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Abstract: Cover crop management with a roller/crimper may reduce the need for herbicide. Weed suppression from a rolled cereal rye cover crop was compared to no cover crop with and without postemergence herbicide application in no-till soybean. The experiment was designed as a two-way factorial with rye termination and soybean planting date as the first factor and weed control treatment as the second. Cereal rye was drill-seeded in late September and managed using glyphosate followed by a roller/crimper in the spring. Soybean was no-till seeded after rolling and glyphosate was applied postemergence about six weeks after planting to half the plots. Rye biomass doubled when delaying rye kill by 10 to 20 days. Weed density and biomass were reduced by the rye cover crop in all site-location combinations except one, but delaying rye kill and soybean planting date only reduced both weed density and biomass at a single location. The cover crop mulch provided weed control similar to the postemergence herbicide in 2 of 4 locations. Treatments did not affect soybean grain yield in 2007. In 2008, yield at Landisville with rye alone was equal to those yields receiving the postemergence herbicide, while at Rock Springs, it was equivalent or less. The net added cost of a rye cover crop was \$123/ha with or \$68.50/ha without a postemergence herbicide application. A rolled rye cover crop sometimes provided acceptable weed control, but weed control alone did not justify the use of the cover crop. The potential for reduced herbicide use and other ecosystem services provided by a cover crop justify further refinement and research in this area.

Manuscript

Running Footer: Rye for Weed Suppression

USE OF A ROLLED RYE COVER CROP FOR WEED SUPPRESSION IN NO-TILL SOYBEANS

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Cover crop management with a roller/crimper may reduce the need for herbicide. Weed suppression from a rolled cereal rye cover crop was compared to no cover crop with and without postemergence herbicide application in no-till soybean. The experiment was designed as a two-way factorial with rye termination and soybean planting date as the first factor and weed control treatment as the second. Cereal rye was drill-seeded in late September and managed using glyphosate followed by a roller/crimper in the spring. Soybean was no-till seeded after rolling and glyphosate was applied postemergence about six weeks after planting to half the plots. Rye biomass doubled when delaying rye kill by 10 to 20 days. Weed density and biomass were reduced by the rye cover crop in all site-location combinations except one, but delaying rye kill and soybean planting date only reduced both weed density and biomass at a single location. The cover crop mulch provided weed control similar to the postemergence herbicide in 2 of 4 locations. Treatments did not affect soybean grain yield in 2007. In 2008, yield at Landisville with rye alone was equal to those yields receiving the postemergence herbicide, while at Rock Springs, it was equivalent or less. The net added cost of a rye cover crop was $123/ha with or $68.50/ha without a postemergence herbicide application. A rolled rye cover crop sometimes provided acceptable weed control, but weed control alone did not justify the use of the cover crop. The potential for reduced herbicide use and other ecosystem services provided by a cover crop justify further refinement and research in this area.

Nomenclature: glyphosate; dandelion, *Taraxacum officinale* Weber; yellow nutsedge, *Cyprus esculentus* L.; common ragweed, *Ambrosia artemisiifolia* L.; pigweed, *Amaranthus spp.;* common lambsquarters, *Chenopodium album* L.; carpetweed, *Mollugo verticillata* L.; purslane, *Portulaca oleracea* L.; giant and yellow foxtail, *Setaria sp.*; rye, *Secale cereale* L.; soybean, *Glycine max* L.

Key Words: Cover crop mulch, glyphosate, herbicide, roller/crimper, termination timing.

Cereal rye is an ideal cover crop for many agronomic systems as plants can: develop a fibrous root system, tolerate low fertility soils, scavenge for available nitrogen, suppress weeds, and prevent soil erosion that commonly occurs when no residue or plant material is left on the soil surface (Clark 2007). Previous research has shown that rye mulch can be a key component of soil conservation throughout the growing season. In an Illinois study, a cereal rye mulch persisted throughout the growing season while a hairy vetch mulch did not (Ruffo and Bollero 2003). The persistence of the rye residue results in longer-lasting soil coverage, which can protect the soil from the erosive forces of wind and rain. In one conservation tillage study, cereal rye reduced soil loss from over 5000 kg/ha to about 500 kg/ha (Edwards et al. 1993). Other research showed that a winter cover crop reduced soil losses in conventionally tilled soybeans from 8250 kg/ha to 1853 kg/ha in Tennessee and from 9979 kg/ha to 1260 kg/ha in Kentucky (Langdale et al. 1991).

In the Northeast U.S., cover crops are promoted as a means for improving soil conservation (Rudisill 2007). Cereal rye is noted for its ability to take up excess nitrate and prevent watershed contamination and nutrient losses (Clark 2007; Rudisill 2007). On the Maryland coastal plain, rye recovered 45% of fall applied N which was more than any of the other cover crops evaluated (Shipley et al. 1992). The ability of rye to produce winter growth and sequester nutrients makes it an ideal winter cover crop candidate, particularly in watersheds that suffer from excess nutrients like the Chesapeake Bay Region of the US.

Besides reducing erosion and sequestering nutrients, a cereal rye cover crop can also aid in weed management. Cereal rye can suppress weeds in at least two ways; first as a living cover by competing for limited resources such as sunlight and nutrients and second as a dead rye mulch on the soil surface that can suppress weed emergence. A study from central Italy showed that a killed rye cover crop reduced weed biomass 54 to 99% and weed suppression was better when cover crop biomass production was higher (Barberi and Mazzoncini

2001). However, not all summer annual species were suppressed by the mulch and a shift in the weed community towards additional troublesome weeds was observed. Others have also noted that normal amounts of rye biomass produced by a cover crop are often insufficient to suppress weeds throughout the growing season (Masiunas et al. 1995; Mohler and Teasdale 1993). In Ontario Canada, cover crop mulches reduced weed biomass early in the season, but the results varied between years and locations (Moore et al. 1994).

