-till drill in both 2011 (visual assessment) and 2012 (population counts), but not 2010, SH soybean were re-seeded with the same soybean variety on June 7, 2011, and June 15, 2012; RH plots were not replanted. The emerged soybean from the initial SH seeding were allowed to remain and PRE herbicides were not re-applied to re-seeded plots. In 2010 and 2012, soybean plants were counted in three 0.25 m^2 quadrats per split–split plot (SH) or three 1-m sections of row (RH) 40 d after planting (DAP); visual assessments only of plant populations were made 2 to 3 wk after planting (WAP) in 2011.

Weed management programs are detailed in Table 1. The same PP program was used in both management programs; RH management included PRE banded herbicide over the crop row at the time of planting, while SH management received a broadcast application within 2 d of planting. In addition to the herbicides applied to the SH treatment, *s*-metolachlor was included with the RH banded treatment (Table 1) to provide residual control of grass weeds; POST glyphosate used in SH soybean was assumed capable of controlling both grass and broadleaf weed escapes, and no

Table 1. Experimental weed control programs applied to corn and soybeans from 2010 to 2012. An integrated program that reduces herbicide use (reduced herbicide [RH]) was compared to herbicide-based (standard herbicide [SH]) control for effectiveness and crop performance. In RH, the same rate of PRE herbicide was applied, but since it was applied in a band the total amount of herbicide applied per ha was reduced by two-thirds.

Crop	Herbicide application timing	Product	Standard Herbicide[a]	Reduced Herbicide
Soybean	PRE-PLANT	Roundup PowerMax[b]	glyphosate	glyphosate
		2,4-D LV4[c]	2,4-D ester	2,4-D ester
				Roller-Crimper
	PRE	Valor XLT[g]	flumioxazin	flumioxazin
			chlorimuron	chlorimuron
		Dual II Magnum[e]		*S*-metolachlor
	POST	Roundup PowerMax[b]	glyphosate	High-residue cultivator (2×)
Corn	PRE-PLANT	Roundup PowerMax[b]	glyphosate	glyphosate
		2,4-D LV4[c]	2,4-D ester	2,4-D ester
	PRE	Prowl H2O[d]	pendimethalin	pendimethalin
		Dual II Magnum[e]	*S*-metolachlor	*S*-metolachlor
		Callisto[e]		mesotrione
	POST	Status[e]	dicamba	High-residue cultivator (2×)
			diflufenzopyr[f]	

[a] Broadcast herbicide rates are, in order: 0.84 kg ha^{-1} ae glyphosate, 0.56 kg ai ha^{-1} 2,4-D, 0.63 kg ai ha^{-1} flumioxazin, 0.21 kg ai ha^{-1} chlorimuron, 0.62 kg ai ha^{-1} *S*-metolachlor (soybean), 1.59 ai kg ha^{-1} pendimethalin, 1.87 ai kg ha^{-1} *S*-metolachlor (corn), 0.09 kg ai ha^{-1} mesotrione, 0.08 kg ai ha^{-1} dicamba (in Status), 0.03 kg ai ha^{-1} diflufenzopyr; in RH, herbicide was applied to only 1/3 of each ha of plot area with banding equipment.

[b] Monsanto Company, St. Louis, MO, http://www.monsanto.com

[c] WinField Solutions, LLC. St. Paul, MN, http://www.winfield.com

[d] BASF Corporation, Research Triangle Park, NC, http://www.basf.com

[e] Syngenta International AG, Basel, Switzerland, http://www.syngenta.com

[f] (2-(1-[([3,5-difluorophenylamino] carbonyl)-hydrazono]ethyl)-3-pyridinecarboxylic acid)

[g] Valent U.S.A. Corporation, Walnut Creek, CA, http://www.valent.com

POST herbicide was applied in RH. In RH, the PRE banded herbicides were applied at 142 l ha^{-1} and 275 kPa using TeeJet TP4002E tips (TeeJet Technologies, Wheaton, IL) positioned on the planter row units about 35 cm above the soil surface in a 25-cm band over the crop row. The broadcast PP, PRE, and POST broadcast herbicides were applied at 187 l ha^{-1} and 275 kPa using TeeJet AI11002 tips using a tractor-mounted boom sprayer. POST herbicide was applied 5 WAP in SH management and POST control in RH was provided with two passes, about 5 and 7 WAP with a John Deere 886 high-residue interrow cultivator equipped with a Sukup Auto Guide (Sukup Manufacturing Co., Sheffield, IA) guidance system.

Soybean were harvested with a Massey Ferguson 550 plot combine (AGCO Corporation, Duluth, GA) on October 22, 2010, and on October 25 in 2011 and 2012; yield was measured from the central 4 m in each split–split plot (27 m long) and adjusted to 13% moisture.