In much of the previous rye-weed suppression research, the rye cover crop was killed by mowing, which accelerates the decomposition of the rye mulch or by herbicides prior to planting a cash crop. Using a roller/crimper to kill the rye instead of a mower allows for greater persistence of the residue (Creamer and Dabney 2002) and, therefore, should provide a better physical barrier to weed emergence. In Alabama, a roller equipped with curved fins to crimp the cover crop, successfully controlled cereal rye at the soft dough stage (Ashford and Reeves 2003). In the same experiment, using a full rate of herbicide alone or combining the roller/crimper with a half rate of herbicide controlled the rye cover crop effectively at an earlier growth stage. In Pennsylvania, rye was consistently controlled at anthesis with a roller/crimper, but rolling the rye prior to anthesis was less effective (Mirsky 2008). In the northeastern U.S., waiting until cereal rye reaches anthesis for effective control can delay planting of the cash crop. Combining an effective herbicide with a roller/crimper could offer the benefits of earlier and excellent cover crop control along with weed suppression offered from the rolled cover crop.

Weed suppression through the use of cover crops is only part of an integrated weed management strategy that should also include ecological approaches that include numerous methods to help suppress weeds. In this study, we combined several tactics (cover crop, timing of planting, and herbicide) to help manage weeds in no-till soybeans. The objectives of this study were to: 1) quantify the amount of weed suppression offered by combining herbicide and rolling/crimping cereal rye at two different relative planting dates in no-till soybean, 2) determine the contribution of a rolled rye cover crop for residual weed control in the cover crop-soybean system, and 3) assess the net economic benefits of adding a rolled cover crop to a no-till soybean system.

Materials and Methods

Field Management. Cereal rye 'Aroostook' was seeded at 157 kg/ha with a no-till drill (19-cm row spacing), on September 22, 2006 and September 21, 2007 at the Russell E. Larson Agricultural Research Farm (Rock Springs), Centre County, PA (40.72 degrees N, 77.93 degrees W). The same variety and seeding rate were used to no-till plant rye on October 14, 2006 and September 27, 2007 at the Penn State Southeast Research and Extension Center, (Landisville) Lancaster County, PA (40.12 degrees N, 76.43 degrees W). The soil at both locations was a Hagerstown silt loam (mesic Typic Hapludalf), a well-drained productive soil common to Pennsylvania (Baker 1981). The soil pH at both Rock Springs and Landisville ranged from 6.5 to 6.7 over the two years and the organic matter at both locations was 3%. The previous crops were small grains at both Rock Springs and Landisville in both years.

The experiment was designed as a two-way factorial with rye termination/soybean planting as the first factor (early vs. late) and weed control method as the second. Plots were 3 m x 11 m arranged in a randomized complete block design with four replications. Within rye termination/soybean planting, three weed control treatments were examined: 1) herbicide treated/rolled rye cover crop without further weed control; 2) herbicide treated/rolled rye cover crop followed by post-emergence herbicide application and; 3) herbicide treated fallow (no cover crop) without further weed control. In 2007/08 the trial was modified by adding a fourth treatment: 4) herbicide treated fallow followed by post-emergence herbicide application.

In order to establish the experiment, the entire study areas were planted to rye. Clethodim was used to selectively remove the cereal rye in the 'no rye' plots by applying 0.175 kg ai/ha clethodim plus 1% v/v methylated seed oil on Oct. 30 and Nov. 1 at Rock Springs and Landisville respectively in 2007 and Nov. 14 at both locations in 2008. In late March and/or early April, urea was broadcast over the entire study at 79 kg N/ha to stimulate rye growth and development to ensure a competitive cover crop, particularly since it followed another cereal grain (oats) likely leaving an N-deficit. Both the early and late rye were terminated by applying glyphosate[1] at 0.84 kg ae/ha using a tractor mounted compressed air sprayer between late April and mid May (Table 1). Just prior to the herbicide application, rye growth stage was determined (Zadoks et al. 1974) and above-ground biomass was sampled from each plot by using a 0.5 m^2 quadrat. Rye biomass was oven-dried at 55 C for at least 48 h and weighed.

One to six days following herbicide application, the plots were rolled using a 3 m wide cover crop roller/crimper (Figure 1). The roller/crimper used in this study was constructed using 41 cm diameter steel with blunt metal blades welded to the outside cylinder in a chevron pattern[2] (Ashford and Reeves 2003). The roller/crimper was filled with water and weighed about 900 kg and was front mounted to the tractor driven at approximately 7.2 km/h. At Rock Springs in 2008, a heavier roller/crimper (1520 kg) was used (Mirsky 2008). The rye was rolled perpendicular to the direction of sowing to obtain maximum soil cover by the cover crop residue and to help facilitate the soybean planting operation (Kornecki et al. 2005). Glyphosate-resistant soybean seed 'Pioneer 93M11' treated with thiamethoxam, mefenoxam [methyl N-(2,6-dimethylphenyl)-N(methoxyacetyl)-D-alaninate], and fludioxonil [4-(2,2-difluror-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile] was no-till planted within 7 days after rolling in the same direction of rolling with a 19 cm-row spacing at a seeding rate of 500,000 seeds/ha. Soybeans were seeded with a Great Plains[3] no-till drill at Rock Springs and by making two passes with a 38-cm row spaced White[4] no-till planter at Landisville. Glyphosate was again applied at 0.84 kg/ha using a hand-held CO_2 backpack sprayer six weeks after soybean planting (WAP) to individual plots that were to receive the postemergence herbicide. All herbicides were applied in water at 187 L/ha at 207 kPa.