Corn Management. In both the SH and RH treatments prior to corn planting, rye (see description in "soybean management") was terminated on May 19, 2010, May 6, 2011, and April 21, 2012, when it was less than 30-cm tall with a broadcast PP herbicide application (Table 1). Slightly different fertility programs were used each year based on manure application rates and recommendations from recent soil nutrient tests before corn planting and from pre-sidedress soil nitrate tests (PSNTs; Penn State Agricultural Analytical Laboratory, University Park, PA). Fertility management was the same in SH and RH plots each season. Liquid dairy manure was injected into 76 cm bands with a shallow-disk manure injector at 34,211 kg ha^{-1} on May 10, 2010, at 41,680 kg ha^{-1} on May 11–13, 2011, and at 49,300 kg ha^{-1} on April 9, 2012, contributing an estimated 98 kg ha^{-1}, 76 kg ha^{-1}, and 110 kg ha^{-1} available N to the corn crop, respectively, based on manure analyses (Penn State Agricultural Analytical Laboratory) and estimated availability (The Pennsylvania State University 2011). Pioneer '35F38′ corn (105 CRM) (DuPont Pioneer, Johnston, IA) was no-till planted at 79,490 seeds ha^{-1} in 76-cm rows with the John Deere 1780 no-till planter described above on May 25, 2010, May 26, 2011, and May 1, 2012.

In SH management, herbicides were broadcast applied immediately following corn planting (PRE) and again (POST) about 5 WAP, as outlined in the soybean section. Herbicides were applied (RH and SH) and cultivation was performed (RH) as described in "soybean management." Mesotrione was added in PRE banded application in the RH treatment for residual broadleaf weed control (Table 1). Due to an outbreak of true armyworm [*Pseudaletia unipuncta* (Haworth)] in 2012, methoxyfenozide was broadcast applied at 0.1 kg ai ha^{-1} to V-4 corn. Corn grain was harvested with an Almaco SPC-40 small plot combine (Almaco, Nevada, IA) on November 11 in 2010 and 2011, and November 13, 2012. Yield was measured by harvesting the central two rows (27 m long) in each split–split plot; measurements were adjusted to 15.5% moisture.

Weed Sampling. Species-level weed density was collected in 2011 and 2012, from two randomly placed 0.8 m^2 (1 m by 76 cm) quadrats at 4 (before POST) and 8 WAP (after POST); density not sampled in 2010. Weed biomass was collected 12 WAP from two quadrats per split-plot each year, as follows: 0.5 m^2 quadrats in 2010, 0.8 m^2 (1 m by 76 cm) quadrats in 2011, and 3 m^2 quadrats (4 m by 76 cm) in 2012 (two 4-m strips between crop rows). Sampled areas increased in size from 2010 to 2012 to help capture emerged weeds and reduce variability. Weeds were oven-dried for 72 h at 60 C and weighed.

Statistical Analysis. Weed, yield, and population data were analyzed using PROC Mixed in SAS statistical software (SAS for Windows v. 9.1.3. SAS Institute, Inc., Cary, NC). The experimental model was a nested split-plot design, with four blocks as replicates. "Block" and any terms interacting with "block" were treated as random factors, and weed management was a fixed factor. Soybean and corn data were not analyzed together. A two-sided F test ($\alpha = 0.01$) was performed with residual values to compare variances among years. When variances were not significantly different, year and weed management by year interactions were included in the model as fixed effects. Weed biomass and density data were transformed [$y = \ln(x + 1)$] to meet the assumptions of ANOVA; reported least-squares means were back-transformed. Where density was sampled within a plot at two dates (before and after POST), data were analyzed with repeated measures, with sampling date ("Date") and its four interactions as additional fixed effects. Least-squares means were generated for preplanned contrasts that compared the weed treatments at each date using the "slice" command. The Satterthwaite degrees of freedom approximation was used in all analyses, except those using repeated measures, which used the Kenward-Roger approximation (Kowalchuck et al. 2004).

A multiple linear regression model was conducted to estimate the effect of soybean population, rye biomass, weed density before and after cultivation and POST herbicide, and weed biomass on soybean yield. Correlations between individual variables alone and yield were evaluated first, then the "all possible regressions approach" was utilized to identify a regression model (Neter et al. 1990). All variables were transformed [$y = \ln(x + 1)$] to meet the assumptions of normality. Variables were kept out of the model if they exhibited multicollinearity with another variable, as indicated by variance inflation factor (VIF) and if removing a term in the model caused a change in coefficient sign (positive or negative) of that or another variable (Neter et al. 1990). The model with the highest F-value and R^2 and lowest Pr>F value was selected.

RUSLE 2 Analysis. The Revised Universal Soil Loss Equation v.2 (RUSLE 2) soil loss estimator software (http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm; NRCS-USDA, Washington, DC) was used to estimate soil loss resulting from management practices in each crop. The RUSLE 2 software generates estimated average annual soil loss ("A") based on local climatic, topographic, and soil conditions, as well as management factors, using the universal soil loss equation (Wischmeier and Smith 1978):

$$A = RKLSCP$$

The output also generates "T," defined as the maximum allowable yearly soil loss for site-specific conditions in order for the practices to meet conservation standard practices dictated by the NRCS (NRCS 2011). Specific management factors were entered into the software for a 2-yr rye–soybean–rye–corn rotation, under RH or SH weed management programs. Experimental site details were used to specify climatic factors (Centre County, PA; cmz 65), soil series (see above), contouring practices (contour farming practiced; absolute grade of 0.2%), and rock cover (18%; NRCS 2007). The model was run for each management (RH or SH) assuming a 2% slope with 91 m slope length (MuA, the experimental soil

Table 2. Rye cover crop biomass before soybean and corn in reduced herbicide (RH) and standard herbicide (SH) treatments. Rye biomass collected before termination with burndown herbicide.