Weed, crop, and economic measurements. At 4 WAP, soybean populations were determined by counting all soybean plants within four rows in three 0.5 m^2 quadrats per plot. Weed density was determined 4, 6, 8, and 10 WAP by counting all weeds by species in three 0.5 m^2 quadrats per plot where no wheel traffic disturbed the rye residue. Weed density measurements were repeatedly taken from the same quadrat location. Above ground weed biomass was collected 10 WAP from the 3 established quadrats per plot, oven dried at 55 C for at least 72 h and weighed. Soybean yield was determined using a small plot combine by harvesting the center 1.5 m of each plot, for the entire length. Soybean grain was weighed and adjusted to 13% grain moisture. Analysis of variance was conducted using the MIXED model procedure in SAS/STAT (SAS Institute, 2004) to test the effects of termination dates, weed control, and their interactions. Because weed density counts were performed in fixed sub-plots at 4, 6, 8, and 10 WAP typical of a repeated measures design, “time” was included as a factor in the model. Where appropriate, a test for homogeneity of variance was performed using residual error terms to determine if data could be pooled across locations and years. Analysis showed significant differences between both locations and between years and, therefore, data were analyzed separately for each location and year. Treatment means were separated using Tukey-Kramer at $P \leq 0.05$, a relatively conservative multiple comparison analyses (Steel et al. 1997).

An economic analysis was performed using a partial budget worksheet (Roth and Hyde 2002) using the average custom rates for small grain drilling and custom spray application in Pennsylvania (Pike 2008). The base system of no-till soybeans without rye cover crop with two herbicide applications was compared with two alternative systems; 1) using a rye cover crop with a roller/crimper and a single preplant burndown herbicide, and 2) using a rye cover crop with a roller/crimper and a preplant and postemergence herbicide. Straight-line depreciation was used for roller/crimper yearly use and tractor speed was assumed to be 8 km/h with a 3 m wide roller/crimper with the Pennsylvania state average rental cost of $32.30/h. Results are reported in US dollars/ha.

Results and Discussion

Cereal Rye Cover Crop. There were major differences in rye biomass between termination dates as well as between years. The differences observed between 2007 and 2008 can mostly be attributed to timing of termination. Early and late termination dates were closer together in 2007 than in 2008 and the rye was planted about a month later at Landisville than at Rock Springs in fall of 2006 decreasing rye biomass production at that location. Previous Pennsylvania research showed that spring rye biomass accumulation increased by about 65% between a late August seeding and mid-October (Mirsky 2008). In three out of the four location/year combinations rye biomass at least doubled from the early rye termination date to the later date (Table 2). This increase in biomass with the delay in termination was expected; cereal rye matured from as early as boot just swollen (Zadok 45) to early anthesis (Zadok 62) between the early and late dates. Previous Pennsylvania research also showed about a 37% increase in spring biomass with each 10 day delay in cover crop termination in May (Mirsky 2008). The amount of rye biomass produced in this study is similar or greater than that reported by Ruffo and Bollero (2003) in Illinois and Westgate et al. (2005) in Iowa. The cereal rye at the later termination dates in this study averaged from 5594 to 8940 kg/ha with plant height increasing 27 to 100% between early and late termination. In addition to cover crop planting and termination date, rainfall and soil fertility will strongly influence biomass accumulation and both were ample during this study.

Weed Management. In 2007 at Rock Springs, perennial weed species included dandelion and yellow nutsedge, while annual broadleaf weeds included common ragweed, pigweed, and common lambsquarters. Annual grasses in 2007 at Rock Springs included giant and yellow foxtail. In 2008, the Rock Springs weed species were similar to 2007. Very few weeds were present at Landisville in 2007 and primary weeds included carpetweed and purslane, generally not major problem weeds in field crops. In 2008, weeds were more prevalent at Landisville than in 2007 and included the species already mentioned.

Weed density and biomass were analyzed separately by year because of differences in species composition and treatment structure between years. Within years, differences in homogeneity of variance did not allow pooling across locations (Steel et al. 1997). At Rock Springs in 2007, despite greater rye biomass at the later termination date, termination date did not impact weed density (Table 3). Time of sampling (4, 6, 8 or 10 WAP) was also not important, but weed control treatment did influence weed density with the highest density occurring in the fallow plots and the lowest density occurring in the treatments that included the cover crop (Table 4). Common lambsquarters, foxtail species, and yellow nutsedge densities were reduced by the rye cover crop at Rock Springs in 2007. At Landisville in 2007, total weed density (mostly carpetweed and purslane) had a significant termination date by weed control treatment interaction where weed density was greatest in the early fallow (EF) and early rye (ER) treatments (Table 4). The purslane and carpetweed likely emerged where there was less residue in the EF residue treatment and in the fallow treatment where the weeds were able to take advantage of light and nutrient resources prior to soybean canopy closure. At both locations in 2007, the post-emergence herbicide application did not improve the level of weed control above the rye treatment alone at the later termination date (Table 4).

At Rock Springs in 2008, termination date, weed control and time of sampling affected weed density (Table 3). In general, the earlier termination date had more weeds than the later date only in the fallow treatments. At 4 WAP, all treatments ranged from 0 to 15 weeds/m^2 and the fallow treatments had the highest weed densities (Figure 2). By 6 WAP, the EF treatments had the highest weed densities followed by the late fallow (LF) with the early (ER) and late (LR) rye cover crop treatments having the lowest weed densities, regardless of termination date. By 8 WAP, treatments that included a postemergence herbicide resulted in a dramatic reduction in weed density, while densities in the EF and LF treatments continued to increase. By 10 WAP, weed density in the ER, LR and

LF plots were not different. The rye residue reduced early season weed density, but as the season progressed the decomposing mulch allowed some weeds to emerge. Treatments with a post-emergence herbicide had the lowest weed density and the EF treatment had more than double the number of weeds of the other treatments (Figure 2). Common lambsquarters and foxtail species were the main contributors to total weed density at Rock Springs in 2008 with lesser amounts of common ragweed and yellow nutsedge.