Rye biomass[a] before each crop	Herbicide treatment	Rye biomass[b]			Significance of fixed effects		
		2010	2011	2012	Yr.	Trmt.[c]	Yr.* Trmt.
		kg ha^{-1}			Pr > F		
Soybean	RH	924 a	4,300 a	7,876 a	0.007	0.03	0.09
	SH	931 b	3,505 b	4,940 b			
Corn	RH	1,114 a	533 a	977 b	0.0007	0.004	0.01
	SH	1,114 a	322 a	1,615 a			

[a] Reported as dry matter.

[b] Different letters (a, b) indicate a statistical significance at $P < 0.05$ between biomass levels within a year.

[c] Trmt. refers to herbicide treatment, SH or RH.

series and slope; slope length from Lightle and Weesies 1998) and also a 10% slope with 37 m slope length (MuC, the experimental soil series with adjusted slope; slope length from Lightle and Weesies 1998), to represent another commonly cultivated slope steepness in Pennsylvania.

Partial Budget Analysis. A partial budget analysis was conducted for each crop separately, to compare income, costs, and net financial returns of crop management, to assist in financial decision-making (Kay et al. 2004). Average yields and production costs over the three experimental years were used to generate enterprise budgets, and subsequently the partial budget comparison between treatments.

Experimental costs were obtained from actual costs incurred where possible, or from budgets generated by the Mississippi State Budget Generator Version 6.0 (Department of Agricultural Economics, Mississippi State University, Mississippi State, MS), or from other sources (The Pennsylvania State University 2011; University of Illinois 2012). Input costs were averaged across years. The rye cover crop was not included in the analysis; however, the ownership, repair and maintenance, and fuel and labor costs of the roller-crimper used before RH soybean were included. Where needed, scale-appropriate cost assumptions were made for both variable and fixed costs based on the hypothetical 97-ha dairy farm modeled in the Penn State Sustainable Dairy Cropping Systems Project. Ownership costs of equipment not available from other sources, such as that of the roller-crimper, were calculated based on actual equipment price, estimated use, and depreciation (Kay et al. 2004). Repair and maintenance costs for these equipment were generated using the Farm Machinery Repair and Maintenance Cost Estimator (Lazarus 2010), with the most similar equipment described by the American Society of Agricultural and Biological Engineers (Joseph, MI) used to model the implements. Estimating repair and maintenance costs required consideration of anticipated annual implement use for the farm modeled by the Penn State Sustainable Dairy Cropping Systems Project, the projected speed of tractor operation for each piece of equipment, estimated lifespan, and actual initial costs of the equipment. Corn and soybean prices used to estimate income were calculated by averaging grain prices received by farmers in Centre County, PA, in 2008 to 2012 (USDA 2013).

Results and Discussion

Weather. Precipitation in March through September was highest in 2011 (72 cm) compared to 2010 and 2012 (52 cm), though much of this precipitation fell in the early and late parts of the season. March and April of 2010 and 2012 were much warmer (average temperature of 9 C) than in 2011 (4 C), though average temperatures in May through October were similar (16 C in 2010 and 2011, 18 C in 2012). In early September of 2011, remnants of two consecutive tropical storms contributed to heavy rainfall in much of the state, including the research site. The warm, dry weather of 2012 allowed for large biomass accumulation of cover crops, though heavy rainfall in May (18 cm) prevented earlier planting dates in this year.

Cereal Rye Cover Crop Biomass. The year by weed management system interaction was not significant (Table 2) for rye biomass before soybean, but RH had greater biomass than SH, which was likely because rye termination in RH was intentionally delayed in 2011 and 2012. Year was significant for rye biomass before soybean, as 2012 rye biomass was greater than 2011 and 2010, and

Table 3. Soybean and corn population and yield under two weed management strategies, reduced herbicide (RH) and standard herbicide (SH). Different letters (a, b) indicate a statistical significance at $P < 0.05$ between treatments, within a crop and year.

Crop	Herbicide treatment	2010	2011	2012	Significance of fixed effects: Yr.	Trmt.[a]	Yr.*Trmt.
					Pr > F		
Soybean				Population[b] (plants ha^{-1})			
	RH	333,300 a	—	108,080 b	0.02	0.03	0.003
	SH	286,620 a	—	280,900 a			
				Yield[c] (kg ha^{-1})			
	RH	4,980 a	3,200 a	2,760 b	0.005	0.04	0.005
	SH	4,860 a	3,850 a	4,060 a			
Corn				Population[d] (plants ha^{-1})			
	RH	73,940 a	72,600 a	73,080 a	0.96	0.11	0.92
	SH	70,180 a	70,440 a	70,580 a			
				Yield[e] (kg ha^{-1})			
	RH	12,980 a	10,620 a	9,860 a	< .0001	0.74	0.52
	SH	12,710 a	10,210 a	10,230 a			

[a] Trmt. refers to herbicide treatment, SH or RH.

[b] Population measured following the second cultivation of RH soybean and after POST; data not collected in 2011.

[c] Soybean yield reported as grain yield at 13% moisture.

[d] Population counts performed at V5 stage of corn.

[e] Corn yield reported as grain yield at 15.5% moisture.

2011 had significantly more biomass than 2010 (Table 2). This was likely due to the combination of a warm March and April in 2012 as compared to 2011; while 2010 was also warm in these months, rye biomass was terminated earlier in 2010.

Rye biomass before corn ranged from 322 to 1,615 kg ha^{-1} across the 3 yr (Table 2). The year by weed management system interaction was significant for rye biomass because rye biomass was similar between treatments in 2010 and 2011, but in 2012, rye biomass was 65% greater in SH management than in RH (Table 2). The rye was intentionally terminated while still vegetative and prior to anthesis in both RH and SH corn management to prevent N-immobilization in corn; rye biomass was expected to be the same between corn weed management treatments. We can only speculate the reason why biomass differed in 2012, but this may have been attributable to higher SH soybean yields (and biologically fixed N) in 2011 compared to RH (Table 3), which preceded the 2012 rye to corn plots. Also, the higher March and April temperatures may have encouraged greater N-mineralization from organic N pools in the soil.

Weed Density and Biomass in Soybean. Soybean weed density could not be analyzed with year and date in the model as data were only collected once (after POST) in 2011; in 2012, data were collected both before and after POST. Weed density did not differ between treatments in 2011 following POST (Table 4). The date by treatment interaction and date did not significantly affect weed density in 2012 soybean (Table 4), but treatment alone was significant as the broadcast herbicide used in SH controlled weeds better than banded herbicide plus cultivation used in RH (Table 1). In both years, the majority of weeds present after POST were summer annuals such as common ragweed (*Ambrosia artemisiifolia* L.), smooth pigweed (*Amaranthus hybridus* L.), and giant foxtail [*Setaria faberi* (Herrm.)]; these weeds were small and scattered, many having emerged following POST, which did not contain any residual herbicide.

Weed biomass was higher in RH than in SH soybean in all 3 yr, though by different magnitudes in each year, resulting in a significant year by treatment interaction (Table 5). Weed biomass in SH was low every year (≤ 0.1 g m^{-2}), but varied more in RH and ranged from 21 g m^{-2} in 2011 to less than 1 g m^{-2} in 2012 (Table 5). Year was also significant, as weed biomass was higher in 2011 than in the other years. In 2012, higher rye biomass levels in RH compared to other years (Table 2) may have contributed to weed suppression; however,

Table 4. Weed density, before and after POST in soybean and corn under standard herbicide (SH) or reduced herbicide (RH) weed management strategies. Before POST collection occurred 4 wk after planting (WAP); after POST at 8 WAP. Corn data analyzed with year in the model as a fixed effect; soybean years analyzed separately as density was not collected before POST in 2011. Different letters (a, b) indicate a statistical significance at $P < 0.05$ within a crop, year, and collection time.

		Weed density								Significance of fixed effects[b]				
		2011				2012								
Crop	Trmt.[a]	Before POST		After POST		Before POST		After POST		Trmt.	Yr.* Trmt.	Date[c]	Date* Trmt.	Yr.* Date* Trmt.
		plants m^{-2}								Pr > F				
Soybean	RH	—		0.4	a	0.3	a	2.2	a	0.05	—	0.22	0.11	—
	SH	—		1.4	a	0.1	b	0	b					
Corn	RH	90.9	a	12.1	a	25.4	a	6.6	a	<.0001	0.03	< .0001	0.03	0.07
	SH	3.3	b	2.1	b	5.2	b	1	b					

[a] Trmt. refers to herbicide treatment, SH or RH.

[b] Significance of fixed effects for soybean refers to 2012 data only.

[c] Date refers to collection date: before POST or after POST weed control tactics.

weed biomass did not differ between 2010 and 2012 in RH soybean, so it is difficult to determine if or how the rye cover crop contributed to weed control in RH soybean. Others have reported that weed suppression provided by the rye cover crop mulch is related to rye biomass at termination (Mirsky et al. 2011; Mischler et al. 2010; Nord et al. 2011). However, weed biomass in SH was still lower than in RH each year (Table 5), suggesting that POST herbicide applications provided better weed control than cultivation in soybean.

Weed Density and Biomass in Corn. The date by treatment interaction was significant for weed density in corn because SH weed density decreased following POST in 2012 only, whereas RH weed density decreased after POST in both years (Table 4). The year by treatment interaction was significant for weed density as the magnitude by which RH exceeded weed density in SH was higher in 2011 compared to 2012 (Table 4). Weed density was always higher in RH than in SH, and weed density was always lower after POST compared to before POST (Table 4). The year by treatment interaction was significant for weed biomass as biomass was greater in RH than in SH in 2011 and 2012 (Table 5), but did not differ between treatments in 2010. Weed biomass never exceeded 19 g m^{-2} in RH and 1 g m^{-2} in SH (Table 5).