At Landisville in 2008, weed density did not differ across termination date or sampling time. Weed density was higher and more diverse than the previous year at Landisville and annual grasses and broadleaves contributed to total weed density. The rye cover crop, rye plus post-herbicide, and fallow plus postemergence herbicide reduced weed density compared with the fallow alone treatment (Table 4). Fallow plots had seven times the total weed density of the rye cover crop plots and 18 times more weeds than a rye cover crop plus post herbicide treatment; this was similar to the results observed at Rock Springs. Once again, weed density was reduced in the presence of rye mulch.

In 2007 at Rock Springs, weed biomass differed across weed control method and responded similarly to the trends observed in weed density. Weed biomass was 85 kg/ha or less in the rye treatments compared with greater than 1200 kg/ha in the fallow treatments (Table 5). Additionally, there was no benefit in delaying cereal rye termination or in using a postemergence herbicide to further reduce weed biomass. At Landisville in 2007, unlike weed density, weed biomass only differed with termination date. Although weed control strategy was not significant (p = 0.07), the weeds that emerged in the earlier termination date treatment that were not controlled with a postemergence herbicide accumulated the greatest dry matter.

In 2008 at Rock Springs, while termination date was an important factor for weed density, it did not impact weed biomass (Table 3). Weed control strategy did affect weed biomass and the rye treatments had lower biomass than the fallow treatments, but more biomass than the treatments that received the postemergence herbicide (Table 5). Averaged over termination and planting date, weed biomass declined from 452 kg/ha with rye to 4 kg/ha with rye plus postemergence herbicide. Unlike 2007, common ragweed was present in 2008 and the postemergence herbicide was more critical to reducing weed biomass. Common ragweed, with its large seed, is likely affected less by surface residues based on work with other large seeded species (Mohler and Teasdale 1993).

At Landisville in 2008, a termination date by weed control treatment interaction occurred (Table 3); all rye cover and postemergence herbicide treatments had lower weed biomass than the EF and LF treatments and EF had more weed biomass than the LF treatment (Table 5). Although weed density was not impacted by termination date, weed biomass was lower in the late termination date compared to the early date in the absence of the cover crop (4367 vs. 2242 kg/ha). Weed emergence research has identified that individual species emergence is closely related to soil or air temperature (Myers et al. 2004). Weeds such as common ragweed and common lambsquarters many exhibit a delay in emergence with later rye termination because of greater rye biomass on the soil surface reducing surface temperature. The rye cover crop not only prevents some small-seeded weeds from acquiring enough light resources to germinate, but emergence is also delayed through slower soil warming. Delayed glyphosate applications in the later terminated rye would likely kill more weed seedlings than an earlier application when there is less rye biomass and fewer weeds.

Soybean Cash Crop. At Rock Springs in 2007, soybean populations differed with the timing of rye termination and soybean planting (Table 3) with higher soybean populations at the early rye termination than at the later termination and planting (Table 6). Dry weather during the late planting date made it more difficult to achieve consistent soybean populations at Rock Springs. The opposite occurred at Landisville in 2007, with higher soybean populations at the later rye termination compared with the early rye termination (Table 6), probably because of timely rainfall and better success with the planter at Landisville compared with the drill at Rock Springs.

At both locations in 2008, soybean populations were reduced on average over 60% from the target plant population and ranged from 76,000 to approximately 187,000 plants/ha (Tables 7 and 8). Cool weather dominated the first half of May after planting at both locations, contributing to the reduced stand. At Rock Springs in 2008, soybean populations were lowest in rye cover crop treatments, but even the fallow treatments had less than 40% of the targeted plant population. To increase plant population, the late rye termination plots were replanted in late June at Rock Springs. This occurred after stand counts were performed, so soybean populations presented do not reflect the final populations. At Landisville in 2008, the early planted soybeans had higher populations than the later planted soybeans and weed control strategy did not influence population (Table 8). Wet soil conditions at Landisville at the late planting date made it difficult to fully close the seed furrow which likely contributed to the low soybean populations in 2008.

In 2007, at both Rock Springs and Landisville, soybean yield did not vary with the timing of rye termination or weed control strategy (Table 3). Grain yields averaged 5192 kg/ha across locations and treatments (Table 6). In 2007, soybean populations ranged from 61 to 105% of the targeted population and growing conditions during the summer months were favorable for good soybean growth and development. In contrast to 2007, the effect of weed control strategy varied with termination date at Rock Springs in 2008 (Table 3). The highest yields occurred where the postemergence herbicide was used, and yield increases due to the rye cover crop were not different than the fallow treatment at each respective termination timing (Table 7). At Landisville in 2008, the fallow treatments had reduced yield relative to treatments with rye cover and postemergence herbicide (Table 8). Yield in the fallow plots without weed control averaged 2757 kg/ha across termination date or at least 2188 kg/ha less than other treatments. At Landisville in 2008, yield in the rye cover crop treatment was not different than the yields that received postemergence herbicide (Table

8), showing that the rye mulch can provide a sufficient barrier to reduce weed density and biomass and maintain soybean yield.