Soybean Population and Yield. The year by treatment interaction was significant for soybean population as SH population was higher than RH in 2012, but populations did not differ not in 2010 (Table 3). This interaction was also significant for soybean yield as yields did not differ between treatments in 2010, but in 2011 and 2012, soybean yield was greater in SH than in RH by 17 and 32%, respectively (Table 3). Early observations of soybean populations in 2011 and 2012 suggested poor establishment of the SH drilled soybean, so these were re-planted at the same initial seeding rate. Midseason population counts after re-drilling of SH in 2012 revealed that while SH soybean population

Table 5. Weed biomass in soybean or corn under reduced herbicide (RH) and standard herbicide (SH) weed management strategies, 2010–2012. Biomass (reported as dry matter) collected approximately 12 wk after planting. Different letters (a, b) indicate a statistical significance at $P < 0.05$ between treatments within a crop and year.

		Weed biomass			Significance of fixed effects		
Crop	Trmt.[a]	2010	2011	2012	Year	Trmt.	Year* Trmt.
		g m^{-2}			Pr > F		
Soybean	RH	4.6 a	21.3 a	0.9 a	0.004	< 0.0001	0.0004
	SH	0 b	0.1 b	0 b			
Corn	RH	2.1 a	18.7 a	7.4 a	0.24	< 0.0001	0.03
	SH	0.9 a	0.1 b	0.3 b			

[a] Trmt. (treatment) refers to herbicide treatment, SH or RH.

Table 6. Significance of effects on soybean yield in 2010, 2011, and 2012 resulting from linear regression analysis. Each individual effect was tested against yield, and then an "all possible regressions" approach was utilized to identify the best multiple linear regression model for predicting soybean yield. All variables were natural-log transformed to fit the assumptions of normality in the analysis.

Regression model	Pr > F	R^2	F	VIF[a]
Population[b]	< 0.0001	0.73	38.35	—
Rye biomass	< 0.0001	0.71	50.47	—
Weed biomass	0.28	0.05	1.23	—
Weed density, before POST[c]	0.15	0.19	2.4	—
Weed density, after POST[d]	0.52	0.02	0.42	—
Multiple linear regression model[b,e]	< 0.0001	0.9	46.48	1.59
Individual factors				
Population	0.002			
Rye biomass	0.001			

[a] Variance inflation factor.

[b] 2010 and 2012 data only.

[c] 2011 and 2012 data only.

[d] 2012 data only.

[e] $y = e^{-191955+37894x-17113z} - 1 + \varepsilon$, where y = soybean yield, x = soybean population, and z = rye biomass.

was close to the desired population (data not shown), only 33% of desired population was achieved in RH soybean, suggesting that these plots also would have benefited from re-planting. Ultimately, soybean population in SH exceeded that of RH by 160%.

Linear regression analysis showed a significant relationship between soybean yield and population, and between soybean yield and rye biomass (Table 6). Weed biomass and density (before and after POST) were not significant in predicting soybean yield (Table 6), and did not strengthen the multiple regression models so were not included in the analysis. Rye biomass and soybean population were negatively correlated ($P = 0.01$; $R^2 = 0.49$), but both variables were kept in the model since the VIF was relatively low (Table 6). The final model had a high R^2 value (Table 6):

$$y = e^{-191955+37894x-17113z} - 1 + \varepsilon \qquad [1]$$

where y = soybean yield; x = soybean population; and z = rye biomass.

Within the model, soybean population and rye biomass were also significant ($P = 0.002$ and $P = 0.001$, respectively). We believe that the yield difference between treatments was attributable to these factors, rather than competition from weeds, because no weed-related effect was significant in predicting soybean yield. Rye biomass was 26% greater in RH than in SH in 2011, and 67% greater in RH in 2012 as a result of later termination (Table 2), so may have had an impact on soybean establishment, as supported by the correlation. While SH soybean were re-drilled in 2011 and 2012, reduced populations in RH were not observed until after it was too late to re-plant. We believe open planting slits caused by a combination of rye residue and high soil moisture caused establishment challenges and also provided ideal habitat for slugs (Douglas and Tooker 2012; Willis et al. 2008), which may have reduced soybean populations after emergence. Challenges in achieving desired soybean populations in high-residue environments have been experienced in other research (Nord et al. 2011) even when cover crop biomass did not have a strong impact on soybean establishment. The drill used in this experiment did not employ specialized row cleaners, while the planter did include residue managers. However, the planter row cleaner attachments used in this study are designed more to move dry plant residue such as corn stover rather than fresh cover crop residue. Alternative row cleaners designed to aggressively move cover crop residue out of the planted row may have aided in cash crop establishment.

Two other factors could have influenced RH soybean yield. First, although we did not observe herbicide injury in this study, the herbicide manufacturer warns that flumioxazin tank-mixed with chloroacetamide-containing products including *s*-metolachlor (as applied to RH soybean; Table 1) can result in injury to soybean when application is followed by prolonged periods of cool-wet weather (Anonymous 2010). This could be expressed as reduced population. Secondly, we do not believe that interrow cultivation impacted soybean population, but it is possible that cultivation may have had a negative effect on soybean yield by drying the soil or by root pruning. In the end, there may have been multiple reasons for the reduced soybean population in RH and because of the correlation between yield and population, replanting the RH soybean might have been warranted.

Corn Population and Yield. Corn population was not impacted by treatment or year (Table 3). Average yields were lower in 2011 and 2012 than in 2010 (Table 3), but did not differ between treatments. Other studies comparing RH inputs plus mechanical weed control strategies in corn have found similar results (Bates et al. 2012; Mohler et al. 1997; Mulder and Doll 1993). Although weed biomass was higher in RH than in SH, the

Table 7. Annual soil loss prediction (A), Soil Conditioning Index (SCI), and Soil Tillage Intensity Rating (STIR) in a 2-yr rye–soybean–rye–corn grain cropping sequence under reduced herbicide (RH) or standard herbicide (SH) management. Values predicted by the RUSLE 2 model[a] for two sites with different slopes and slope lengths in Centre County, PA. The maximum allowable yearly soil loss (T) for this site is 9.0 Mg ha^{-1}.

Slope	Herbicide Treatment	A	SCI[b]	STIR[c]
		Mg ha^{-1} yr^{-1}		
2%	SH	1.1	0.6	11.8
	RH	1.3	0.6	27.9
10%	SH	3.6	0.5	11.8
	RH	7.2	0.2	27.9

[a] RUSLE 2: Revised Universal Soil Loss Equation v. 2. National Resources Conservation Service (NRCS). Washington, DC: USDA.

[b] This value is a measure of the rate of predicted change in soil organic matter (SOM) over time and has a range of [–2, 2]; negative values indicate a predicted loss in SOM, and positive values indicate a predicted increase in SOM over time.

[c] STIR: based on the frequency and type of soil disturbances that occur. In order to meet the NRCS general standard for no-till (NRCS 2011) this value must be under 30.

combination of banded herbicide plus cultivation sufficiently suppressed weeds such that yields did not differ between treatments. We can only speculate, but dairy manure was used as a nutrient source in both treatments and may have helped support equivalent corn yields in spite of greater weed biomass in the RH treatment. Previous research showed that corn grown in systems with organic nutrient sources were less vulnerable to weed competition and experienced less yield loss with higher weed biomass as compared to corn grown in systems with no regular addition of organic matter through cover crop residues or manure (Ryan et al. 2010). Unlike this study, mechanical weed control sometimes results in crop population losses (Bates et al. 2012; Mohler et al. 1997), but this depends on the type of cultivation equipment used. Population losses from cultivation can be reduced with sensory guidance systems (Liebman et al. 2001), which our experiment utilized.

RUSLE 2 Analysis. Analysis using RUSLE 2 indicated that the maximum allowable soil loss (T) for the two-years was 9 Mg ha^{-1}; given the experimental soil type and climate conditions (Table 7). On land with an average 2% slope and 91 m slope length, both the SH and RH managements of the two-year crop sequence were predicted to generate similar levels of average soil loss (A) of only 1.1 Mg ha^{-1} and 1.3 Mg ha^{-1} (Table 7), respectively. On a 10% slope, A is higher for both management systems compared to a 2% slope, and though both management systems were less than T, A was twice as high in RH (7.6 Mg ha^{-1}) compared to SH (3.2 Mg ha^{-1}; Table 7).

Predicted soil loss was higher for corn than soybean (data not shown); this is primarily a function of the interaction of soil cover during periods where the Erosivity Index (E.I.) is highest (Hudson 1995). Higher levels of early-season rye residue in soybean compared to corn (Table 2) resulted in lower A for soybean, which is a time of high erosivity (Hudson 1995). RH soybean had lower A than SH at a 2% slope (data not shown) due to higher levels of rye; this benefit was likely augmented with the flattening effect of the roller-crimper, which is more protective than standing rye. While rye residue was predicted to dissipate more quickly following cultivation, higher initial residue levels meant that more remained on the soil surface in RH soybean than in SH following POST. Still, the difference in A between the corn systems was greater than the difference in soybean because cereal rye was terminated at the same time in RH and SH corn, so predicted A for the 2-yr sequence was slightly higher under RH management due to cultivation.

At both slope-steepness factors and under both management regimes, the 2-yr soybean–corn sequence has a soil conditioning index (SCI) of 0.6 and should thus experience an increase in SOM over time, although less rapidly at a slope steepness of 10% (Table 7). The Soil Tillage Intensity Rating (STIR) is greater for RH management than for SH in the 2-yr rotation (Table 7) regardless of slope factors. This difference is expected given the mechanical weed control instead of herbicide at several points in the rotation. The no-till conservation standard requires that STIR be under 30; despite the two high-residue cultivation events per year, the 2-yr sequence under RH management even with a 10% slope meets this no-till conservation requirement with a STIR value of 27.9 (Table 7; NRCS 2011). This indicates that under both slope-steepness and slope-length factors, soil disturbance caused by high-residue cultivation in a soybean–corn crop rotation will achieve conservation goals of no-till practices.