Economic Assessment. Partial budgeting (Table 9) was calculated to compare a base case of no rye cover crop (fallow) with two glyphosate applications (pre- and post-soybean planting) to the scenario of using a rye cover crop terminated with glyphosate followed by the roller/crimper. A second alternative system was also compared where the rye cover crop was terminated with glyphosate followed by the roller/crimper and a second postemergence glyphosate application was used for weed management. This would be a more typical production practice for no-till growers who might consider using a rye cover crop. Fallow treatments that did not receive any post emergence herbicide were not included in the comparison, because they were included in the experimental design as weedy check plots and are not considered a viable production practice. Planting date data (early and late) were not included in the economic comparison since yields did not differ between early and late dates in this study. In the first scenario, the total net added cost of using the rye cover crop is $68.50/ha (Table 9) which would save one herbicide application. The value of soybean grain in Pennsylvania from 2000 to 2007 ranged from $0.1562/kg to $0.3575/kg (Anonymous 2008c). Using these costs would require an additional 192 to 439 kg/ha soybean grain yield to offset the added cost of the rye cover crop. Comparing the second alternative system, using a rye cover crop with two glyphosate applications, the total net added costs would be $123.00/ha (Table 9).

Using the same price scenario, an additional 344 to 787 kg/ha grain would be needed to off-set the costs of this system compared with a conventional no-till system without the rye cover crop.

The main cost associated with the use of cover crops for soil conservation and added weed management is cover crop seed. Seed cost was calculated using a price of $0.33/kg (Anonymous 2008a) and a seeding rate of 157 kg/ha (Table 9). With some cover crop incentive programs, the cost of seed may be subsidized. For example, a 2008 Bedford County, Pennsylvania Cover Crop Incentive Program paid $49.40/ha to include a winter rye cover crop on the farm (Anonymous 2008b). As another example, Maryland has a program through the Department of Agriculture that includes the cost of the seed plus other establishment costs. The Maryland program includes a base payment of $99/ha per year for using cover crops and up to $210/ha per year if farmers meet certain other guidelines (targeted watersheds, manure management, etc.) (Maryland Dept. Agric. 2009). In our example, if seed cost is removed from the partial budget through government subsidies or other incentive programs, there is still a $16.50/ha total net added cost when using the alternative single herbicide application cover crop system. Even without seed costs, it would still require between 46 and 106 kg/ha increased grain yield to compensate for the added cost of the alternative cover crop based system. If rolling and planting were done in one-pass, or if producers were willing to potentially delay soybean planting and roll the rye when herbicides are no longer necessary for successful control

(Mirsky 2008), then the profitability of implementing a rye cover crop and using a roller/crimper would be more favorable.

Finally, cover crops also have many other benefits besides offering the potential for short-term weed suppression and reducing herbicide inputs as outlined in this paper. Cover crops reduce soil erosion thereby keeping watersheds free of excess sediments and pesticides (Clark 2007; Langdale et al. 1991); they also sequester nutrients which help in the prevention of nutrients being lost into sensitive ecosystems (Shipley et al. 1992), such as the Chesapeake Bay. Long-term, societal, and environmental benefits are difficult to evaluate financially and do not accrue directly to the farmer, especially on farm land managed under a short-term lease agreement. Therefore, the indirect grower benefits fall outside of standard economic analyses such as this.

This study shows that it is possible to reduce weed density and biomass with the integration of a rye cover crop into a no-till soybean cropping system. In this study, delaying rye termination by 10 to 20 days nearly doubled cover crop biomass, but did not consistently improve weed control. This may have been due to relatively early termination dates (April 24th to May 17th) followed by soybean planting along with competitive rye cover crops at all locations. Even at early rye termination, weed density and biomass were reduced compared with no rye cover crop. Although this study did not examine rolled rye versus rye that was not rolled, placing the cover crop mulch in a unidirectional pattern on the soil surface should provide better weed suppression and could allow for easier soybean seed placement when direct seeding into high biomass cover crops.

This potential advantage should be explored more fully. In 2008, soybean populations were reduced at both locations, partially as a result of the cover crop surface mulch. Large amounts of cover crop residue at planting time will continue to challenge growers that direct seed. Improvement in planter and drill technology should help alleviate some of these problems.

This study showed that a rye cover crop can help reduce herbicide inputs and could be a step towards a more diverse weed management strategy that improves agricultural sustainability. While the short-term economics do not favor the use of a rolled rye cover crop, there are numerous long-term advantages that were not included in this study, which justifies further research to determine if improvements can be incorporated into this practice.

Sources of Materials

[1] Roundup WeatherMax 4S (540 g ae/L, potassium salt formulation), Monsanto Co., 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[2] Roller/crimper, I&J Manufacturing, 5302 Amish Rd., Gap, PA 17527.

[3] Great Plains no-till drill, Great Plains Mgf., Inc. 1525 E North Street, P.O. Box 5060, Salina, KS 67401.

[4] White no-till planter, AGCO Corp., 4205 River Green Parkway, Duluth, GA 30096.

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Table 1. Date of field operations at Rock Springs and Landisville, PA in 2006 to 2008.

	Rock Springs		Landisville	
Field Operation	2006/2007	2007/2008	2006/2007	2007/2008
Early				
Burn-down herbicide	May 8	Apr 25	May 4	Apr 25
Roll rye	May 10	Apr 26	May 8	May 1
Planting soybeans	May 10	May 2	May 8	May 3
Post herbicide application	Jun 16	Jun 13	Jun 12	Jun 12
Late				
Burn-down herbicide	May 17	May 14	May 14	May 13
Roll rye	May 18	May 15	May 17	May 14
Planting soybeans	May 19	May 26[a]	May 18	May 25
Post herbicide application	Jun 29	Jul 11	Jun 27	Jun 28
Harvest soybeans	Oct 22	Oct 23	Oct 25	Oct 19

[a] Replanted on June 25 in late rye plots due to low soybean populations.

Table 2. Effect of rye termination timing on rye growth stage, height, and dry matter production at Rock Springs and Landisville, PA in 2007 and 2008.