Partial Budget Analysis. In partial budget analyses of soybean, SH management had greater net returns by \$43.69 ha^{-1} than RH management,

Table 8. Itemized partial budget comparison of standard herbicide (SH) and reduced herbicide (RH) management of soybean and corn. Only items that differ between RH and SH treatments are reported. Yields and production costs reflect experimental yields and costs in 2010–2012. The "SH-RH" column reflects the difference between the two treatments; negative numbers reflect greater income, costs, total costs, and net returns under RH management. Positive numbers reflect greater values under SH management.

Crop	Source of difference	SH	RH	Difference	Notes and sources
		dollars ha^{-1}			
Soybean	Income				
	Soybean grain	$1,823.34	$1,562.54	$260.80	Based on experiment yields (Table 3); regional price received for soybean 2010–2012 ($11.66 bu^{-1})
	Costs				
	Seed	$675.17	$405.08	$270.09	SH re-drilled soybeans in 2 out of 3 yr
	Herbicides				
	PRE	$28.71	$25.09	$3.62	PRE spray in RH included metolachlor (Table 1)[a]
	POST	$8.75	$0.00	$8.75	No POST spray in RH (Table 1)[a]
	Labor and fuel				
	Roller-crimper	$0.00	$13.00	−$13.00	Only used in RH (Mischler et al. 2010)
	Planting	$21.82	$18.53	$3.29	RH includes labor associated with herbicide banding equipment mounted on no-till planter. SH uses no-till drill (3.2 m), re-planted in 2 out of 3 yr[b]
	Spraying	$14.82	$0.00	$14.82	6.1 m boom used; doubled fuel and labor of 12.2 m boom[b]
	Cultivator	$0.00	$31.30	−$31.30	Added 34.8% cost of 7 m field cultivator to estimate 4.5 m cultivator[b]
	Drying	$63.16	$54.42	$8.74	Difference attributable to yield differences[c]
	Ownership costs				
	Planting equipment	$51.14	$53.85	−$2.71	No-till drill in SH; 6-row no-till planter in RH[c]
	Sprayer equipment	$10.57	$25.12	−$14.55	Boom sprayer only needed in SH.[c] Herbicide banding equipment (RH) price (C. Dillon, personal communication), assuming a straight line depreciation over 10 yr; covering 16 ha^{-1} yr^{-1}[d]
	Cultivator	$0.00	$32.23	−$32.23	Used only in RH; price from Deere & Company (Moline, IL, http://www.deere.com); assuming straight line depreciation over 25 yr; covering 16 ha^{-1} yr^{-1}[d]
	Roller-crimper	$0.00	$16.60	−$16.60	Used only in RH; price from I&J Manufacturing (Gap, PA 17527); assuming straight line depreciation over 25 yr; covering 8 ha^{-1} yr^{-1}[d]
	Repairs and maintenance	$16.18	$27.84	−$11.66	Reflects difference in equipment needed for each treatment[e]
	Total costs	$1,343.58	$1,156.20	$217.11	Difference in Net Returns = $43.69 ha^{-1}

based on the actual study yields and costs (Table 8). While total costs of production under SH management were $217.11 ha^{-1} greater than RH production costs, income was also $260.80 ha^{-1} greater (Table 8) due to higher yields in 2 of 3 yr (Table 3). The costs of seed, herbicide, herbicide application, and drilling soybean were greater in SH, in part because of the need to re-drill SH soybean in 2 out of 3 yr. The ownership and repair and maintenance costs were greater in RH because of the added equipment needed to complete weed control in this treatment (Table 8). Herbicide costs were higher in SH than in RH (Table 8), but the total fuel, labor, and herbicide costs of the roller-

Table 8. Continued.

Crop	Source of difference	SH	RH	Difference	Notes and sources
Corn	Income				
	Corn grain	$2,409.85	$2,432.46	−$22.61	Based on experiment yield (Table 3), regional price received for corn 2010–2012 ($5.54 bu^{-1})
	Costs				
	Herbicide				
	PRE	$96.35	$44.22	$52.13	PRE spray in RH included mesotrione (Table 1)[a]
	Labor and fuel				
	No-till Planter	$11.12	$18.53	−$7.41	RH includes labor associated with spraying as banding equipment mounted on no-till planter[b]
	Spraying	$14.82	$0.00	$14.82	6.1-m boom used in experiment; doubled fuel and labor of 12.2 m boom[b]
	Cultivator	$0.00	$31.30	−$31.30	Added 34.8% cost of 7-m field cultivator to estimate 4.5 m cultivator[b]
	Drying	$174.85	$176.48	−$1.63	Difference attributable to yield differences[c]
	Ownership costs				
	Sprayer equipment	$10.57	$25.12	−$14.55	Boom sprayer only needed in SH.[c] Herbicide banding equipment (RH) price (C. Dillon, personal communication, 2013), assuming a straight line depreciation over 10 yr; covering 16 ha^{-1} yr^{-1}[d]
	Cultivator	$0.00	$32.23	−$32.23	Used only in RH; price from Deere & Company (Moline, IL, http://www.deere.com); assuming straight line depreciation over 25 yr; covering 16 ha^{-1} yr^{-1}[d]
	Repairs and maintenance	$16.18	$27.02	−$10.84	Reflects difference in equipment needed for each treatment[e]
	Total costs	$1,291.78	$1,280.73	$11.05	Difference in Net Returns = −$33.65 ha^{-1}