Location	Year	Timing of rye termination	Growth Stage [a]	Height	Biomass [b]
			Zadok	m	Kg/ha
Rock Springs	2007	Early	47	0.75	5013 b
		Late	59	1.37	6955 a
	2008	Early	44.5	0.91	3090 b
		Late	59	1.45	6498 a
Landisville	2007	Early	45	0.61	2593 b
		Late	59	1.22	5594 a
	2008	Early	54	1.22	4515 b
		Late	62	1.55	8940 a

[a] Growth stage and height data collected from random samples throughout the experiment inappropriate for statistical analysis.

[b] Different letters in columns, within a location/year indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

Table 3. ANOVA (PROC MIXED) for termination date (TD), weed control (WC) and sampling time (4, 6, 8, 10 wks after planting) for weed density, biomass, soybean (SB) population and yield at Rock Springs and Landisville, PA in 2007 and 2008. Weed density and biomass analysis includes all sampled species.

	Year							
	2007				2008			
Location/Effect	weed density	weed biomass	SB population	SB yield	weed density	weed biomass	SB population	SB yield
Rock Springs	p-value							
Termination date	0.2205	0.9985	0.0028	0.3412	0.0482	0.7473	0.0012	0.2294
Weed control	<.0001	0.0017	0.2033	0.2155	<.0001	<0.001	0.006	<0.0001
TD*WC	0.8122	0.9699	0.8494	0.7111	0.0590	0.206	0.0099	0.0293
Time	0.246	-	-	-	0.0007	-	-	-
Landisville								
Termination date	<.0001	0.0065	<0.0001	0.6495	0.5009	0.0371	0.0039	0.067

Weed control	0.0072	0.0709	0.1122	0.4566	<.0001	<0.0001	0.7888	<0.0001
TD*WC	0.008	0.0988	0.7529	0.5455	0.3706	0.0143	0.9694	0.4849
Time	0.3878	-	-	-	0.6243	-	-	-

Table 4. Effect of rye termination timing (early and late) and weed control method (fallow, rye, rye+post, fallow+post) on weed density by species and total weed density at Rock Springs (RS) and Landisville (LV), PA in 2007 and 2008[a].

Location/ year	Treatment	Common ragweed	Common lambsquarters	Foxtail species	Yellow nutsedge	Total [b]
		----------	----------	plants/ m^2 [c]	----------	----------
RS 2007	Fallow	- [d]	45 b	7.0 b	8.0 b	128 b
	Rye	-	2.0 a	2.0 a	3.0 a	22 a
	Rye+post	-	0.0 a	0.0 a	1.0 a	9.0 a
LV 2007						
Early	Fallow	-	-	-	-	81.6 c
	Rye	-	-	-	-	39.7 b
	Rye+post	-	-	-	-	8.1 a
Late	Fallow	-	-	-	-	5.2 a
	Rye	-	-	-	-	6.3 a
	Rye+post	-	-	-	-	6.2 a
RS 2008 [e]						
Early	Fallow	4.0 b	15.5 c	16.75 b	5.0 b	45 c
	Rye	3.0 b	1.75 b	3.5 a	1.5 ab	15 b
	Rye+post	0.0 a	0.25 ab	0.5 a	0.0 a	0.5 a
	Fallow+post	0.0 a	0.75 ab	0.25 a	0.5 a	1.2 ab
Late	Fallow	3.0 b	10 c	2.25 a	3.75 ab	16.25 b
	Rye	2.25 ab	2.75 b	5.0 a	4.25 b	12.5 b
	Rye+post	0.0 a	0.0 a	0.0 a	0.25 a	0.25 a
	Fallow+post	0.0 a	0.0 b	0.0 a	0.0 a	0.0 a
LV 2008	Fallow	-	-	67 b	9.3 a	110 b
	Rye	-	-	6.0 a	0.25 a	15.0 a
	Rye+post	-	-	1.0 a	0.0 a	6.0 a

Fallow+post	-	-	10.0 a	2.1 a	34 a

[a]Data pooled across 4, 6, 8, and 10 weeks after termination except Rock Springs 2008 where the data presented is 10 weeks after planting (due to significant time effect as outlined in Figure 2).

[b] Total weeds included purslane and carpetweed at Landisville in 2007 and in addition to those listed, smooth and redroot pigweed at Landisville in 2008.

[c] Different letters in columns indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

[d] Weed species were not present.

[e]Termination date by weed control interaction significant at $p = 0.06$.

Table 5. Effect of rye termination timing (early or late) and weed control method (fallow, rye, rye+post, fallow+post) on total weed biomass 10 weeks after planting at Rock Springs and Landisville, PA in 2007 and 2008.[a]

	2007		2008		
				Landisville[c]	
Main effect	Rock Springs[b]	Landisville	Rock Springs	Early termination	Late termination
Termination	kg/ha				
Early	449 a	201 b	339 a	-	-
Late	450 a	8 a	370 a	-	-
Weed control					
Fallow	1251 b	166 b	959 c	4367 c	2242 b
Rye	85 a	141 b	452 b	329 a	200 a
Rye+post	12 a	6 b	4 a	0 a	0 a
Fallow+post	-	-	1 a	0 a	38 a

[a] Main effects of termination date and weed control significant at Rock Springs in 2007 and 2008 and at Landisville in 2007. The termination date by weed control interaction significant at Landisville in 2008.

[b] Different letters in columns within termination and weed control indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

[c] Different letters within both the early and late termination date columns indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

Table 6. Effect of rye termination timing (early or late) on soybean population and grain yield at Landisville and Rock Springs, PA in 2007.