[a] Herbicide prices provided by a WinField Solutions LLC (Shoreview MN 55126) retailer (personal communication, 2013).

[b] University of Illinois (2012). Fuel assumed at $0.92 l^{-1}.

[c] Mississippi State Budget Generator Version 6.0 (Dept. of Agricultural Economics, Mississippi State University, Mississippi State, MS, http://www.agecon.msstate.edu).

[d] Kay et al. (2004).

[e] The Pennsylvania State University (2011).

crimper, herbicide banding, and two high-residue cultivator passes utilized for weed control in RH were $24.52 ha^{-1} greater than the two broadcast herbicide applications used for weed control in SH (data not shown). Also, while PRE herbicide was only applied to one-third the area in RH as compared with SH, the cost was only $3.62 ha^{-1} greater in SH soybean due to the addition of a higher cost herbicide (*s*-metolachlor; Table 1) in RH soybean, which somewhat reduced the cost–benefit of banding herbicide.

This study did not consider the cost of planting the rye cover crop, as this would have been equivalent in both treatments aside from the roller-crimper used in RH soybean, but others have found that the weed control benefit from a rye cover crop alone in soybean may not justify the cost of the cover crop (Mischler et al. 2010). The same GR soybean was used in both SH and RH management though RH management did not employ POST glyphosate. The economics for the RH program might be more favorable if nonherbicide resistant soybeans had been used due to lower seed costs (Fernandez-Cornejo et al. 2014). Fernandez-Cornejo et al. (2014) report that farmers may choose to plant herbicide-resistant crops even if net returns are not always higher, due to simplified weed management, lower labor demands, and thus more opportunity for other pursuits such as off-farm work.

In corn, partial budget analysis of SH and RH management based on experimental costs and yields, revealed that RH offered a \$33.65 ha^{-1} advantage over SH management (Table 8). Income differed between the treatments as average RH corn yields in all 3 yr were numerically, though not statistically higher than in SH (Table 3). Although the ownership, repair, and maintenance costs of the high-residue cultivator and herbicide banding equipment added \$57.63 ha^{-1} in costs to RH management, the labor, fuel, and herbicide costs of weed control in RH were \$67.76 ha^{-1} less than those in SH (Table 8). These results mirror those found in previous studies where cultivation was used as POST (Bates et al. 2012; Mulder and Doll 1993).

Integrated or RH weed management of no-till corn as investigated in this research resulted in equivalent yields, and higher net returns to management compared to SH management. The results do not support the hypothesis that both management scenarios will result in equal yields for soybean, as higher yields were achieved under SH management. Soybean yield reduction in RH was associated with reduced soybean populations and rye residue. Planting equipment, residue management, and insect and slug control in high-residue no-till systems should be further investigated to ensure successful soybean establishment and competitive yields in Pennsylvania. Choosing different herbicides or nonherbicide resistant seed might also alter the net returns to management of an RH program, assuming equivalent efficacy.

The RH herbicide program achieved a 48% reduction in herbicide active ingredient or acid equivalent in corn, whereas RH management in soybean achieved a 12% reduction. This reduction might be smaller or larger depending on the herbicides selected, and future research should also consider environmental toxicity of different herbicide programs. Our research also showed that weed density and biomass were often greater under RH management, and current research is monitoring the weed seedbank over time under these management strategies (Caswell et al. 2015), as a long-term buildup of weeds could affect the efficacy of the weed management program, crop yields, and the sustainability of these systems. Herbicides used for banding should be carefully selected based on problematic weed species and crop safety, and cultivation should be timed to effectively control the weeds. In situations where weed severity is high, or certain problematic species such as burcucumber (*Sicyos angulatus* L.) or Palmer amaranth (*Amaranthus palmeri* S.Wats.) are present, broadcasting PRE and POST herbicides, producing high levels of cover crop biomass for weed suppression, and supplementing with mechanical weed control might be necessary to achieve sufficient weed suppression.

Under the conditions of this study, high-residue interrow cultivation met the conservation standard for no-till (Table 7) and could be considered to reduce herbicide use and diversify weed management tactics. However, at a 10% slope, soil loss under RH management approaches T, signaling that over time this level of soil loss may be detrimental. The results from this research highlight tradeoffs when diversifying weed management in a conservation tillage system. The combinations of tactics involved in effort to achieve a more sustainable weed management system results in a complex management system that requires attention to specific field, crop, and climate conditions for success.

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