	Landisville [a]		Rock Springs [a]	
Treatment	Soybean population	Grain yield	Soybean population	Grain yield
	no./ha	kg/ha	no./ha	kg/ha
Early	353305 b	5142 a	372155 a	5368 a
Late	529085 a	5147 a	304564 b	5096 a

[a] Different letters in columns indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

Table 7. Effect of rye termination timing (early or late) and weed control method (fallow, rye, rye+post, fallow+post) on soybean population (SB) and grain yield at Rock Springs, PA in 2008. Terrmination date by weed control interaction significant at Rock Springs.

	SB population		Grain yield	
	Termination [a]			
	Early	Late [b]	Early	Late
Weed control	No./ ha		Kg/ha	
Fallow	91667 b	186667 a	1905 c	2660 bc
Rye	91667 b	75833 b	2590 bc	2811 ab
Rye+post	83334 b	106667 b	3530 a	3126 ab
Fallow+post	117500 a	176667 a	3036 ab	3086 ab

[a]Different letters within both the early and late termination date columns indicate a statistical difference between treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

[b] Soybean population does not include replanted soybeans for Rock Springs late terminated rye treatments.

Table 8. Effect of rye termination timing (early or late) and weed control method (fallow, rye, rye+post, fallow+post) on soybean population (SB) and grain yield at Landisville, PA in 2008. Main effects of termination date and weed control significant at Landisville

Main effect	SB population [a]	Grain yield [a]
Termination	No./ha	kg/ha
Early	158750 b	4933 a
Late	125625 a	4347 a
Weed control		
Fallow	145833 a	2757 b
Rye	136250 a	4945 a
Rye+post	137916 a	5766 a
Fallow+post	148750 a	5092 a

[a] Different letters in columns indicate a statistical difference between main effect treatments at $p \leq 0.05$ (Tukey-Kramer mean separation).

Table 9. Partial budgets for comparing 1) a base treatment of no cover crop plus two glyphosate applications (pre and post planting), 2) a rye cover crop terminated with one glyphosate application and a roller/crimper, and 3) a rye cover crop terminated with a glyphosate application and a roller/crimper and a post plant application of glyphosate.

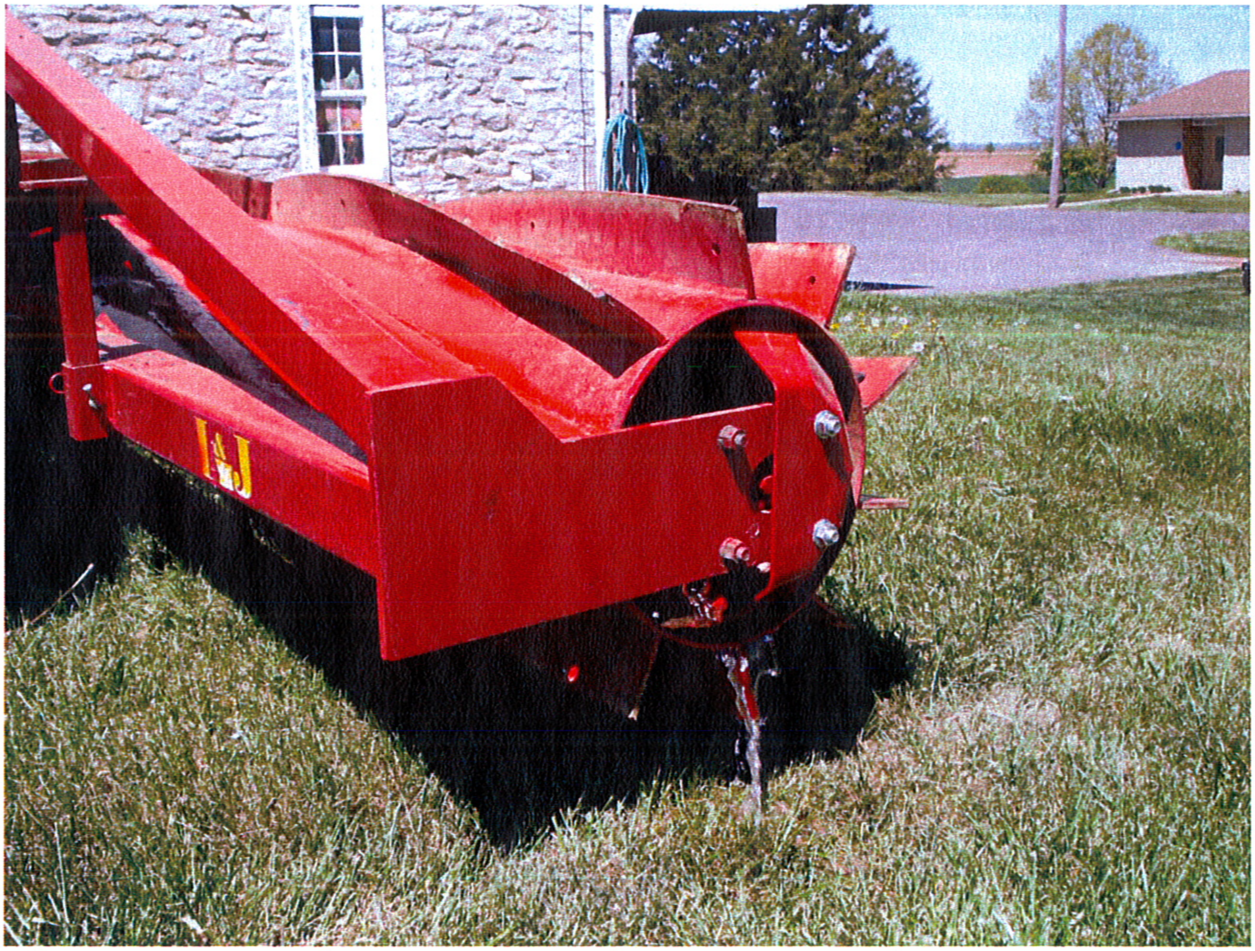
Program	Description	Amount
		$/ha
1. Base with no rye cover crop		
Herbicide	Glyphosate applied at 0.84 kg ae/ha (1.6 L/ha Roundup Weathermax) twice (pre and post) at a cost of $19.30 L (Anonymous, 2008c)	$62.00
Custom spray application	Two applications (Pike 2008)	$47.00
Total cost		**$109.00**
2. Rye cover crop with roller/crimper and one glyphosate application (pre only).		
Herbicide	Glyphosate applied at 0.84 kg ae/ha (1.6 L/ha Roundup Weathermax) once at a cost of $19.30 L (Anonymous, 2008c)	$31.00
Custom spray application	One application (Pike 2008)	$23.50
Rye seed	$0.33/kg at seeding rate of 157 kg/ha (Anonymous 2008a).	$52.00
Rye establishment	Drilling small grain (Pike 2008).	$43.00
Roller/crimper depreciation	Straight line depreciation with roller/crimper. Initial cost $3000 with the salvage value of $0 over 5 years used on 40 ha/year (I&J Manufacturing Inc.;	$15.00

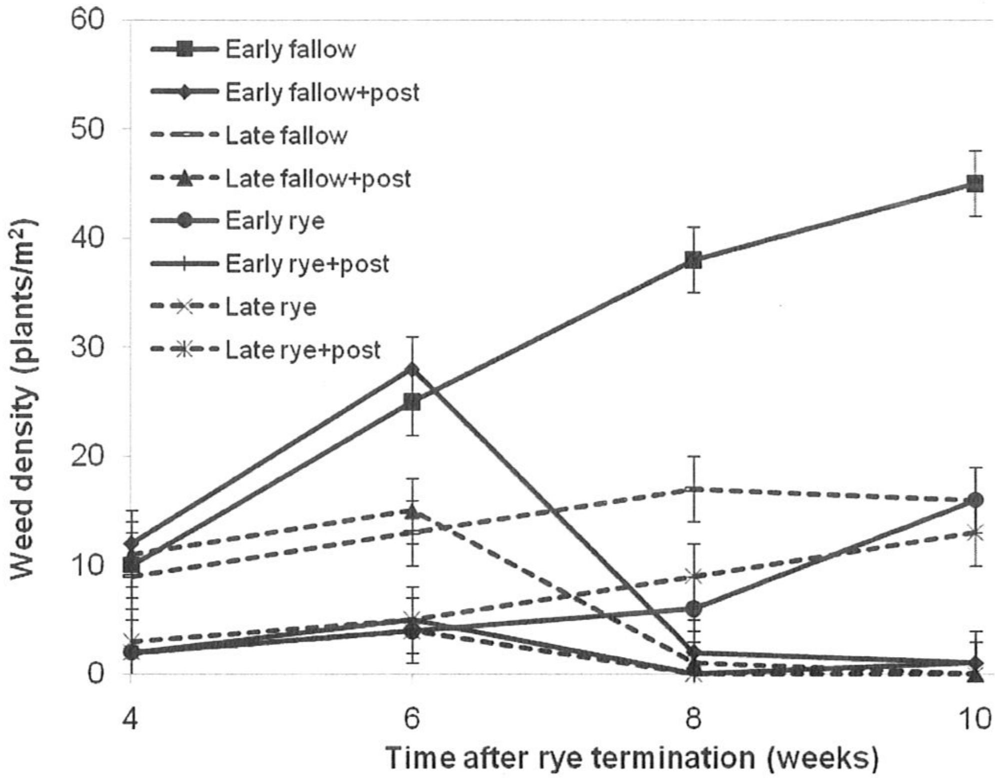
	Roth and Hyde 2008).	
Tractor use for roller/crimper	Driven at 8 km/h at with 80 to 120 HP, PA 2008 average rental price of $32.30/h (Pike 2008).	$13.00
Total cost		**$177.50**
Net benefit or loss	**(Program 2 compared to Base)**	**-$68.50**
3. Rye cover crop with roller/crimper + 2 glyphosate applications (pre/post planting)		
Herbicide	Glyphosate applied at 0.84 kg ae/ha (1.6 L/ha Roundup Weathermax) twice at a cost of $19.30 L (Anonymous, 2008c)	$62.00
Custom spray application	Two applications (Pike 2008)	$47.00
Rye seed	$0.33/kg at seeding rate of 157 kg/ha (Anonymous, 2008a).	$52.00
Rye establishment	Drilling small grain (Pike 2008).	$43.00
Roller/crimper depreciation	Straight line depreciation with roller/crimper. Initial cost $3000 with the salvage value of $0 over 5 years used on 40 ha/year (I&J Manufacturing Inc.; Roth and Hyde 2008).	$15.00
Tractor use for roller/crimper	Driven at 8 km/h at with 80 to 120 HP, PA 2008 average rental price of $32.30/h (Pike 2008).	$13.00
Total cost		**$232.00**
Net benefit or loss	**(Program 3 compared to Base)**	**-$123.00**

Figure Captions

Figure 1. Side view of an I&J cover crop roller/crimper with chevron blade pattern (I&J manufacturing, Gap, PA).

Figure 2. Total weed density at Rock Springs in 2008 at 4, 6, 8, and 10 wks after rye termination. Early rye terminated treatments are shown with a solid line while late terminated treatments are shown with a dashed line. Bars represent standard error of the means.





Weed density (plants/m²)
60
50
40
30
20
10
0
4
6
8
10
Time after rye termination (weeks)
Early fallow
Early fallow+post
Late fallow
Late fallow+post
Early rye
Early rye+post
Late rye
Late rye+post

*Response to Reviewers